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Wpływ wybranych czynników agrotechnicznych na wzrost roślin, plon i jakość owoców papryki słodkiej (*Capsicum annuum* L.) w uprawie hydroponicznej

Effect of chosen agrotechnical factors on growth, yield, and fruit quality of sweet pepper (*Capsicum annuum* L.) under hydroponic cultivation

Rozprawa doktorska

Doctoral thesis

Rozprawa doktorska wykonana pod kierunkiem

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Serdecznie dziękuję
Pani dr hab. inż. Katarzynie Kowalczyk, prof. SGGW
oraz
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za opiekę naukową, cenne wskazówki i pomoc,
a także za życzliwość i wyrozumiałość
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Słowa uznania i wdzięczności kieruję także do Pracowników
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SPIS TREŚCI

STRESZCZENIE

Wpływ wybranych czynników agrotechnicznych na wzrost roślin, plon i jakość owoców papryki słodkiej (*Capsicum annuum* L.) w uprawie hydroponicznej

Celem badań była ocena wpływu wybranych czynników agrotechnicznych, takich jak: doświetlanie LED w produkcji rozsady papryki, nawożenie z użyciem polifosforanów oraz dolistne i dokorzeniowe zastosowanie kwasu salicylowego, na efektywność plonowania i jakość owoców papryki w uprawie hydroponicznej. W nawiązaniu do celu głównego postawiono pięć hipotez badawczych: (I) Doświetlanie lampami LED korzystnie wpływa na wzrost oraz jakość rozsady papryki przeznaczonej do upraw hydroponicznych, (II) Zastosowanie polifosforanów do fertygacji w uprawach hydroponicznych wpływa na wzrost i metabolizm roślin papryki, co skutkuje wyższym plonowaniem, (III) Zastosowanie dolistne kwasu salicylowego stymuluje wzrost roślin papryki w warunkach stresu wywołanego wysokim EC pożywki do fertygacji roślin, poprawiając ich metabolizm, (IV) Kwas salicylowy zwiększa odporność roślin papryki na niekorzystne warunki środowiskowe w uprawie hydroponicznej, (V) Dolistne stosowanie kwasu salicylowego poprawia plon oraz jakość owoców papryki w uprawie hydroponicznej – pod względem zawartości składników odżywczych, potencjału antyoksydacyjnego i cech sensorycznych.

W latach 2018–2021 w Szklarniowym Ośrodku Doświadczalnym SGGW w Warszawie przeprowadzono badania nad uprawą papryki w systemie hydroponicznym, z wykorzystaniem podłoża mineralnego, oraz w systemie aeroponicznym. Do badań użyto dwóch odmian papryki słodkiej o owocach czerwonych: 1) 'Aifos' F1 (firmy Seminis, Bayer) o owocach typu „block", 2) 'Palermo' F1 (firmy Rijk Zwaan) o owocach wydłużonych, typu 'Dulce Italiano'. W pierwszej części badań oceniano efektywność stosowania lamp LED, zamiast tradycyjnie używanych lamp sodowych, do doświetlania rozsady papryki produkowanej w podłożu mineralnym oraz efektywność zastosowania w uprawie hydroponicznej papryki fosforu w formie polifosforanów, w porównaniu do ortofosforanów. W części drugiej podjęto badania nad stresem abiotycznym u papryki, wywołanym wysokim EC pożywki do fertygacji roślin i nad zastosowaniem kwasu salicylowego jako czynnika łagodzącego negatywne skutki stresu. Oceniano wpływ dolistnego i dokorzeniowego zastosowania kwasu salicylowego na wybrane parametry fizjologiczne i biochemiczne papryki rosnącej w systemie aeroponicznym, w warunkach stresu wysokiego EC uzyskanego poprzez dwukrotne zwiększenie stężenia roztworu pożywki do fertygacji roślin. W kolejnych badaniach oceniano wpływ dolistnego

opryskiwania roślin 0,03% roztworem kwasu salicylowego i 0,7% roztworem azotanu wapnia oraz roztworem zawierającym oba te składniki w podanych stężeniach na wzrost roślin, plon oraz jakość owoców papryki uprawianej w podłożu z wełny mineralnej. W toku badań oceniano wybrane parametry morfologiczne roślin, zawartość chlorofilu w liściach (w jednostkach względnych SPAD) i fluorescencję chlorofilu *a* oraz stężenie składników mineralnych w liściach. Do oceny komórek liści roślin doświetlanych LED użyto mikroskopii świetlnej i konfokalnej. W celu oceny reakcji roślin papryki na stres wysokiego EC pożywki oraz na zastosowanie kwasu salicylowego, badano zawartość białka rozpuszczalnego, H_2O_2 i enzymów antyoksydacyjnych, takich jak dysmutaza ponadtlenkowa i katalaza. W doświadczeniach uprawowych określano liczbę i masę owoców handlowych i owoców z zaburzeniem fizjologicznym BER (sucha zgnilizna wierzchołkowa). Badano barwę i twardość owoców oraz zawartość cukrów, kwasów organicznych, witaminy C, karotenoidów i składników mineralnych w owocach. Oceniano potencjał antyoksydacyjny owoców metodą DPPH, ABTS i TPC oraz dokonywano oceny sensorycznej owoców papryki.

Doświetlanie rozsady papryki lampami LED korzystnie wpływało na rozwój aparatu asymilacyjnego roślin – zwiększeniu uległa grubość liści oraz liczba chloroplastów, a także parametry fluorescencji chlorofilu *a*. Zastosowanie 30% fosforu w formie polifosforanów w pożywce do uprawy hydroponicznej istotnie zwiększało aktywność fotosyntetyczną liści oraz udział plonu handlowego w plonie całkowitym owoców, szczególnie w przypadku odmiany wykazującej większą podatność na suchą zgniliznę wierzchołkową. Egzogenna aplikacja kwasu salicylowego, niezależnie od EC pożywki, ograniczała występowanie objawów BER oraz aktywowała mechanizmy obronne związane z metabolizmem antyoksydacyjnym. Pozytywne efekty uzyskano także przy łącznym stosowaniu dolistnym kwasu salicylowego i wapnia, co skutkowało zwiększeniem parametrów fluorescencji chlorofilu *a* w liściach papryki, zawartości karotenoidów w owocach oraz odporności roślin na BER. Owoce uzyskane w tych warunkach charakteryzowały się większą jędrnością i soczystością oraz wyższą ogólną oceną sensoryczną. Owoce odmiany 'Palermo' wykazywały korzystniejsze parametry jakościowe oraz wyższą aktywność antyoksydacyjną, co czyni tę odmianę papryki słodkiej szczególnie cenną w kontekście prozdrowotnym. Dolistna aplikacja kwasu salicylowego w stężeniu 0,03% istotnie wpłynęła na poprawę właściwości prozdrowotnych owoców papryki, w tym zwiększenie zawartości związków karotenoidowych. Wykazano wysoką zawartość przede wszystkim kapsantyny,

β-karotenu, luteiny i α-karotenu (odpowiednio: 1226, 736, 210 i 168 $\mu g \cdot 100\ g^{-1}$ świeżej masy owocu). Dla obu odmian stwierdzono dodatnią korelację pomiędzy zawartością cukrów ogółem i stosunkiem cukrów do kwasów w owocach w przypadku zastosowania opryskiwania roślin papryki roztworem kwasu salicylowego razem z roztworem wapnia. Na podstawie przeprowadzonych badań potwierdzono postawione hipotezy badawcze.

Słowa kluczowe: stres abiotyczny, fluorescencja chlorofilu, mikroskopia konfokalna, aktywność antyoksydacyjna, analiza sensoryczna

SUMMARY

Effect of chosen agrotechnical factors on the growth, yield, and fruit quality of sweet pepper (*Capsicum annuum* L.) under hydroponic cultivation

This study aimed to evaluate the impact of chosen agrotechnical factors, such as: LED lighting during pepper seedling production, fertilization in hydroponic cultivation using polyphosphates and foliar and root application of salicylic acid on yield efficiency and fruit quality of sweet pepper. In accordance with the main objective, five research hypotheses were formulated: (I) Supplementary lighting with LED lamps positively influences the growth and quality of pepper seedlings produced for hydroponic cultivation, (II) The use of polyphosphates for fertigation in hydroponic cultivation affects the growth and metabolism of pepper plants, resulting in higher yields, (III) Foliar application of salicylic acid stimulates the growth of pepper plants under stress caused by high EC of the fertigation solution, improving their metabolism, (IV) Salicylic acid increases the resistance of pepper plants to adverse environmental conditions in hydroponic cultivation, (V) Foliar application of salicylic acid improves the yield and quality of pepper fruits in hydroponic cultivation in respect of the content of nutrients, antioxidant potential, and sensory attributes.

Between 2018 and 2021, research was conducted at the Greenhouse Experimental Station of the Warsaw University of Life Sciences (SGGW), focusing on the cultivation of sweet pepper in hydroponic system, using mineral substrate, and in aeroponic system. Two red-fruited sweet pepper cultivars were used: (1) 'Aifos' F1 (Seminis, Bayer), a block-type cultivar; and (2) 'Palermo' F1 (Rijk Zwaan), an elongated 'Dulce Italiano' type cultivar. The first part of the study assessed the efficiency of LED lighting compared to traditional sodium lamps during pepper seedling production on mineral substrate and the effectiveness of phosphorus supplied as polyphosphates versus orthophosphates in hydroponic cultivation. The second part focused on the problem of abiotic stress in pepper plants caused by high EC levels in fertigation solution and the application of salicylic acid to mitigate its negative effects. The impact of foliar and root application of salicylic acid on selected physiological and biochemical parameters in pepper plants grown in an aeroponic system under high EC stress (induced by doubling the concentration of the nutrient solution) was assessed. Further studies examined the effects of foliar spraying with 0.03% salicylic acid, 0.7% calcium nitrate, and a mixture of these solutions, on plant growth, yield, and fruit quality of pepper grown on mineral wool substrate. Evaluations included selected morphological parameters,

chlorophyll content (in SPAD units), chlorophyll *a* fluorescence, and mineral concentration in leaves. Light and confocal microscopy were used to examine the leaf cells of LED-supplemented plants. To analyze the response of pepper plants to high EC stress and the application of salicylic acid, soluble protein content, H_2O_2 levels, and the activity of antioxidant enzymes – superoxide dismutase and catalase – were measured. Cultivation experiments determined the number and weight of marketable fruits and fruits affected by physiological disorder BER (blossom-end rot). Fruit color, firmness, content of sugars, organic acids, vitamin C, carotenoids, and minerals were analyzed. Antioxidant potential was evaluated using DPPH, ABTS, and TPC methods. Sensory evaluation was also performed.

LED lighting during pepper seedling production positively influenced the development of the assimilative apparatus in plants – leaf thickness and chloroplast number increased, as did chlorophyll *a* fluorescence parameters. The application of 30% phosphorus in the form of polyphosphates in the hydroponic nutrient solution significantly improved leaf photosynthetic activity and increased marketable yield, particularly in the cultivar more prone to BER. Exogenous application of salicylic acid, regardless of EC level, reduced BER incidence and activated antioxidant-related defense mechanisms. Positive effects were also observed with the combined foliar application of salicylic acid and Ca, resulting in improved chlorophyll *a* fluorescence, higher carotenoid content in fruits, and enhanced plant resistance to BER. Fruits produced under these conditions showed greater firmness, juiciness, and improved overall sensory quality. The 'Palermo' cultivar displayed better quality parameters and higher antioxidant activity, making it particularly valuable from a health-promoting perspective. Foliar application of 0.03% salicylic acid significantly improved the health-promoting properties of pepper fruits, including carotenoid content. Particularly high content of capsanthin, β-carotene, lutein, and α-carotene was found (1226, 736, 210, and 168 $\mu g \cdot 100\ g^{-1}$ fresh weight, respectively). In both cultivars, a positive correlation was observed between total sugar content and the sugar-to-acid ratio in fruits of plants treated with a mixture of salicylic acid and calcium solutions. The results of the conducted studies confirmed all proposed research hypotheses.

Keywords: abiotic stress, chlorophyll fluorescence, confocal microscopy, antioxidant activity, sensory analysis

PUBLIKACJE BĘDĄCE PODSTAWĄ ROZPRAWY DOKTORSKIEJ

1. **Sobczak A.**, Kowalczyk K., Gajc-Wolska J., Kowalczyk W., Niedzińska M. 2020. Growth, yield and quality of sweet pepper fruits fertilized with polyphosphates in hydroponic cultivation with LED lighting. Agronomy 10(10): 1560. https://doi.org/10.3390/agronomy10101560 (IF_{2020} 3,417, 100 pkt MNiSW)

2. **Sobczak A.**, Sujkowska-Rybkowska M., Gajc-Wolska J., Kowalczyk W., Borucki W., Kalaji H.M., Kowalczyk K. 2021. Photosynthetic efficiency and anatomical structure of pepper leaf (*Capsicum annuum* L.) transplants grown under high-pressure sodium (HPS) and light-emitting diode (LED) supplementary lighting systems. Plants 10(10): 1975. https://doi.org/10.3390/plants10101975 (IF_{2021} 4,658, 70 pkt MNiSW)

3. **Sobczak A.**, Kućko A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2023. Effect of salicylic acid on the growth and development of sweet pepper (*Capsicum annum* L.) under standard and high EC nutrient solution in aeroponic cultivation. Agronomy 13(3): 779. https://doi.org/10.3390/agronomy13030779 (IF_{2023} 3,3, 100 pkt MNiSW)

4. **Sobczak A.**, Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2024. Effect of salicylic acid and calcium on growth, yield, and fruit quality of pepper (*Capsicum annuum* L.) grown hydroponically. Agronomy 14(2): 329. https://doi.org/10.3390/agronomy14020329 (IF_{2024} 3,3, 100 pkt MNiSW)

5. **Sobczak-Samburska A.**, Pióro-Jabrucka E., Przybył J.L., Sieczko L., Kalisz S., Gajc-Wolska J., Kowalczyk K. 2025. Effect of foliar application of calcium and salicylic acid on fruit quality and antioxidant capacity of sweet pepper (*Capsicum annuum* L.) in hydroponic cultivation. Agriculture 15(1): 26. https://doi.org/10.3390/agriculture15010026 (IF_{2025} 3,3, 100 pkt MNiSW)

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WYKAZ SKRÓTÓW

AA	kwas askorbinowy
ABA	kwas abscysynowy
ABTS	2,2'-azino-bis(3-etylo-6-benzotiazol sulfonowy) (metoda oznaczania aktywności antyoksydacyjnej)
BER	sucha zgnilizna wierzchołkowa
CAT	katalaza
DAS	dni od siewu
DPPH	2,2-difenylo-1-pikrylohydrazyl (metoda oznaczania aktywności antyoksydacyjnej)
EC	przewodność elektrolityczna
Fm′	maksymalna fluorescencja w warunkach świetlnych
Fs	bieżący poziom fluorescencji
Fv/Fm	maksymalna wydajność kwantowa fotosystemu PSII w ciemności
GA	giberelina
GAE	równoważnik kwasu galusowego
H_2O_2	nadtlenek wodoru
HPLC	wysokosprawna chromatografia cieczowa
HPE	ekstrakt o wysokiej aktywności biologicznej
HPS	wysokociśnieniowa lampa sodowa
HSP/HSPs	białka szoku cieplnego
IAA	kwas indolilo-3-octowy
JA	kwas jasmonowy
KOH	wodorotlenek potasu
LED	dioda elektroluminescencyjna
NBT	błękit nitrotetrazolowy
NPR	nieindukowane białko odpornościowe
$O_2^{-}\bullet$	anionorodnik ponadtlenkowy
•OH	rodnik hydroksylowy
OP	ortofosforany
PAR	aktywne promieniowanie fotosyntetyczne
PCA	analiza głównych składowych
PEA	przenośny miernik fluorescencji

PI	wskaźnik wydajności fotosystemu
PP	polifosforany
PPFD	gęstość strumienia fotonów fotosyntetycznie czynnych
PSII	fotosystem II
QDA	ilościowa analiza opisowa
RAE	równoważnik aktywności retinolu
RDA	zalecane dzienne spożycie
RH	wilgotność względna
ROS	reaktywne formy tlenu
RNS	reaktywne formy azotu
SA	kwas salicylowy
SAR	nabyta odporność systemiczna
SOD	dysmutaza ponadtlenkowa
SPAD	wskaźnik zawartości chlorofilu
TCA	kwas trichlorooctowy
TGA	czynniki transkrypcyjne wiążące sekwencję TGACG
TPC	całkowita zawartość polifenoli
TS	całkowita zawartość cukrów
TSS	całkowita zawartość składników rozpuszczalnych w soku komórkowym
ΦPSII (φPSII)	efektywna wydajność kwantowa fotosystemu PSII

WSTĘP

Papryka słodka (*Capsicum annuum* L.) stanowi jedną z ważniejszych roślin warzywnych uprawianych zarówno w Polsce, jak i na świecie. Jej owoce są źródłem wielu cennych składników bioaktywnych, takich jak witamina C, karotenoidy, potas, czy związki fenolowe. Jakość i skład biochemiczny owoców zależy od wielu czynników, a wśród nich bardzo dużą rolę pełnią warunki uprawy. Współczesne trendy konsumenckie są ukierunkowane na żywność o wysokiej wartości prozdrowotnej, co stawia przed producentami oraz naukowcami nowe wyzwania, związane z doskonaleniem technologii uprawy pod kątem poprawy zarówno jakości plonu, jak i jego wartości odżywczej i prozdrowotnej oraz sensorycznej.

Z uwagi na intensyfikację produkcji warzywniczej, prowadzonej w nowoczesnych obiektach szklarniowych, rośnie znaczenie czynników środowiskowych i agrotechnicznych, które wpływają na efektywność fotosyntezy, wzrost roślin, plonowanie oraz jakość owoców. Jednym z kluczowych aspektów w tego typu produkcji jest odpowiednie zarządzanie światłem asymilacyjnym, dostępnością składników pokarmowych, jak również stosowanie biostymulatorów, które mogą łagodzić skutki stresów środowiskowych.

W ostatnich latach obserwuje się coraz większe zastosowanie diod elektroluminescencyjnych (LED) w ogrodnictwie jako uzupełniającego źródła światła w uprawach szklarniowych. Badania wykazały, że odpowiednio dobrane widmo światła korzystnie wpływa na efektywność aparatu fotosyntetycznego oraz dynamikę wzrostu roślin. Udowodniono także zróżnicowaną reakcję roślin na skład spektralny sztucznych źródeł światła, co sugeruje konieczność indywidualizacji strategii świetlnej w zależności od uprawianego gatunku czy odmiany [Claypool i Lieth 2021, Zhan i in. 2023]. W kontekście mineralnego żywienia roślin, często analizuje się rolę różnych form składników pokarmowych, między innymi dotyczy to polifosforanów. W uprawach hydroponicznych szczególne znaczenie ma zdrowy, dobrze rozbudowany, aktywny system korzeniowy, który umożliwia odpowiednie odżywienie roślin fosforem [Naciri i in. 2024].

Obok technologii związanych z oświetleniem i nawożeniem, równie dużą uwagę w intensywnej produkcji roślinnej poświęca się biostymulatorom, wśród których szczególne miejsce zajmuje kwas salicylowy. Jego rola w aktywacji mechanizmów obronnych roślin, poprawie parametrów fotosyntetycznych oraz łagodzeniu skutków stresów środowiskowych została potwierdzona w licznych badaniach [Aamer i in. 2022,

Kaya i in. 2023]. W uprawach hydroponicznych, szczególnie przy stosowaniu recyrkulacji pożywki, wysokie stężenie jonów w strefie systemu korzeniowego podnosi EC pożywki, co szczególnie u roślin wrażliwych może wywołać stres oksydacyjny.

W świetle powyższego, podjęcie kompleksowych badań nad wpływem wybranych czynników agrotechnicznych, takich jak doświetlanie LED w produkcji rozsady papryki, stosowanie polifosforanów do fertygacji i kwasu salicylowego do zwiększania efektywności plonowania i bioaktywności owoców papryki słodkiej uprawianej hydroponicznie, wydaje się nie tylko uzasadnione, lecz również istotne z punktu widzenia nowoczesnego ogrodnictwa.

1. PRZEGLĄD LITERATURY

1.1. Pochodzenie, systematyka i charakterystyka morfologiczna papryki

Papryka (*Capsicum* spp.) należy do rodziny *Solanaceae*, do której zaliczane są także inne ważne rośliny uprawne, takie jak pomidor (*Solanum lycopersicum* L.), ziemniak (*Solanum tuberosum* L.) czy bakłażan (*Solanum melongena* L.). Papryka pochodzi z Ameryki Środkowej i Południowej. Archeologiczne dowody wskazują, że papryka była uprawiana tam już ponad 6000 lat temu, zwłaszcza na terenie dzisiejszego Meksyku, Peru i Boliwii. Jedną z cech rodzaju *Capsicum* jest bardzo duże zróżnicowanie morfologiczne, zarówno w obrębie poszczególnych gatunków, jak i odmian. Jest to wynikiem długotrwałej hodowli i selekcji prowadzonej przez człowieka, jak również adaptacji roślin do zróżnicowanych warunków środowiskowych [Zhang i in. 2020a, Anani i in. 2024]. Szczególnie bogate zasoby dziko rosnących gatunków z rodzaju *Capsicum* występują w dolinie Amazonki, gdzie warunki klimatyczne sprzyjały różnorodności genetycznej tej rośliny [Gai i in. 2020, Paredes-Andrade i in. 2020]. Do rodzaju *Capsicum* należy około 35 gatunków, z czego tylko pięć ma znaczenie użytkowe jako rośliny uprawne, są to: *C. annuum* L., *C. frutescens* L., *C.chinense* Jacq., *C. baccatum* L., *C. pubescens* R. & P. [Azab 2020, Gai i in. 2024]. Papryka w naszym klimacie uprawiana jest jako roślina jednoroczna. Zależnie od gatunku i odmiany oraz sposobu uprawy może osiągać wysokość od 30 cm do ponad 2 metrów. System korzeniowy papryki jest palowy, z licznymi korzeniami bocznymi. Łodyga jest wzniesiona, pokryta drobnymi włoskami. Liście są pojedyncze, o kształcie eliptycznym lub lancetowatym, ułożone skrętolegle. Kwiaty papryki są samopylne, zbudowane z pięciu zrośniętych działek kielicha oraz pięciu wolnych, białych lub fioletowych płatków korony. W centrum kwiatu papryki znajduje się pięć pręcików oraz jeden słupek. Owocem papryki jest jagoda o zróżnicowanym kształcie, wielkości i kolorze. Kształt owocu może być okrągły, stożkowy, aż do podłużnego. Natomiast kolor owocu zmienia się od zielonego (w dojrzałości zbiorczej) do czerwonego (w fazie pełnej dojrzałości fizjologicznej). Występują także odmiany, których owoce są w kolorze żółtym, pomarańczowym lub fioletowym [de Sá Mendes i de Branco 2020]. Nasiona papryki są gładkie, płaskie, okrągłe, o barwie kremowej lub żółtawej. Zawierają duże ilości substancji odżywczych, głównie tłuszczów i białek, co sprzyja ich szybkiemu kiełkowaniu w optymalnych warunkach. Nasiona papryki zachowują zdolność kiełkowania przez kilka lat [Batiha i in. 2020].

1.2. Cechy użytkowe owoców papryki słodkiej

Odmiany uprawne papryki słodkiej różnią się kształtem, barwą i wielkością owocu. Wśród najbardziej poszukiwanych przez rynek są odmiany o owocach typu „block" (owoce duże, mięsiste o kształcie regularnego graniastosłupa) i typu Kapia (owoce wydłużone, zwężające się ku dołowi, ostro zakończone) [Cruz i in. 2024].

Barwa owoców papryki jest determinowana obecnością różnych związków barwnych, takich jak chlorofile, karotenoidy oraz antocyjany. Zmienia się w miarę dojrzewania owoców, co ma istotne znaczenie dla walorów estetycznych, składu chemicznego i jakości [Xue i in. 2024]. Owoce papryki stanowią cenne źródło składników odżywczych o dużym znaczeniu zarówno dla zdrowia człowieka, jak i dla zastosowania kulinarnego oraz przemysłowego. Skład chemiczny owoców wpływa na ich wartość odżywczą, smak oraz możliwości przetwórcze. Papryka słodka charakteryzuje się szczególnie wysoką zawartością w owocach witaminy C, β-karotenu oraz związków fenolowych, które wykazują silne działanie antyoksydacyjne, neutralizując wolne rodniki, oraz wspierają układ odpornościowy [Sran i Jindal 2022]. Świeże owoce czerwonej papryki zawierają w 100 g około 127 mg witaminy C (kwasu L-askorbinowego), co stanowi ponad 140% RDA dla kobiet i ponad 127% RDA dla mężczyzn. W produktach naturalnych witamina C występuje w kompleksie z innymi substancjami, co dodatkowo wpływa na jej przyswajalność, w porównianiu z czystym kwasem L-askorbinowym [Piekut i in. 2018]. Poza witaminą C, owoce papryki słodkiej zawierają znaczące ilości β-karotenu – około 2400 μg w 100 g świeżej masy, co odpowiada około 27% RDA witaminy A (przy przeliczeniu: 12 μg β-karotenu = 1 μg RAE). β-karoten wspomaga kondycję skóry i wzroku. Zawarte w owocach papryki związki fenolowe (205–344 mg GAE na 100 g św. m.), wykazują działanie przeciwzapalne i przeciwwirusowe. Istotnymi składnikami kształtującymi smak owoców są cukry (około 6 g w 100 g św. m.) oraz kwasy organiczne. Papryka zawiera również szereg składników mineralnych, takich jak potas (średnio 211 $mg \cdot 100\ g^{-1}$ św. m.), który reguluje ciśnienie krwi i wspiera pracę mięśni, magnez (12 $mg \cdot 100\ g^{-1}$ św. m.), niezbędny dla funkcjonowania układu nerwowego i mięśni oraz wapń (7 $mg \cdot 100\ g^{-1}$ św. m.), który jest kluczowy dla kości i zębów [Leng i in. 2022]. W przypadku papryki ostrej, dodatkowym składnikiem aktywnym jest kapsaicyna – protoalkaloid odpowiedzialny za ostry smak. Jej zawartość zależy od odmiany i może wynosić od 0,5 do nawet 9,7 mg w 100 g owocu. Kapsaicyna znajduje zastosowanie nie tylko w kuchni (jako składnik ostrych przypraw), ale również w przemyśle farmaceutycznym, między innymi

w maściach przeciwbólowych i rozgrzewających. Natomiast papryka słodka zawiera bardzo niski poziom kapsaicyny, mniej niż 0,01 mg w 100 g owocu [Orellana-Escobedo i in. 2013, Olatunji i Afolayan 2020, Martínez-Ispizua i in. 2021].

1.3. Kierunki rozwoju uprawy papryki pod osłonami w Polsce

Papryka jest jedną z najważniejszych roślin warzywnych uprawianych pod osłonami w Polsce. Dzięki rosnącemu zapotrzebowaniu na wysokiej jakości owoce papryki, uprawa papryki w tunelach foliowych i szklarniach stała się istotnym elementem krajowego sektora warzywniczego. Uprawa papryki w Polsce prowadzona jest głównie w tunelach foliowych, rzadziej w szklarniach [Cebula i in. 2015]. Dominującym regionem produkcji papryki jest województwo mazowieckie, a w szczególności okolice Radomia. Paprykę w tunelach foliowych uprawia się przede wszystkim metodą tradycyjną, w gruncie. Jednak coraz częściej producenci papryki wybierają także metody bezglebowe, do których zalicza się uprawy hydroponiczne w podłożach stałych, takich jak maty uprawowe z włókna kokosowego lub z wełny mineralnej. W uprawach hydroponicznych stosowana jest fertygacyja, czyli nawadnianie razem z nawożeniem roślin systemem kapilar, co pozwala na precyzyjne dostarczanie roślinom składników odżywczych.

Do upraw towarowych papryki wybierane są odmiany charakteryzujące się wysoką plennością, odpornością na choroby oraz długim okresem owocowania [Al Meselmani 2024]. W Polsce pod osłonami dominują odmiany papryki o owocach typu „block" i Kapia. Sezon dostępności owoców papryki z upraw krajowych pod osłonami trwa od końca maja do października, z możliwością jego wydłużenia dzięki zastosowaniu ogrzewania tuneli foliowych i szklarni oraz użyciu nowoczesnych technologii do doświetlania asymilacyjnego.

Produkcja papryki pod osłonami ma duże znaczenie dla gospodarki rolnej w Polsce [Krasniqi i Drvoshanova 2024]. Zgodnie z danymi opublikowanymi przez Główny Urząd Statystyczny w opracowaniu pt. „Rolnictwo w 2023 roku", całkowita powierzchnia upraw warzyw prowadzonych pod osłonami w Polsce wyniosła 4,5 tys. hektarów. W strukturze gatunkowej warzyw uprawianych pod osłonami istotne miejsce zajmuje papryka, której udział w całkowitej powierzchni tego typu upraw oszacowano na 19,4%. Przy uwzględnieniu łącznej powierzchni upraw warzywniczych pod osłonami, powierzchnia uprawy papryki wynosiła około 873 hektary. Polska jest jednym z czołowych producentów papryki w Europie Środkowo-Wschodniej.

Również obserwuje się każdego roku wzrost eksportu świeżych owoców papryki z Polski [Tran i in. 2022, Nosecka 2024].

Współczesne rolnictwo zmaga się z wieloma wyzwaniami, w tym ograniczoną dostępnością gruntów rolnych, degradacją gleby oraz rosnącym zapotrzebowaniem na żywność wysokiej jakości. W odpowiedzi na te wyzwania rozwijają się kontrolowane i efektywne metody uprawy roślin, wśród których szczególne znaczenie mają hydroponika i aeroponika. Obie te technologie należą do grupy metod bezglebowych, które eliminują tradycyjne stosowanie podłoży uprawowych. Źródłem składników mineralnych dla roślin w tych uprawach nie jest podłoże, lecz roztwór wodny składników mineralnych, tzw. pożywka, dozowana do systemu korzeniowego roślin w postaci kropli lub mgły [Kundal i Sharma 2024]. Jedną z kluczowych zalet hydroponiki i aeroponiki jest precyzyjna kontrola podaży składników odżywczych, co pozwala na optymalizację wzrostu roślin i ograniczenie strat wynikających z wymywania substancji pokarmowych [Monisha i in. 2023, Jassim i in. 2024]. W uprawach hydroponicznych z zastosowaniem podłoża stałego, szczególnie w wielkotowarowej produkcji warzyw pod osłonami, dominującym podłożem jest wełna mineralna. Jej powszechne użycie w uprawach roślin wynika z odpowiednich właściwości fizycznych i chemicznych, które umożliwiają precyzyjne zarządzanie dostępnością wody i składników odżywczych w strefie korzeniowej [Tzortzakis i in. 2022]. Wełna mineralna jest materiałem inertnym, chemicznie obojętnym, co oznacza, że nie wpływa na skład pożywki do fertygacji roślin, nie uwalnia związków chemicznych do otoczenia i nie absorbuje składników pokarmowych [Sattler i in. 2020, Kozub 2024, Licastro i in. 2024]. Bezglebowe, hydroponiczne metody uprawy mają także zastosowanie w przypadku papryki.

Przyszłość uprawy papryki pod osłonami w Polsce zależy od kilku kluczowych czynników. Jednym z nich są zmiany klimatyczne, które powodują coraz bardziej ekstremalne warunki pogodowe. Wymaga to inwestycji w rozwój odpowiednich technologii produkcji. Obejmuje on wdrażanie efektywnych sposobów ochrony, metod upraw hydroponicznych, automatyzacji nawadniania i nawożenia oraz nowych odmian odpornych na choroby. Ważnym czynnikiem jest także rozwój kanałów dystrybucji, które wymagają dostosowania produkcji do wymagań rynku Unii Europejskiej oraz zwiększenia eksportu [Sindhu 2023].

1.4. Wybrane czynniki agrotechniczne w uprawie bezglebowej papryki

W kontekście zrównoważonego rolnictwa, uprawa bezglebowa, a w szczególności hydroponika, przyczynia się do znacznej oszczędności wody w porównaniu z tradycyjnymi metodami uprawy. Jednocześnie możliwość stosowania obiegu zamkniętego i recyrkulacji pożywki minimalizuje straty nawozów i wody. Ponadto eliminacja gleby zmniejsza ryzyko występowania chorób roślin przenoszonych przez patogeny glebowe, co ogranicza konieczność stosowania pestycydów [Méndez-Guzmán i in. 2022, Jimoh i in. 2024]. Na efektywność upraw hydroponicznych wpływa wiele czynników. Dotyczą one zarówno parametrów mikroklimatu, jak i nawożenia, strategii nawadniania czy doświetlania asymilacyjnego. Poniżej omówiono czynniki agrotechniczne w uprawie hydroponicznej papryki zastosowane w badaniach, wyniki których przedstawiono w załączonych publikacjach.

1.4.1. Polifosforany

Jednym z niezbędnych makroelementów uczestniczących w podstawowych procesach komórkowych, takich jak fotosynteza, oddychanie, fosforylacja enzymów czy ekspresja genów, jest fosfor. Jego głównym źródłem są skały fosforanowe, których zasoby są ograniczone i nieodnawialne. Tradycyjne nawozy fosforowe zawierają ortofosforany, jednak ich biodostępność w glebie jest niska, zwłaszcza przy skrajnych wartościach pH, co prowadzi do nadmiernego stosowania nawozów [Berde i in. 2021, Saha i in. 2024]. Polifosforany, będące rozpuszczalnymi formami fosforu o strukturze polimerowej, cechują się wyższą efektywnością i pozwalają na redukcję dawek nawozowych. Ich zastosowanie, zwłaszcza w uprawach hydroponicznych, umożliwia precyzyjne zarządzanie nawożeniem i ogranicza zużycie fosforu. Rośliny pobierają fosfor głównie jako jony ortofosforanowe ($H_2PO_4^-$, HPO_4^{2-}), a niedobory fosforu prowadzą do zahamowania wzrostu i spadku biomasy [Erel i in. 2023, Zhou i in. 2023]. Polifosforany pełnią również funkcje regulatorowe – wpływają na ekspresję genów, odpowiedź na stres i metabolizm energetyczny. Choć ich obecność w roślinach znana jest od dawna, ich biologiczna rola pozostaje przedmiotem intensywnych badań [Lorenzo-Orts i in. 2020].

1.4.2. Doświetlanie asymilacyjne w technologii LED

W ostatnich latach do doświetlania asymilacyjnego roślin zaczęto coraz częściej stosować lampy LED. Technologia LED, oparta na diodach elektroluminescencyjnych, wyróżnia się wysoką wydajnością energetyczną, możliwością precyzyjnego doboru widma światła oraz wysoką trwałością [Paradiso i Proietti 2022]. Lampy LED umożliwiają dostosowanie spektrum światła do specyficznych wymagań różnych gatunków, odmian i faz wzrostu roślin. Spektrum światła, które można regulować w przypadku lamp LED, pozwala na precyzyjne kierowanie poszczególnymi procesami fizjologicznymi, co wpływa na ilość i jakość uzyskiwanego plonu [Barceló-Muñoz i in. 2021, Didaran i in. 2024].

Uprawy szklarniowe warzyw należą do energochłonnej produkcji roślinnej. Dlatego bardzo ważne jest rozpoczynanie takiej produkcji od sadzenia rozsady wyrównanej i o bardzo dobrej jakości. W trakcie przygotowywania rozsady do uprawy hydroponicznej należy zapewnić roślinom optymalne warunki wzrostu. W kontekście produkcji rozsady papryki, istotnym elementem wpływającym na jakość materiału roślinnego jest odpowiednie doświetlanie roślin w okresie niedoboru światła naturalnego. W wielu gospodarstwach ogrodniczych wciąż dominującym rozwiązaniem do doświetlania rozsad warzyw są wysokoprężne lampy sodowe (HPS), które charakteryzują się korzystnym spektrum promieniowania fotosyntetycznie czynnego (PAR), lecz jednocześnie wysokim poborem energii elektrycznej. W związku z rosnącymi kosztami nośników energii oraz potrzebą zwiększania efektywności energetycznej gospodarstw, obserwuje się wzrost zainteresowania alternatywnymi technologiami oświetlenia, w tym szczególnie modułami LED [Dong i in. 2022].

1.4.3. Kwas salicylowy

1.4.3.1. Rola w roślinie

Kwas salicylowy ($C_7H_6O_3$) to naturalny związek fenolowy zaliczany do fitohormonów i regulatorów wzrostu roślin. Jego struktura chemiczna oparta jest na szkielecie kwasu benzoesowego z grupą hydroksylową w pozycji orto, co nadaje mu właściwości bioaktywne i umożliwia udział w licznych reakcjach metabolicznych [Mohamed i in. 2020, Hu i in. 2022]. Kwas salicylowy jest syntetyzowany endogennie w komórkach roślinnych, głównie poprzez dwa szlaki biosyntezy: szlak kwasu szikimowego (kwas choryzmowy przekształcany jest w kwas izochoryzmowy, a następnie w kwas salicylowy (SA) oraz szlak fenylopropanoidowy, w którym

substratem jest fenyloalanina [Mishra i in. 2021]. Wytworzony SA może być transportowany w roślinie na duże odległości zarówno ksylemem, jak i floemem, co umożliwia jego systemowe działanie [Özden i Kulak 2023].

Endogenny SA odgrywa kluczową rolę w regulacji procesów wzrostowych, takich jak kiełkowanie nasion, elongacja pędów i korzeni, a także morfogeneza liści [Tucuch-Haas i in. 2021, Zhou i in. 2022]. Wpływa on na aktywność enzymów hydrolitycznych, modulując dostępność składników zapasowych w nasionach. Optymalne stężenie SA korzystnie wpływa na rozwój systemu korzeniowego, lecz jego nadmiar może prowadzić do stresu oksydacyjnego i zahamowania wzrostu [Aamer i in. 2022]. SA oddziałuje także na transport i biosyntezę innych fitohormonów, takich jak auksyny, cytokininy, kwas abscysynowy czy gibereliny, wykazując często działanie antagonistyczne lub synergistyczne [Saleem i in. 2021]. Za jego działanie odpowiadają m.in. białka NPR oraz czynniki transkrypcyjne TGA, uczestniczące w regulacji ekspresji genów odpowiedzialnych za odporność oraz metabolizm wtórny [Lu i in. 2024].

1.4.3.2. Zastosowanie SA jako biostymulatora

Kwas salicylowy pierwszy raz został wyizolowany w 1828 roku przez Johannesa Buchnera z kory wierzby (*Salix* spp.) jako glikozyd alkoholu salicylowego [Marson i Pasero 2006]. Struktura chemiczna substancji została określona przez Raffaele Pirię, który dokonał izolacji kwasu salicylowego z liści topoli. Przeprowadził także syntezę SA z salicyny, co umożliwiło rozpoczęcie produkcji syntetycznej formy kwasu salicylowego na skalę przemysłową w drugiej połowie XIX wieku [Rainsford 2007]. Kwas salicylowy, aplikowany w postaci opryskiwań dolistnych lub poprzez system korzeniowy, wykazuje istotny wpływ na odporność i kondycję roślin w warunkach stresów abiotycznych, takich jak susza, zasolenie, niedobory składników pokarmowych czy stres termiczny [Engel i in. 2024]. Zwiększa efektywność fotosyntezy poprzez indukcję syntezy chlorofilu oraz poprawę działania aparatów szparkowych [Yu i in. 2025]. SA aktywuje enzymy antyoksydacyjne (dysmutaza ponadtlenkowa, katalaza, peroksydaza), które odpowiadają za neutralizację reaktywnych form tlenu, chroniąc komórki przed stresem oksydacyjnym [Kudoyarova i in. 2022].

Kwas salicylowy należy do szerokiej grupy biostymulatorów, obok aminokwasów, hydrolizatów białkowych, ekstraktów z alg, kwasów huminowych i fulwowych oraz pożytecznych mikroorganizmów [Sleighter i in. 2023]. W porównaniu do nich wyróżnia się wyjątkowo szerokim spektrum działania – od regulacji wzrostu,

przez wspomaganie fotosyntezy i gospodarki wodnej, po wzmacnianie odporności systemicznej. Szczególne znaczenie SA zyskał w rolnictwie zrównoważonym, umożliwiając redukcję stosowania środków ochrony roślin i nawozów mineralnych [Ding i in. 2022]. W nowoczesnych technologiach rolniczych SA stosowany jest jako czynnik poprawiający wydajność produkcji roślinnej, zwłaszcza w systemach hydroponicznych, a jego aplikacja może zwiększać kiełkowanie nasion i wigor siewek oraz poprawiać jakość i ilość plonu (sałata, pomidor, ogórek) [Hui i in. 2015, Sousa i in. 2022, Arikan i in. 2023, Miao i in. 2024, Ben Youssef i in. 2025].

1.5. Wybrane czynniki obniżające efektywność uprawy papryki

1.5.1. Stresy abiotyczne

Papryka, roślina o wysokich wymaganiach siedliskowych i agrotechnicznych, jest szczególnie podatna na stresy abiotyczne, które istotnie ograniczają jej wzrost i plonowanie. Stres abiotyczny to wpływ niekorzystnych czynników środowiskowych niemających pochodzenia biologicznego, prowadzący do zaburzeń homeostazy rośliny [Rajametov i in. 2021]. Do głównych stresów abiotycznych oddziałujących na paprykę należą: światło, temperatura, zasolenie, niedobory składników pokarmowych, susza i stres oksydacyjny. W uprawach hydroponicznych roślin częstym problemem jest nadmierny wzrost EC podłoża czy pożywki i wysoka temperatura. Wysokie EC prowadzi do stresu osmotycznego w wyniku podwyższonego przewodnictwa elektrycznego podłoża. Ogranicza to pobieranie wody przez korzenie, wywołując objawy podobne do suszy. Roślina w odpowiedzi aktywuje transportery jonowe, syntetyzuje osmoprotektanty (prolina) i stabilizuje struktury komórkowe [Aasim i in. 2022]. Wysoka temperatura (powyżej 35 °C) powoduje denaturację białek oraz zaburzenia w funkcjonowaniu aparatów fotosyntetycznych. Papryka reaguje produkcją białek szoku cieplnego (HSPs), które stabilizują białka i zapobiegają ich agregacji [Mukhametzyanov i in. 2021]. Wysoka temperatura prowadzi także do wtórnego stresu wodnego (nasilone parowanie, utrudnione pobieranie wody) oraz stresu oksydacyjnego. Stres oksydacyjny, będący efektem działania wysokiej temperatury i zasolenia, objawia się nadmierną akumulacją reaktywnych form tlenu (ROS), takich jak H_2O_2 (nadtlenek wodoru), $O_2^{-}\bullet$ (anionorodnik ponadtlenkowy) czy •OH (rodnik hydroksylowy). Powodują one uszkodzenia białek, lipidów i DNA. Roślina w reakcji obronnej uruchamia syntezę enzymów antyoksydacyjnych (SOD i CAT) oraz związków niskocząsteczkowych, takich jak glutation czy kwas askorbinowy [Sharma i in. 2019, Mittler i in. 2022].

1.5.2. Zaburzenie fizjologiczne BER

Wapń odgrywa kluczową rolę w metabolizmie roślin, pełniąc funkcje strukturalne i sygnalizacyjne. Jest jednym z podstawowych makroelementów niezbędnych do prawidłowego wzrostu i rozwoju roślin [Dixit i in. 2021]. Wapń jest pierwiastkiem, który w roślinie występuje głównie w postaci jonowej (Ca^{2+}). Jego funkcje obejmują stabilizację ścian komórkowych poprzez tworzenie pektynianów wapnia, regulację przepuszczalności błon komórkowych, udział w sygnalizacji komórkowej jako wtórny przekaźnik oraz wspieranie podziałów komórkowych i wzrostu merystematycznego. Niedobory wapnia skutkują deformacjami wzrostu i zwiększoną podatnością na stresy środowiskowe [Kim i in. 2024]. Mogą prowadzić do zaburzeń fizjologicznych, w tym do wystąpienia suchej zgnilizny wierzchołkowej owoców (BER – Blossom-End Rot), szczególnie u gatunków takich jak pomidor czy papryka [Dixit i in. 2021]. Główne czynniki sprzyjające wystąpieniu BER to niedobór wapnia w owocach, spowodowany jego ograniczonym transportem przez ksylem. Wpływa na to nierównomierne nawodnienie, wysoka zawartość azotu amonowego w podłożu, stres termiczny oraz zasolenie gleby czy innego podłoża [Sethi i in. 2024]. Objawy BER obejmują pojawienie się wodnistych plam na wierzchołkowej części owocu, które stopniowo brunatnieją, a nekrozy tkanki prowadzą do występowania suchych, skorkowaciałych obszarów, deformacji owoców oraz zahamowania ich wzrostu, a także wtórnych infekcji grzybowych lub bakteryjnych na obumarłej tkance [Reitz i in. 2021]. Sucha zgnilizna wierzchołków owoców stanowi poważny problem w uprawie papryki i innych gatunków roślin z rodziny *Solanaceae*. Chociaż tradycyjnie etiologia tego zjawiska wiązana jest z lokalnym niedoborem wapnia w tkankach owocu, współczesne badania wskazują na wieloczynnikowy charakter tego zaburzenia fizjologicznego, w którym kluczową rolę odgrywają fitohormony regulujące wzrost i rozwój roślin.

Kwas abscysynowy odgrywa centralną rolę w odpowiedzi roślin na stresy abiotyczne, w tym suszę, poprzez indukcję zamykania aparatów szparkowych oraz regulację ekspresji genów odpowiedzialnych za transport jonów wapnia i utrzymanie integralności błon komórkowych [de Freitas i in. 2011]. Zastosowanie egzogennego ABA w badaniach nad owocami pomidora skutkowało wzrostem koncentracji Ca^{2+} oraz ograniczeniem objawów BER, co sugeruje potencjalne działanie ochronne tego fitohormonu [de Freitas i in. 2011]. Antagonistyczna interakcja kwasu abscysynowego z giberelinami stanowi kolejny istotny element w kontekście patofizjologii BER. Gibereliny, poprzez indukcję ekspansji komórkowej oraz stymulację

wzrostu owocu, mogą prowadzić do zwiększenia zapotrzebowania metabolicznego na wapń, co w warunkach jego ograniczonej dostępności skutkuje pojawieniem się nekroz wierzchołkowych [Mahouachi i in. 2005]. ABA, poprzez hamowanie biosyntezy GA oraz ograniczanie ekspansji komórkowej, przyczynia się do homeostazy tkanek owocu i tym samym może redukować ryzyko wystąpienia BER [Ho i White 2005].

Auksyny, w szczególności kwas indolilo-3-octowy, odgrywają fundamentalną rolę w procesach morfogenezy i wzrostu owocu, niemniej jednak nadmiar auksyn może prowadzić do nadmiernej proliferacji komórek i niekontrolowanego wzrostu, zwiększając tym samym ryzyko dysproporcji w dystrybucji wapnia i wystąpienia BER [de Freitas i in. 2018]. Współdziałanie auksyn z giberelinami może synergistycznie pogłębiać ten efekt, powodując dodatkowe obciążenie układu przewodzącego i systemu transportu wapnia w roślinie [de Freitas i in. 2012].

Istotnym aspektem jest także rola ABA w regulacji ekspresji genów kodujących pektynę i enzymy rozkładające pektyny, takie jak pektynometylotransferazy, co może wpływać na strukturę ścian komórkowych i ich zdolność do wiązania wapnia [de Freitas i in. 2012]. W warunkach niedoboru wapnia, zmieniona ekspresja tych genów może prowadzić do destabilizacji strukturalnej tkanek owocu.

Kwas salicylowy stanowi istotny komponent złożonej sieci sygnalizacyjnej roślin, biorąc udział zarówno w indukcji odpowiedzi obronnych, jak i w regulacji procesów wzrostu i rozwoju. Coraz większe znaczenie przypisuje się badaniom nad molekularnymi mechanizmami jego działania oraz nad interakcjami SA z innymi fitohormonami, takimi jak kwas jasmonowy, etylen, auksyny, czy kwas absysynowy, które mogą przyjmować formę zarówno synergistycznych, jak i antagonistycznych współoddziaływań. Zrozumienie tych zależności stanowi klucz do pełniejszego poznania roli SA w fizjologii roślin oraz potencjalnych możliwości jego aplikacji w biotechnologii i ochronie roślin [Devi i in. 2023, Mu i in. 2025].

2. CEL BADAŃ I HIPOTEZY BADAWCZE

Celem podjętych badań, przedstawionych w załączonych publikacjach, była ocena wpływu wybranych czynników agrotechnicznych na wzrost, plonowanie oraz jakość i wartość prozdrowotną owoców papryki słodkiej (*Capsicum annuum* L.) w uprawie hydroponicznej.

W pierwszej części badań oceniano efektywność doświetlania rozsady papryki, produkowanej w podłożu mineralnym, światłem LED, w porównaniu do lamp sodowych, oraz efektywność zastosowania do fertygacji w uprawie hydroponicznej papryki fosforu w formie polifosforanów i ortofosforanów. W części drugiej podjęto badania nad stresem abiotycznym u papryki, wywołanym wysokim EC pożywki do fertygacji roślin w uprawie aeroponicznej i nad zastosowaniem kwasu salicylowego jako czynnika łagodzącego negatywne skutki tego stresu. Natomiast w uprawie papryki w wełnie mineralnej oceniano wpływ kwasu salicylowego na wzrost roślin, plon oraz jakość iwłaściwości prozdrowotne owoców w porównaniu do opryskiwania roślin wapniem przeciwko występowaniu suchej zgnilizny na owocach papryki, w celu wskazania najbardziej efektywnych strategii uprawowych prowadzących do uzyskania plonu o najwyższej jakości.

Hipotezy badawcze:

1. Doświetlanie lampami LED korzystnie wpływa na wzrost oraz jakość rozsady papryki przeznaczonej do upraw hydroponicznych.
2. Zastosowanie polifosforanów do fertygacji w uprawach hydroponicznych wpływa na wzrost i metabolizm roślin papryki, co skutkuje wyższym plonowaniem.
3. Zastosowanie dolistne kwasu salicylowego stymuluje wzrost roślin papryki w warunkach stresu wywołanego wysokim EC pożywki do fertygacji roślin, poprawiając ich metabolizm.
4. Kwas salicylowy zwiększa odporność roślin papryki na niekorzystne warunki środowiskowe w uprawie hydroponicznej.
5. Dolistne stosowanie kwasu salicylowego poprawia plon oraz jakość owoców papryki w uprawie hydroponicznej – pod względem zawartości składników odżywczych, potencjału antyoksydacyjnego i cech sensorycznych.

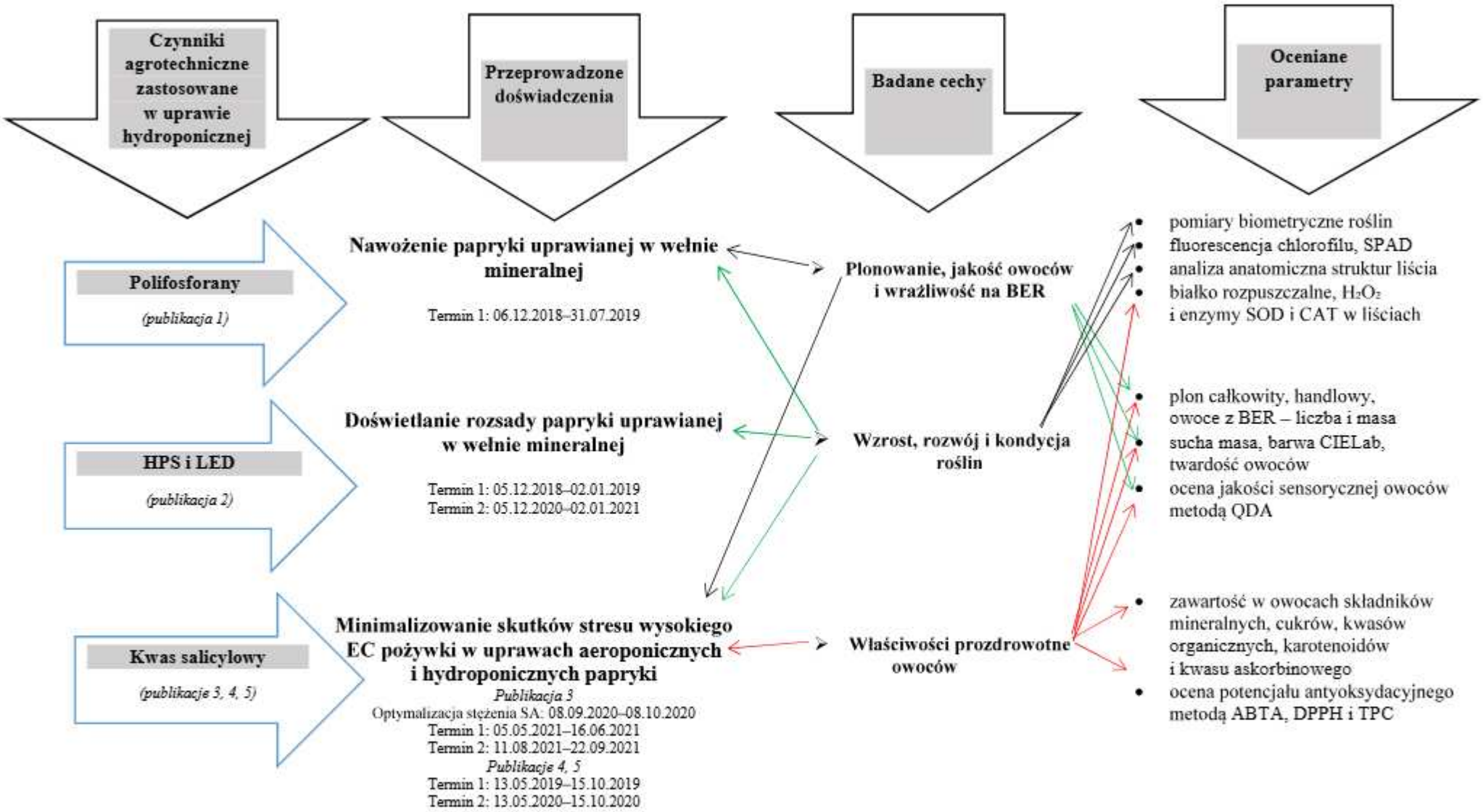
3. MATERIAŁY I METODY

Doświadczenia uprawowe przeprowadzono w latach 2018–2021 w Szklarniowym Ośrodku Doświadczalnym SGGW w Warszawie.

Na etapie produkcji rozsady papryki w wełnie mineralnej badano wpływ doświetlania asymilacyjnego lampami LED, w porównaniu do lamp sodowych, na wydajność fotochemiczną i strukturę anatomiczną liści oraz wzrost i jakość rozsady (publikacja 2). Wpływ formy fosforu użytej w pożywce (polifosforany, ortofosforany) badano na plon i jakość owoców papryki słodkiej w uprawie hydroponicznej prowadzonej w podłożu mineralnym z doświetlaniem asymilacyjnym roślin lampami LED (publikacja 1). Następnie oceniano wpływ kwasu salicylowego na wybrane parametry fizjologiczne i biochemiczne papryki rosnącej w systemie aeroponicznym w warunkach stresu wysokiego EC pożywki do fertygacji roślin, uzyskanego poprzez dwukrotne zwiększenie stężenia roztworu pożywki (publikacja 3). W kolejnych badaniach oceniano wpływ dolistnego opryskiwania roślin 0,03% roztworem kwasu salicylowego i 0,7% roztworem azotanu wapnia oraz roztworem zawierającym oba te składniki w podanych stężeniach na wzrost roślin, plon oraz jakość owoców papryki uprawianej w podłożu z wełny mineralnej (publikacja 4). Analizowano wpływ dolistnego stosowania kwasu salicylowego i wapnia na poprawę jakości fizykochemicznej, sensorycznej oraz potencjału antyoksydacyjnego owoców papryki uprawianej hydroponicznie w podłożu z wełny mineralnej (publikacja 5).

Analizę materiału roślinnego oraz ocenę jakości owoców papryki bezpośrednio po zbiorze przeprowadzono w laboratoriach Katedry Roślin Warzywnych i Leczniczych w Instytucie Nauk Ogrodniczych (publikacje 1–5).

Na rysunku 1 przedstawiono schemat badań, których wyniki zostały opublikowane w publikacjach 1–5, stanowiących integralną część niniejszej rozprawy doktorskiej. Szczegółowy opis materiałów i metod zastosowanych w celu zweryfikowania hipotez badawczych zamieszczono w publikacjach.



Rys. 1. Schemat badań

Źródło: Opracowanie własne.

3.1. Charakterystyka warunków przeprowadzonych badań

Badania dotyczyły papryki słodkiej (*Capsicum annuum* L.) uprawianej w kontrolowanych warunkach szklarniowych, z zastosowaniem różnych metod uprawy i warunków mikroklimatycznych, w celu oceny wpływu wybranych czynników agrotechnicznych na wzrost i rozwój roślin oraz jakość owoców.

Badaniami objęto dwie odmiany papryki słodkiej o czerwonych owocach:

1) 'Aifos' F1 – odmiana firmy nasiennej Seminis, Bayer; rośliny o zwartym pokroju, owoce typu „blok", o grubym miąższu owocni (10 mm) i średniej masie owocu około 220 g,

2) 'Palermo' F1 – odmiana firmy nasiennej Rijk Zwaan; rośliny o luźnym pokroju, owoce wydłużone typu 'Dulce Italiano', o cienkim miąższu owocni, wysokiej zawartości cukru i średniej masie owocu około 125 g.

Podłoże uprawowe stanowiła wełna mineralna firmy Grodan w asortymencie: „koreczki" typ Multiblok 200 (do wysiewu nasion) i kostki Grodan Delta (do produkcji rozsady) oraz maty Grotop Master (do uprawy na miejscu stałym). Podłoże przed użyciem było nasączane pożywką o odpowiednim składzie i stężeniu jonów w zależności od etapu badań i fazy rozwojowej rośliny (EC 1,4–2,8 $dS \cdot m^{-1}$, pH 5,5). W okresie uprawy roztwór pożywki dozowano do każdej rośliny kroplowo, pojedynczą kapilarą o wydajności 3 $dm^3 \cdot h^{-1}$ z kroplownikiem oraz kompensacją ciśnienia, za pomocą komputera nawożeniowego (publikacja 1–5).

Badania w Szklarniowym Ośrodku Doświadczalnym SGGW w Warszawie prowadzono w pojedynczych kamerach uprawowych o powierzchni użytkowej 40 m^2 (wyposażonych w 3 zagony uprawowe, każdy o wymiarach 1,2 m × 9,0 m) i w kamerze o powierzchni użytkowej około 120 m^2 (wyposażonej w 9 zagonów, każdy o wymiarach 1,2 m × 10,0 m). Parametry mikroklimatu w kamerach uprawowych kontrolowano za pomocą komputera klimatycznego Hortimax Clima 500, zarządzanego przez program komputerowy Synopta.

Rośliny papryki w doświadczeniach uprawowych prowadzono na dwa pędy i w systemie „V" (sadząc rośliny w jednym rzędzie, pośrodku każdego zagonu). W czasie zabiegów pielęgnacyjnych w głównym rozgałęzieniu rośliny, tzw. „czaszy", usuwano kwiaty i zawiązki owoców. Cięcie roślin na dwa pędy przeprowadzano w zależności od tempa wzrostu roślin, zwykle co około 10 dni. Polegało ono na usuwaniu pędów bocznych i pozostawianiu najsilniejszych i odpowiednio usytuowanych

na roślinie dwóch pędów głównych. Przyjęto zasadę, aby na każdy zawiązek owocu zostawiać po dwa liście.

Eksperymenty realizowano w układzie losowym. Liczba powtórzeń i roślin w kombinacjach różniła się w zależności od badania – szczegółowe informacje metodyczne podano w publikacjach.

W ramach prowadzonych działań fitosanitarnych zastosowano biologiczne metody ochrony roślin z wykorzystaniem drapieżnych roztoczy *Amblyseius swirskii*. Są one powszechnie stosowane w integrowanej ochronie upraw pod osłonami. Wykazują wysoką skuteczność w zwalczaniu wciornastka, mączlika oraz młodocianych stadiów przędziorka. Zastosowanie roztoczy umożliwiło ograniczenie stosowania chemicznych środków ochrony roślin. Nie było konieczności przeprowadzania w trakcie badań zabiegów środkami grzybobójczymi.

Publikacja 1: Rozsadę dwóch odmian papryki 'Aifos' i 'Palermo' przygotowano w kostkach z wełny mineralnej. Warunki mikroklimatu w kamerze doświadczalnej kontrolowano komputerowo: temperatura dzień/noc 22/20 °C, 60–70% RH, stężenie CO_2 około 800 ppm. Rośliny doświetlano przez 16 godzin dziennie przy zastosowaniu lamp HPS, zapewniających PPFD na poziomie 170 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Po posadzeniu rozsady na miejsce stałe w kamerze uprawowej, średnia temperatura w dzień wynosiła 22–25 °C, w nocy 18–20 °C, 75% RH, a stężenie CO_2 800 ppm. Rośliny w okresie uprawy doświetlano lampami LED: od góry lampami Green Power LED (Philips) (DR/W–LB, 195 W), a do doświetlania międzyrzędowego użyto jednej linii lamp LED (moduł 2,5 m HO DR/B 100 W) (Philips). Rośliny doświetlano 16 godzin na dobę. Komputer klimatyczny wyłączał lampy automatycznie, gdy promieniowanie słoneczne było wyższe niż 250 $W \cdot m^{-2}$. Warunki świetlne pod względem PAR (oświetlenie górne i międzyrzędowe) wyniosły około 185 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (PPFD). Natężenie światła mierzono za pomocą światłomierza Li-Cor LI-250A, czujnika kwantowego LI-190. Do fertygacji roślin systemem kapilarnym, korzystano z pożywek stukrotnie stężonych przygotowywanych z nawozów pojedynczych firmy Yara Poland Sp. z o.o. Pożywkę roboczą (z pożywek stężonych) przygotowywano i dozowano przy użyciu komputera z mieszalnikiem do nawozów z automatyczną kontrolą EC i pH, FertiMix 400 firmy HortiMax. Średnie wartości EC pożywki do zasilania papryki wynosiły 2,8–3,3 $dS \cdot m^{-1}$, a pH 5,5–5,8. Stężenie składników mineralnych (w $mg \cdot dm^{-3}$)

dla każdej kombinacji nawozowej wynosiło: N-NO_3–195, P–57, K–273, Mg–47, Ca–187, Fe–2, Mn–0,6, B–0,3, Cu–0,15, Zn–0,3, Mo–0,05.

Publikacja 2: Dwutygodniowe siewki papryki dwóch odmian 'Aifos' i 'Palermo' posadzono do kostek z wełny mineralnej. Połowa produkowanej rozsady papryki w kostkach z wełny mineralnej do uprawy hydroponicznej była doświetlana lampami HPS (Gavita GAN 400 W), a druga połowa lampami Green Power LED (DR/W–LB, 195 W) firmy Philips. Użyte lampy LED charakteryzowały się 87,5% udziałem światła czerwonego o zakresie długości fal od 630 do 660 nm, w tym z najwyższym udziałem fal długości 660 nm oraz 12,5% udziałem światła niebieskiego o zakresie od 440 do 460 nm (pomiar fito-foto-radiometrem firmy Gigahertz-Optik). Dzienny czas ekspozycji roślin na światło wynosił 16 godzin, przy poziomie światła PAR ~170 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD. Lampy wyłączały się automatycznie, gdy promieniowanie słoneczne było wyższe niż 250 $W \cdot m^{-2}$. Średnie dzienne promieniowanie słoneczne w okresie wzrostu rozsady papryki wynosiło około 186,9 $J \cdot cm^{-2}$. Parametry mikroklimatu w kamerze uprawowej wyniosły średnio: temperatura dzień/noc 22/20 °C, 60–70% RH i stężenie CO_2 800 ppm. Pożywka do zasilania rozsady papryki zawierała następujące składniki (w $mg \cdot dm^{-3}$): N-NO_3–195, P–57, K–273, Mg–47, Ca–187, Fe–2, Mn–0,6, B–0,3, Cu–0,15, Zn–0,3, Mo–0,05. EC pożywki wynosiło około 2,8 $dS \cdot m^{-1}$, a pH 5,5.

Publikacja 3:

Optymalizacja stężenia SA

W pierwszej części badań przeprowadzono eksperyment testowy w celu ustalenia odpowiedniego stężenia SA do dolistnego opryskiwania i do podlewania (zabieg dokorzeniowy) roślin papryki. W tym celu nasiona papryki odmiany 'Palermo' wysiano do „paluszków" z wełny mineralnej, nasączonych pożywką o EC 1,4 $dS \cdot m^{-1}$ i pH 5,5. Siewki papryki (14 dni po siewie) posadzono do kostek z wełny mineralnej, nasączonych pożywką o EC 2,5 $dS \cdot m^{-1}$ i pH 5,5. Średnia temperatura wynosiła dzień/noc 22/20 °C, 60–70% RH, stężenie CO_2 800 ppm.

System uprawy aeroponicznej

Badania nad wpływem SA na wzrost, plon i jakość owoców papryki w warunkach standardowego i wysokiego EC pożywki przeprowadzono w uprawie aeroponicznej w dwóch terminach. Do badań użyto odmianę papryki słodkiej 'Palermo'. W tym celu, rozsadę papryki posadzono w kamerze uprawowej, którą wyposażono w system

do uprawy aeroponicznej. W kamerze uprawowej warunki mikroklimatyczne były kontrolowane komputerowo. Temperatura wynosiła dzień/noc 20–23/17–19 °C, 70–75% RH, stężenie CO_2 800 ppm. Papryka w systemie aeroponicznym była zasilana standardowym roztworem pożywki roboczej o składzie ($mg \cdot dm^{-3}$): $N\text{-}NO_3$–195, P–57, K–273, Mg–47, Ca–187, Fe–2, Mn–0,6, B–0,3, Cu–0,15, Zn–0,3, Mo–0,05. EC pożywki wynosiło 3,3 $dS \cdot m^{-1}$, a pH 6,2. Do przygotowania pożywki stężonej 100-krotnie, z której przygotowano pożywkę standardową (1%), użyto następujących nawozów: $Ca(NO_3)_2 \times 4H_2O$, KNO_3, $MgSO_4 \times 7H_2O$, KH_2PO_4, $K_2SO_4 \times 2H_2O$, HNO_3 oraz Superba/Micromix firmy Yara International ASA. Zwiększenie EC roztworu pożywki uzyskano poprzez dodanie dwukrotnie większej ilości skoncentrowanego roztworu nawozowego do wody (2%) w porównaniu do standardowej dawki (1%). W rezultacie, wartość EC w kombinacjach z wysokim EC pożywki, oznaczonych w publikacji „High EC", wynosiła około 7 $dS \cdot m^{-1}$.

Publikacja 4: Doświadczenie uprawowe prowadzono w dwóch analogicznych okresach wegetacji w dwóch kolejnych latach (terminach). W obu terminach w celu przygotowania rozsady do założenia uprawy korki („paluszki") z wełny mineralnej do siewu nasion nasączono roztworem pożywki o EC wynoszącym 1,4 $dS \cdot m^{-1}$ i pH 5,5. Nasiona papryki po wysianiu przykryto wermikulitem i „paluszki" umieszczono w komorze klimatyzacyjnej (Sharma Scientific Co., Delhi, Indie) w temperaturze 28 °C dzień/noc do momentu wykiełkowania nasion. Następnie, po 14 dniach od siewu nasion, siewki papryki umieszczono w kostkach wełny mineralnej Grodan Delta firmy Grodan, namoczonych w pożywce o EC 2,8 $dS \cdot m^{-1}$ i pH 5,5. Rozsadę papryki, w 28 dniu po siewie nasion, posadzono do mat uprawowych z wełny mineralnej Grotop Master firmy Grodan, nasączonych pożywką o EC 3,3 $dS \cdot m^{-1}$ i pH 5,5–5,8. W kamerze uprawowej w pierwszym roku badań (termin 1), średnia temperatura dzień/noc wynosiła 25,5/20,9 °C, a w roku drugim (termin 2), odpowiednio 25,8/20,8 °C. Bardzo często w okresie wegetacji roślin, w każdym z badanych terminów uprawy, średnia temperatura dzienna była bliska 30 °C, a nocna 25 °C. Przyczyną tak wysokiej temperatury w szklarni było występujące w tym okresie promieniowanie słoneczne. Suma promieniowania w okresie prowadzenia badań w pierwszym roku (termin 1) wyniosła 192,11 $kJ \cdot cm^{-2}$, natomiast w drugim roku badań (termin 2) – 209,41 $kJ \cdot cm^{-2}$. Całkowite dzienne wartości promieniowania w okresie wegetacji roślin wyniosły średnio 1231 $J \cdot cm^{-2}$ w terminie 1 i 1342 $J \cdot cm^{-2}$ w terminie 2. Pożywka do uprawy papryki zawierała (w $mg \cdot dm^{-3}$):

N-NO_3–230, P–57, K–330, Mg–55, Ca–180, Fe–2.5, Mn–0,8, B–0,33, Cu–0,15, Zn–0,33, Mo–0,05. Wysokość EC pożywki dozowanej kapilarami do roślin wyniosła, średnio z całego okresu wegetacji roślin, od 2,9 do 3,2 $dS \cdot m^{-1}$, a pH 5,5–5,8.

Publikacja 5: Publikację przygotowano na podstawie wyników badań wybranych cech jakościowych i właściwości antyoksydacyjnych owoców papryki odmian 'Aifos' i 'Palermo', prowadzonych w pierwszym i drugim roku doświadczeń uprawowych. Warunki uprawy scharakteryzowano przy opisie publikacji 4.

3.2. Terminy i czynniki agrotechniczne zastosowane w badaniach

W pracy dokonano analizy wpływu wybranych czynników agrotechnicznych na wzrost, rozwój oraz jakość owoców papryki. Badania przeprowadzono w różnych warunkach uprawy i terminach, stosując różne technologie (z doświetlaniem asymilacyjnym lampami sodowymi i lampami LED) oraz systemy uprawowe, takie jak hydroponika oraz aeroponika.

Publikacja 1: Rozsadę dwóch odmian papryki ('Aifos' i 'Palermo') posadzono 6 grudnia 2018 r. do mat uprawowych z wełny mineralnej typu Grotop Master 100 × 20 × 10 cm (po 2 rośliny), a produkcję zakończono w lipcu 2019 r. Gęstość roślin wynosiła 2,5 rośliny na m^2 powierzchni użytkowej. Nawożenie prowadzono, stosując trzy różne pożywki. Każda pożywka miała jednakowe stężenie składników mineralnych, a różnicę stanowiła forma użytego fosforu w pożywce:

(1) C (kontrola, 100% fosforu w formie ortofosforanów),
(2) P-15 (15% fosforu w formie polifosforanów, 85% w formie ortofosforanów),
(3) P-30 (30% fosforu w formie polifosforanów, 70% w formie ortofosforanów).

Publikacja 2: Badania przeprowadzono w okresie zimowym 2018 i 2020 roku. Rozsadę dwóch odmian papryki ('Aifos' i 'Palermo') przygotowywano w podłożu z wełny mineralnej. Siewki papryki posadzono do kostek z wełny mineralnej 5 grudnia w obu latach prowadzenia badań. Połowa roślin w czasie produkcji rozsady z przeznaczeniem do uprawy hydroponicznej była doświetlana lampami HPS (Gavita GAN 400 W), a druga połowa lampami Green Power LED (DR/W–LB, 195 W) firmy Philips (charakterystyka składu spektralnego światła emitowanego przez użyte w badaniu lampy LED została opisana w rozdziale 3.1.). W obrębie stołu zalewowego przeznaczonego do przeprowadzenia badań wyznaczono poletka doświadczalne o jednakowej powierzchni, w których rozmieszczono rośliny zgodnie z losowym

układem kombinacji czynników badawczych. Każde poletko obejmowało 10 roślin danej odmiany. Doświadczenie prowadzono w trzech powtórzeniach po 10 roślin w każdym. Materiał doświadczalny w każdym roku badań stanowiło łącznie 120 roślin uprawianych w kostkach wełny mineralnej.

Publikacja 3:

Optymalizacja stężenia SA

W badaniu nad optymalizacją stężenia SA, jedną partię roślin papryki opryskiwano dolistnie roztworem kwasu salicylowego w czterech stężeniach (1, 2, 5, 10 mmol SA), a rośliny kontrolne opryskiwano wodą (0 SA). Natomiast drugą partię roślin, u których testowano dokorzeniowe zastosowanie SA, podlewano pożywką z dodatkiem SA w czterech stężeniach (100, 150, 500, 1000 ppm SA), a rośliny kontrolne podlewano pożywką, bez kwasu salicylowego (0 SA). W każdej kombinacji badano po 10 roślin, w trzech powtórzeniach. Pierwsze opryskiwanie roślin kwasem salicylowym przeprowadzono w 21 dniu po siewie, a następne w 24 i 27 dniu po siewie. Roztwory do opryskiwania dolistnego (1, 2, 5, 10 mmol SA) uzupełniono o środek powierzchniowo czynny Tween 20.

Roztwory do podlewania roślin (100, 150, 500, i 1000 ppm SA) stosowano z pożywką do zasilania rozsady papryki. Wszystkie rośliny podlewano w momencie, gdy masa kostki z wełny mineralnej nasączonej pożywką (100%) obniżyła się o około 35%. W każdej kombinacji były 3 powtórzenia, po 10 roślin w każdym.

Doświadczenie uprawowe

Wyniki dotyczące optymalizacji stężenia SA do dolistnego opryskiwania roślin i zastosowania dokorzeniowego wykorzystano w doświadczeniach uprawowych. Badanie wpływu SA na wzrost i jakość owoców papryki w warunkach standardowego i wysokiego EC pożywki wykonano w uprawie aeroponicznej, w dwóch terminach. Do badań użyto odmianę 'Palermo'. Siew nasion w pierwszym terminie przeprowadzono 7 kwietnia 2021 r., a w drugim terminie 14 lipca 2021 r. Zabieg pikowania siewek wykonano w 14 dni po siewie nasion, w obu terminach uprawy. Rozsadę papryki posadzono do systemu aeroponicznego 28 dnia po wysiewie nasion zarówno w terminie 1, jak i w terminie 2. Rośliny umieszczono w ażurowych doniczkach, które następnie włożono do otworów wykonanych na górze specjalnych pojemników bez dna o wymiarach 0,28 m × 0,36 m × 0,27 m. Każdy pojemnik wyposażono w kapilarę, którą zainstalowano w specjalnie wykonanym otworze w bocznej ściance pojemnika.

Na końcu każdej kapilary umieszczono dyszę ciśnieniową, która rozpylała (w formie drobnych kropel) pożywkę na korzenie roślin. Następnie pożywka spływała na dno pojemnika zbiorczego, skąd po uzupełnieniu nowym roztworem nawozów wracała po przefiltrowaniu do systemu aeroponicznego. Rośliny rosły w kamerze uprawowej w gęstości 2,5 rośliny na 1 m^2 powierzchni użytkowej. Doświadczenie miało układ losowy. W każdym z czterech, niezależnych poletek uprawowych znajdowało się 20 roślin zasilanych pożywką w systemie aeroponicznym. Testowano kombinacje:

(1) Niskie EC – rośliny w tej kombinacji zasilano pożywką standardową dla papryki, o EC 3,3 $dS \cdot m^{-1}$,

(2) Niskie EC + SA stosowany dolistnie – rośliny w tej kombinacji zasilano pożywką standardową, jak w kombinacji (1), i opryskiwano dolistnie SA (5 mmol/l),

(3) Wysokie EC – rośliny w tej kombinacji zasilano pożywką o EC 7 $dS \cdot m^{-1}$, uzyskaną poprzez 2-krotne stężenie składników użytych do pożywki w kombinacji Niskie EC,

(4) Wysokie EC + SA stosowany dolistne + SA stosowany dokorzeniowo – w tej kombinacji rośliny zasilano taką pożywką, jak w kombinacji Wysokie EC (3), i opryskiwano dolistnie rośliny SA, jak w kombinacji (2), oraz stosowano SA dokorzeniowo, razem z pożywką.

Doświadczenie zakończono 70 dni po siewie nasion papryki w obu terminach (termin 1: 16 czerwca 2021 r., termin 2: 22 września 2021 r.).

Publikacja 4: Badania przeprowadzono w latach 2019 (termin 1) i 2020 (termin 2). W obu latach rozsadę dwóch odmian papryki ('Aifos' i 'Palermo') posadzono na miejsce stałe 13 maja, a uprawę zakończono 15 października. W obu terminach paprykę uprawiano hydroponicznie w podłożu z wełny mineralnej. W szklarniowej kamerze uprawowej znajdowało się 9 zagonów, każdy o długości około 10 m i szerokości około 1,2 m. W każdym zagonie było 9 mat uprawowych z wełny mineralnej. Na każdej macie uprawowej posadzono po 3 rośliny papryki. Gęstość roślin w kamerze uprawowej wynosiła 2,5 rośliny na 1 m^2 powierzchni użytkowej.

W doświadczeniu zbadano wpływ opryskiwania roślin wapniem i kwasem salicylowy na wzrost roślin, plonowanie i jakość owoców dwóch odmian papryki uprawianych hydroponicznie w wełnie mineralnej.

Zastosowane kombinacje:

(1) Kontrola – rośliny opryskiwane dolistnie wodą,
(2) SA – rośliny opryskiwane dolistnie kwasem salicylowym o stężeniu 0,03% (2,17 mmol/l),
(3) Ca – rośliny opryskiwane dolistnie azotanem wapnia o stężeniu 0,7%,
(4) SA + Ca – rośliny opryskiwane dolistnie jednocześnie kwasem salicylowym (0,03%) i azotanem wapnia (0,7%).

W każdej z zastosowanych kombinacji użyto adiuwant Olejan 85 EC.

Eksperyment założono w układzie losowanych bloków. Każda kombinacja była w czterech powtórzeniach, po sześć roślin w każdym. Rośliny opryskiwano dolistnie raz w tygodniu, zaczynając od 7 dnia po posadzeniu rozsady, aż do 151 dnia po posadzeniu rozsady. W doświadczeniu wykonano 21 opryskiwań kwasem salicylowym. Doświadczenie zakończono w 158 dniu po posadzeniu rozsady.

Publikacja 5: Owoce papryki obu odmian ('Aifos' i 'Palermo'), z przeznaczeniem do analiz fizykochemicznych i oceny sensorycznej, zebrano w fazie dojrzałości konsumpcyjnej, w pełni wybarwione. W obu sezonach uprawy (termin 1 – 2019 r. i termin 2 – 2020 r.) owoce badano w 84 dniu (sierpień) i 140 dniu (wrzesień) po posadzeniu rozsady. Szczegóły warunków uprawy i założenia metodyczne doświadczenia uprawowego opisano w publikacji 4. Badano jakość owoców papryki ze wszystkich kombinacji doświadczalnych (kontrola, Ca, SA, Ca + SA), dla obu odmian. Próbę owoców do analiz stanowiło 10 owoców losowo wybranych z różnych roślin w obrębie czterech powtórzeń danej kombinacji. Oznaczenia fizykochemiczne oraz ocenę sensoryczną przeprowadzano tego samego dnia, bezpośrednio po zbiorze i odpowiednim przygotowaniu próbek.

3.3. Zakres wykonanych prac

Publikacja 1: W badaniach z użyciem polifosforanów w pożywce do fertygacji papryki oceniano wzrost, kondycję roślin, plonowanie i jakość owoców. Mierzono dobową ilość pożywki zasilającej rośliny (pożywki z kapilary) i ilość drenażu w przeliczeniu na roślinę oraz EC i pH pożywki z kapilary, drenażu i podłoża, używając przenośnego miernika EC/pH+T firmy DGT Senmatic. Czujniki GroSens firmy Grodan wykorzystywano także do pomiaru EC podłoża, wilgotności podłoża i temperatury podłoża, głównie w celu kontroli zarządzania strategią nawożenia razem z nawadnianiem. W badanych kombinacjach porównywano tygodniowe przyrosty długości łodygi i liczbę liści na

roślinie. Dwukrotnie w okresie wegetacji (8 i 16 tygodni po posadzeniu roślin, zarówno w terminie 1 i 2) mierzono na młodych, w pełni wyrośniętych liściach papryki względne stężenie chlorofilu *a* + *b* za pomocą aparatu Minolta SPAD-502 i fluorescencję chlorofilu *a* aparatami FMS-2 i PEA. Stan odżywienia roślin składnikami mineralnymi: N, P, K, Mg, Na, Ca, Fe, Mn, Cu, Zn, B, określono na podstawie analizy próbek liści 8 i 16 tygodni po posadzeniu (w terminie 1 i 2).

Pierwszy zbiór owoców papryki wykonano w 76 dniu od siewu. Owoce zbierano w fazie owocu dojrzałego, wybarwionego w 2/3 części i w pełni wybarwionego, co 7 dni. W plonie oceniano liczbę i masę owoców ogółem oraz owoców handlowych i niehandlowych z objawami suchej zgnilizny wierzchołkowej (BER). Jakość owoców badano dwukrotnie (94 i 150 dni po posadzeniu rozsady). W celu porównania jakości owoców w badanych kombinacjach, oznaczono zawartość suchej masy w owocach, stężenie kwasu askorbinowego, stężenie składników rozpuszczalnych w soku komórkowym, całkowitą zawartość cukrów, a także stężenie azotanów, jonów P, K i Ca. Wykonano także ocenę sensoryczną owoców papryki z poszczególnych kombinacji doświadczenia.

Publikacja 2: W badaniach z użyciem do doświetlania asymilacyjnego lamp LED jako alternatywy dla lamp sodowych w produkcji rozsady papryki, porównywano wzrost i kondycję roślin. Pomiary wysokości roślin i liczby liści przeprowadzano co tydzień na pięciu losowo wybranych roślinach z każdej kombinacji, po 7, 14, 21 i 28 dniach uprawy. W tych terminach mierzono także względną zawartość chlorofilu *a* + *b* w liściach, które były w pełni rozwinięte, i w tych samych liściach mierzono fluorescencję chlorofilu zarówno w świetle otoczenia, jak i po adaptacji roślin do ciemności.

Do badań anatomicznych, po 28 dniach uprawy (42 dni od siewu), pobrano fragmenty młodych, w pełni rozwiniętych liści rozsady papryki – z trzech roślin z każdej kombinacji. Mierzono grubość całkowitą liści, liczbę i grubość warstw miękiszu palisadowego oraz gąbczastego, rozmiary komórek mezofilu, a także liczbę aparatów szparkowych. Badano także rozmieszczenie chlorofilu i karotenoidów w komórkach.

Publikacja 3: W badaniu z zastosowaniem SA w uprawie papryki w celu obniżenia negatywnych skutków stresu abiotycznego wywołanego wysokim EC pożywki, oceniano wzrost, kondycję roślin, jakość plonu oraz poziom wybranych enzymów stresu i reaktywnych form tlenu. W każdej kombinacji wybrane rośliny testowe były monitorowane pod względem dynamiki wzrostu, od posadzenia rozsady do

zakończenia badań, po 35 dniach uprawy w systemie aeroponicznym. Wszystkie usunięte liście, pędy boczne oraz zawiązki owoców z roślin testowych ważono na wadze laboratoryjnej w celu oceny całkowitej świeżej masy wyprodukowanej przez rośliny. Po zakończeniu doświadczenia określono masę zielonych części rośliny, zawiązków owoców oraz korzeni.

Pomiary morfologiczne prowadzono raz w tygodniu przez pięć tygodni, począwszy od 35 dnia od siewu nasion (termin sadzenia rozsady do systemu aeroponicznego), następnie po 7, 14, 21 i 28 dniach od sadzenia rozsady. Określano wysokość roślin oraz liczbę w pełni rozwiniętych liści na roślinie. Oceniono całkowitą liczbę i masę zawiązanych owoców, w tym owoców z BER oraz wytworzoną masę nadziemną roślin i korzeni. Doświadczenie zakończono 35 dnia od sadzenia rozsady. Wyliczono stosunek masy nadziemnej do masy korzeni papryki w zależności od zastosowanych kombinacji. Wpływ kwasu salicylowego na aktywność fotosyntetyczną badano poprzez pomiar fluorescencji chlorofilu *a* liści oraz zawartości względnej chlorofilu w jednostkach SPAD. W doświadczeniu oznaczono również zawartość białka rozpuszczalnego, produkcję H_2O_2 oraz aktywność enzymatyczną SOD i CAT jako kluczowych enzymów antyoksydacyjnych.

Publikacja 4: W doświadczeniach uprawowych założonych w dwóch kolejnych sezonach wegetacyjnych badano wpływ SA, Ca i SA + Ca na wzrost roślin, plonowanie oraz jakość owoców papryki. W tym celu prowadzono pomiary dynamiki wzrostu roślin i liczby w pełni rozwiniętych liści na sześciu reprezentatywnych roślinach testowych w każdej kombinacji w okresie od 7 dnia do 158 dnia od posadzenia rozsady na miejsce stałe. W 31 i 102 dniu od rozpoczęcia uprawy oceniano fluorescencję chlorofilu *a* liści w różnym wieku: młodszych (5. liść, licząc od wierzchołka pędu owocującego) i starszych (10. liść, licząc od wierzchołka pędu owocującego), mierząc takie parametry, jak: wydajność fluorescencji w stanie stacjonarnym, maksymalna fluorescencja przy świetle, wydajność kwantowa PSII, maksymalna wydajność kwantowa PSII po adaptacji do ciemności oraz PI – wskaźnik witalności PS II. Równocześnie dokonywano pomiaru zawartości względnej chlorofilu za pomocą miernika SPAD. Zbiory owoców rozpoczęto w 56 dniu uprawy i kontynuowano co około 10 dni do 158 dnia uprawy. Zebrane owoce analizowano pod kątem masy i liczby w podziale na plon całkowity, handlowy oraz owoce z objawami BER. Wybrane reprezentatywne próby owoców dojrzałych

wybarwionych analizowano również pod względem zawartości suchej masy, parametrów barwy w skali CIE Lab* oraz cech sensorycznych.

Publikacja 5: W badaniu określono wpływ zastosowanych w uprawie hydroponicznej papryki czynników, takich jak SA, Ca i SA + Ca na cechy jakościowe i właściwości prozdrowotne owoców papryki. Badano aktywność antyoksydacyjną oraz wykonano ocenę sensoryczną owoców papryki. Owoce badano w każdym roku uprawy: 84 dni i 140 dni po rozpoczęciu uprawy opisanej w publikacji 4, odpowiednio zarówno w pierwszym jak i w drugim roku badań dnia 5 sierpnia i 30 września. Do badań wybrano owoce dojrzałe, w pełni wybarwione. Z próby 10 owoców z każdej kombinacji losowo wytypowano pięć owoców, które poddano analizom fizykochemicznym. Oznaczono zawartość suchej masy, całkowitą zawartość witaminy C, całkowitą zawartość składników rozpuszczalnych w soku komórkowym, całkowitą zawartość cukrów, kwasowość ogólną, stosunek cukrów do kwasów organicznych, stężenie azotanów (NO_3^-) oraz zawartość K i Ca. Określono także zawartość karotenoidów (β-karotenu, luteiny, zeaksantyny, kapsantyny). w owocach. Ocenę sensoryczną wykonano na 15 owocach dojrzałych, w pełni wybarwionych, zebranych losowo z każdej kombinacji.

3.4. Metody badawcze

3.4.1. Parametry morfologiczne roślin, SPAD i fluorescencja chlorofilu *a*

W celu określenia tygodniowego przyrostu długości pędu owocującego papryki, w każdej kombinacji do pomiarów wybierano sześć reprezentatywnych roślin testowych, zaznaczano miejsce wierzchołka pędu na sznurku, którym okręcano pęd w miarę jego wzrostu. Po 7 dniach mierzono odległość od wierzchołka pędu do wcześniej zaznaczonego punktu na sznurku, odpowiadającego pozycji wierzchołka sprzed tygodnia. Pomiar ten wykonywano raz w tygodniu. Raz w tygodniu mierzono wysokość roślin (od szyjki korzeniowej do wierzchołka pędu głównego) za pomocą taśmy mierniczej, a także liczono w pełni rozwinięte liście. Liczbę liści podawano jako sumę liści rozwiniętych na dwóch głównych pędach rośliny. Wyniki przedstawione są w publikacji 1, 2, 3, 4. Dodatkowo mierzono średnicę pędu głównego w odległości 1 cm powyżej szyjki korzeniowej przy użyciu suwmiarki oraz określano świeżą masę nadziemnej części rośliny (liści i łodygi) z dokładnością do 0,1 g. Pomiarów dokonywano dla pięciu losowo wybranych roślin z każdej kombinacji. Wyniki przedstawiono w publikacji 3.

Względną zawartość chlorofilu w liściach oceniano za pomocą testu SPAD wykorzystując przenośny miernik Minolta SPAD-502 Plus. Pomiar przeprowadzono na 5. oraz 10. w pełni rozwiniętym liściu, licząc od wierzchołka pędu owocującego. Fluorescencję chlorofilu badano przy użyciu przenośnego systemu monitorowania fluorescencji chlorofilu z modulacją impulsów FMS-2 (Hansatech Instruments Ltd., King's Lynn, Norfolk, Wielka Brytania). Mierzono takie parametry, jak: Fs – bieżący poziom fluorescencji, Fm' – maksymalna fluorescencja w warunkach świetlnych oraz ΦPSII – efektywność kwantowa fotosystemu PS II. Maksymalną wydajność kwantową fotosystemu PS II w warunkach ciemności (Fv/Fm) oznaczano po 30-minutowym okresie adaptacji liści do ciemności. Bezpośredni pomiar fluorescencji przeprowadzano przy użyciu przenośnego miernika fluorescencji PEA (Hansatech Instruments Ltd., King's Lynn, Norfolk, Wielka Brytania). Wyniki przedstawiono w publikacjach 1, 2, 3 i 4.

3.4.2. Mikroskopia świetlna i konfokalna w ocenie komórek liści

Do badań anatomicznych, które przeprowadzono w Katedrze Botaniki, w Instytucie Rolnictwa SGGW w Warszawie, pobrano liście w pełni rozwinięte z roślin dwóch odmian papryki doświetlanych lampami HPS i LED. Dla każdej kombinacji fragmenty liści utrwalano przez 3 godziny w pożywce Karnovsky'ego, traktowano 1% czterotlenkiem osmu, odwadniano serią etanolową z tlenkiem propylenu i zatapiano w żywicy epoksydowej (Serva, Niemcy). Skrawki o grubości 3 µm barwiono błękitem toluidyny i analizowano pod mikroskopem świetlnym (Olympus-Provis). Mierzono grubość liścia, warstw komórek palisadowych i gąbczastych, rozmiar komórek oraz liczbę aparatów szparkowych na 600 µm² za pomocą oprogramowania Olympus-Provis cellSens Standard przy powiększeniu 10×. Ultracienkie przekroje (80 nm) przygotowano ultramikrotomem Leica UCT, barwiono octanem uranylu i cytrynianem ołowiu, a następnie badano mikroskopem transmisyjnym TEM FEI 268D „Morgagni" (z kamerą Olympus-SIS „Morada"). Obrazy zapisywano w formacie jpg i edytowano w Photoshop CS 8.0. Chloroplasty w komórkach palisadowych badano mikroskopem konfokalnym (Leica TCS SP5II), rejestrując fluorescencję chlorofilu i karotenoidów po wzbudzeniu przy 488/633 nm i emisji przy 520-580/660-705 nm. Obrazy uzyskiwano w odstępach 0,18 µm, poddawano dekonwolucji (cyfrowe przetwarzanie obrazu) i cyfrowo rozdzielano kolory. Poziomy fluorescencji mierzono w centralnych obszarach chloroplastów, omijając granule skrobi. Wyniki przedstawiono w publikacji 2.

3.4.3. Zawartość białka rozpuszczalnego, H_2O_2 i enzymów antyoksydacyjnych SOD i CAT w liściach

Zawartość białka rozpuszczalnego oznaczano za pomocą metody kolorymetrycznej, opierającej się na wiązaniu barwnika z białkami, a wyniki wyrażano w mg białka na g świeżej masy. Zawartość białka rozpuszczalnego oznaczano metodą Bradforda [1976]. Zawartość nadtlenku wodoru (H_2O_2) oznaczano przy użyciu zmodyfikowanej procedury analitycznej [Wilmowicz i in. 2011]. Materiał badawczy pobierano z pięciu roślin testowych z każdej kombinacji doświadczalnej, tworząc próbę zbiorczą. Próbę stanowiły liście w pełni rozwinięte (10. liść, licząc od wierzchołka rośliny), zebrane ręcznie (bez użycia narzędzi) o godzinie 8:00, przy zachmurzeniu. Materiał bezpośrednio po zbiorze umieszczano w woreczkach z folii aluminiowej, zamrażano w ciekłym azocie, a następnie przechowywano w zamrażarce o temperaturze –81°C. Do analizy H_2O_2 liście (200 mg) homogenizowano w 1 ml 1% kwasu trichlorooctowego (TCA). Uzyskane homogenaty wirowano, a supernatanty przenoszono do nowych probówek i dostosowywano ich pH do 7,5 przy użyciu wodorotlenku potasu. Następnie próbki ponownie wirowano, a 1 ml supernatantu mieszano z 250 µl roztworu kwasu 3-(dimetyloamino)-benzoesowego (19,8 mM) w 0,5 M buforze fosforanowym (pH 6,5), 230 µl roztworu hidrazonu 3-metylo-2-benzotiazolinonu (0,456 mM) oraz 20 µl peroksydazy (0,25 U – jednostka enzymatyczna odpowiadająca ilości enzymu przekształcającej µmol substratu na minutę w optymalnych warunkach reakcji). Absorbancję mierzono przy długości fali 590 nm, a zawartość H_2O_2 wyrażano w µmol H_2O_2 na gram świeżej masy (µmol·g^{-1} św. m.).

Ekstrakty do pomiaru aktywności enzymatycznej przygotowywano przez homogenizację 0,2 g zamrożonych liści w 1 ml buforu ekstrakcyjnego zawierającego 50 mM fosforanu potasu (pH 7,6) oraz 0,1 mM Na-EDTA. Homogenaty wirowano przy 15 000 obr./min przez 15 minut, a supernatanty wykorzystywano do dalszych analiz enzymatycznych. Aktywność dysmutazy ponadtlenkowej określano, monitorując redukcję błękitu nitrotetrazolowego indukowaną przez rodniki ponadtlenkowe. Mieszanina reakcyjna o objętości 1 ml zawierała 50 mM fosforanu potasu (pH 7,8), 6,5 mM metioniny, 50 µM NBT, 20 µM ryboflawiny, 10 µM EDTA oraz 55 µl ekstraktu enzymatycznego. Po wymieszaniu, próbki inkubowano w świetle przez 15 minut, a reakcję monitorowano poprzez pomiar absorbancji przy długości fali 560 nm. Wyniki wyrażano jako jednostki aktywności enzymatycznej na miligram białka.

Całkowitą aktywność dysmutazy ponadtlenkowej oznaczano zgodnie z metodą Giannopolitisa i Riesa [1977].

Aktywność katalazy oznaczano poprzez pomiar degradacji H_2O_2. W tym celu 0,2 ml ekstraktu białkowego mieszano z 1,0 ml roztworu zawierającego 65 pmoli $H_2O_2 \cdot ml^{-1}$ w 60 mM buforze fosforanowo-sodowo-potasowym (pH 7,4) i inkubowano w temperaturze 37 °C przez 60 sekund. Reakcję enzymatyczną zatrzymywano, dodając 1,0 ml roztworu triazolu lub molibdenianu amonu, w zależności od użytej procedury. Zawartość H_2O_2 w mieszaninie reakcyjnej określano polarograficznie lub spektrofotometrycznie, mierząc absorbancję żółtego kompleksu przy długości fali 405 nm. Wyniki wyrażano jako jednostki aktywności enzymatycznej (U) na miligram białka. Aktywność katalazy określono według metody Gótha [1991]. Wyniki przedstawiono w publikacji 3.

3.4.4. Zawartość składników mineralnych w liściach

Stan odżywienia papryki, przy zastosowaniu różnej formy fosforu w pożywce do fertygacji roślin, określano na podstawie analizy zawartości makro- i mikroskładników w młodych, w pełni dojrzałych wskaźnikowych liściach (badania wykonano w Laboratorium Analiz Chemicznych, w Instytucie Ogrodnictwa – Państwowym Instytucie Badawczym w Skierniewicach). Materiał do analizy pobrano dwukrotnie w okresie wegetacji, 8 i 16 tygodni po posadzeniu roślin (w terminie 1 i terminie 2). Próbki wysuszono w temperaturze 60 °C w piecu z wymuszonym obiegiem powietrza, a następnie zmielono w młynku ze stali nierdzewnej. Próbki poddano trawieniu mikrofalowemu w HNO_3, używając zamkniętych naczyń teflonowych. Pierwiastki (P, K, Mg, Na, Ca, Fe, Mn, Cu, Zn, B) oznaczono za pomocą spektrometru plazmowego sprzężonego indukcyjnie (ICP, model OPTIMA 2000DV, PerkinElmer, Boston, USA). W celu oznaczenia całkowitego N materiał roślinny zmineralizowano po wysuszeniu w stężonym kwasie siarkowym w obecności katalizatora miedziowo-potasowego. Zawartość N oznaczano za pomocą aparatu Kjeldahla (Vapodest, Königswinter, Niemcy). Po oddestylowaniu azotu w formie NH_3 zawartość N oznaczano metodą miareczkową. Wyniki przedstawiono w publikacji 1.

3.4.5. Plon całkowity, handlowy i owoce z BER oraz twardość w skali HPE i barwa owoców w skali CIE Lab

Dojrzałe owoce papryki zbierano co 7–10 dni, w godzinach porannych. Podczas zbiorów określano liczbę oraz masę wszystkich owoców, jak również owoców handlowych i niehandlowych i owoców z BER. Za owoce niehandlowe uznawano te, które wykazywały wady rozwojowe lub mechaniczne uszkodzenia powstałe w trakcie pielęgnacji roślin. Wyniki przedstawiono w publikacjach 1, 3, 4, 5.

Do analiz wybierano owoce pozbawione oznak uszkodzeń mechanicznych, chorób oraz działalności szkodników, dojrzałe i całkowicie wybarwione. Do analizy twardości wybrano losowo pięć owoców handlowych z każdej kombinacji. Twardość owoców mierzono twardościomierzem HPE z trzpieniem o średnicy 5 mm, ustawionym pod kątem 90° względem powierzchni owocu. Pomiary wykonywano w trzech miejscach owocu: w pobliżu szypułki, w centralnej części owocu oraz w okolicy przykwiatowej, a uzyskane wyniki uśredniano. Wyniki wyrażano w jednostkach HPE w skali od 0 do 100. Barwę owoców oceniano za pomocą przenośnego spektrofotometru światła odbitego MiniScan XE PLUS D/8-S, uprzednio skalibrowanego przy użyciu standardowej białej płytki. Wyniki przedstawiano w systemie CIE Lab, gdzie parametr a* wskazuje na udział barwy zielonej i czerwonej, parametr b* na udział barwy niebieskiej i żółtej, a parametr L* oznacza jasność barwy. Pomiar twardości i barwy przeprowadzano w trzech powtórzeniach. Wyniki przedstawiono w publikacji 4.

3.4.6. Zawartość suchej masy, kwasów organicznych, cukrów, karotenoidów oraz kwasu askorbinowego w owocach

Do analiz wybierano owoce pozbawione oznak uszkodzeń mechanicznych, chorób oraz działalności szkodników, dojrzałe i całkowicie wybarwione. Z każdej kombinacji losowo pobierano po trzy owoce. Zawartość suchej masy oznaczano metodą wagową w temperaturze 105 °C, po wcześniejszym przeprowadzeniu homogenizacji owoców. Wyniki przedstawiono w publikacjach 1, 4, 5.

Zawartość β-karotenu, luteiny oraz chlorofilu *a* i *b* w owocach określano za pomocą wysokosprawnej chromatografii cieczowej w Katedrze Roślin Warzywnych i Leczniczych, w Instytucie Nauk Ogrodniczych SGGW w Warszawie, wykorzystując aparaturę Shimadzu Scientific Instruments. Homogenizację materiału roślinnego prowadzono z dodatkiem 2 g Na_2SO_4 na 100 g próbki. Homogenizowany materiał w ilości 5 g rozcierano w moździerzu z zimnym acetonem (–20 °C) oraz piaskiem

kwarcowym. Uzyskane ekstrakty przenoszono ilościowo do kolb miarowych o pojemności 50 ml i uzupełniano zimnym acetonem do odpowiedniej objętości. Próbki odwirowywano w probówkach (15 000 obr. min^{-1}), a supernatant poddawano filtracji za pomocą filtra strzykawkowego (Supelco IsoDisc™ PTFE 25 mm × 0,22 µm). Otrzymane ekstrakty przechowywano w 1 ml pojemnikach w automatycznym podajniku próbek SIL-20AC HT, utrzymując temperaturę tacy na poziomie 4 °C. Do analizy chromatograficznej nanoszono 5 µl ekstraktu na kolumnę chromatograficzną Kinetex 2,6 µm C18 100 Å o wymiarach 100 mm × 4,6 mm (Phenomenex). Rozdział związków uzyskiwano metodą elucji izokratycznej z użyciem metanolu jako fazy ruchomej w temperaturze 40 °C. Pomiar prowadzono w odpowiednich zakresach długości fal: dla β-karotenu 450 nm, dla chlorofilu *a* 430 nm, dla chlorofilu *b* 470 nm, zgodnie z metodami podanymi m.in. przez Schoefsa [2002] oraz Rodriguez-Amayę [2001], z modyfikacjami. Na podstawie uzyskanych wyników obliczono sumaryczną zawartość chlorofilu *a* i *b*. Każda kombinacja badana była w trzech niezależnych powtórzeniach, a każda próbka była następnie analizowana trzykrotnie w ramach powtórzeń pomiaru. Wyniki przedstawiono w publikacji 5.

Całkowitą zawartość witaminy C oznaczono w Katedrze Technologii i Oceny Żywności, w Instytucie Nauk o Żywności SGGW w Warszawie, metodą wysokosprawnej chromatografii cieczowej z użyciem detektora UV–vis SPD-10A VP (Shimadzu, Kioto, Japonia), pompy LC-10AT (Shimadzu, Kioto, Japonia), pieca CTO-10AS VP (Shimadzu, Kioto, Japonia), degazera DEGASSEX model D-4400 (Shimadzu, Kioto, Japonia), przy użyciu oprogramowania do zbierania danych LC Solution (Shimadzu, Kioto, Japonia, wersja 1.21 SP1). Użyto kolumny OnyxMonolithic C18, 100 × 4,6 mm (Phenomenex). Fazą ruchomą był roztwór H_3PO_4. Wyniki rejestrowano przy 254 nm. Wyniki przedstawiono w publikacji 5.

Kwasowość owoców papryki oznaczano metodą miareczkowania potencjometrycznego. Całkowitą zawartość cukru w badanych owocach oznaczano metodą Luffa-Schoorla [PN-90/A-75101/07]. Wyniki przedstawiono w publikacjach 1, 4, 5. Stosunek całkowitej zawartości cukru do kwasowości owoców papryki określono jako iloraz TS:TA. Wyniki przedstawiono w publikacji 5. Składniki rozpuszczalne w soku komórkowym (TSS) oznaczano za pomocą cyfrowego refraktometru, podając wynik w Brix. Wyniki przedstawiono w publikacjach 1, 5.

3.4.7. Zawartość azotanów i jonów K, P i Ca w owocach

Do oznaczenia zawartości azotanów, K, P i Ca w owocach losowo wybierano z każdej kombinacji po trzy owoce dojrzałe, w pełni wybarwione. Owoce oczyszczano z nasion i łożyska oraz szypułki, dzielono na ćwiartki i po jednej z każdego z 3 owoców homogenizowano. Z uzyskanej mieszanki trzykrotnie pobierano próbki homogenatu o masie 10 g, do których dodawano 0,5 g węgla aktywnego oraz 100 ml 2% kwasu octowego. Po 30 minutach wytrząsania próbki na wytrząsarce laboratoryjnej, powstały roztwór przesączano przy użyciu filtra karbowanego. W roztworze ekstrakcyjnym oznaczano zawartość azotanów (NO_3), K, P i Ca. Azotany oznaczono spektrofotometrycznie, stosując analizator Fiastar 5000, przy długości fali 540 nm. Do oznaczenia fosforu stosowano test kolorymetryczny, który polega na reakcji chemicznej powodującej zmianę barwy próbki proporcjonalnie do stężenia oznaczanego pierwiastka w próbce. Pomiaru barwy (absorbancji) dokonywano przy długości fali 430 nm, za pomocą spektrofotometru UV-Vis Shimadzu 1700 [PN-R-04023:1996]. Stężenia potasu i wapnia oznaczano za pomocą fotometru płomieniowego Sherwood Scientific model 420. Wyniki przedstawiono w publikacjach 1, 5.

3.4.8. Ocena potencjału antyoksydacyjnego owoców metodą DPPH, ABTS i TPC

Z każdej kombinacji losowo pobierano po trzy owoce. Ekstrakty przygotowywano z miąższu owocni wraz ze skórką, bez nasion i szypułki (próbka reprezentatywna 10 g). Owoce zostały uprzednio całkowicie zmiksowane w celu uzyskania jednorodnego homogenatu, który następnie poddano ekstrakcji wspomaganej ultradźwiękami. Proces prowadzono w temperaturze pokojowej z użyciem metanolu jako rozpuszczalnika (25 ml na 1 g surowca) przez 60 minut. Po filtracji i odwirowaniu próbki przechowywano w temperaturze 4 °C do czasu analizy. Aktywność antyoksydacyjną badano trzema metodami: DPPH i ABTS i TCP. W teście DPPH oceniano zdolność redukcji stabilnego rodnika DPPH, monitorując zmianę koloru z fioletowego na bladożółty przy 517 nm, a wyniki wyrażano jako procent inhibicji rodnika. W metodzie ABTS mierzono zdolność redukcji intensywnie zabarwionego rodnika ABTS+ do formy bezbarwnej, rejestrując absorbancję przy 734 nm. Oznaczenie całkowitej zawartości polifenoli wykonywano metodą kolorymetryczną, z wykorzystaniem odczynnika Folina-Ciocalteu, wyrażając wynik jako ekwiwalent katechiny (mg CE na 100 g świeżej masy). Wszystkie pomiary przeprowadzano spektrofotometrycznie za pomocą spektrofotometru UV–Vis Shimadzu

1700, a analizy poprzedzono przygotowaniem odpowiednich roztworów kalibracyjnych i roboczych. Wyniki przedstawiono w publikacji 5.

3.4.9. Analiza sensoryczna owoców

Analizę sensoryczną owoców przeprowadzono w Pracowni Analizy Sensorycznej Katedry Roślin Warzywnych i Leczniczych, która spełnia normy PN–EN ISO 8589:2010/A1:2014-07 (2014). Z każdej kombinacji badawczej losowo wybrano po pięć dojrzałych i całkowicie wybarwionych owoców papryki. Po dokładnym umyciu pod bieżącą wodą oraz usunięciu nasion, łożyska i szypułki owocu, każdy owoc przekrojono na trzy równe części: górną, środkową oraz wierzchołkową. Z każdego z wymienionych segmentów wycięto fragmenty o wymiarach około 2–3 cm, przy czym szczególną uwagę zwrócono na zapewnienie reprezentatywności próby poprzez zachowanie równych proporcji materiału pochodzącego z każdej części owocu. Otrzymane fragmenty z poszczególnych segmentów każdego owocu połączono w celu uzyskania jednorodnej, złożonej próbki reprezentatywnej. Tak przygotowany materiał umieszczono w uprzednio oznakowanych pojemnikach laboratoryjnych i poddano ocenie. Ocenę jakości sensorycznej owoców przeprowadzono z wykorzystaniem metody QDA. Badanie zostało zrealizowane przez zespół 20 (publikacja 1) i 18 (publikacja 4) przeszkolonych osób, posiadających doświadczenie w ocenie sensorycznej produktów żywnościowych. Ocenę przeprowadzono w dwóch niezależnych powtórzeniach, w standaryzowanych warunkach laboratoryjnych. Analizie poddano cechy jakościowe obejmujące zapach, teksturę oraz smak badanych próbek. Każdy z oceniających dokonywał oceny próbek za pomocą niestrukturalnej skali graficznej, w formie odcinka linii prostej o oznaczonych krańcach skali na monitorach komputerów. Graniczne punkty skali odpowiadały natężeniu danej cechy od minimalnego (0) do maksymalnego (10). Oznaczenia zespołu oceniającego były następnie przeliczane na wartości liczbowe w jednostkach od 0 do 10, z dokładnością do 0,1 jednostki. Dodatkowo w ramach analizy QDA oceniano również ogólne wrażenie jakości sensorycznej, określane jako „jakość ogólna". Ten parametr obejmował syntetyczną ocenę wszystkich cech sensorycznych, w oparciu o subiektywne wrażenie ogólnej jakości produktu. Podobnie jak pozostałe cechy, jakość ogólna była oceniana na skali od 0 (niska jakość) do 10 (wysoka jakość). Równolegle do analizy eksperckiej przeprowadzono test półkonsumencki preferencji owoców papryki. W badaniu tym zastosowano niestrukturalną skalę, której krańcowe punkty odniesienia zostały zdefiniowane jako: „Nie lubię" (lewy kraniec) oraz „Bardzo lubię" (prawy kraniec).

Uczestnicy badania zaznaczali swoje preferencje na skali, a wartości te były następnie przekształcane na jednostki liczbowe w zakresie od 0 do 10, umożliwiając dalszą analizę statystyczną wyników. Wyniki przedstawiono w publikacjach 1 i 4.

3.4.10. Analiza statystyczna

Publikacja 1: Analizę statystyczną przeprowadzono przy użyciu dwuczynnikowej analizy wariancji ANOVA (Statistica, wersja 13, Warszawa, Polska). Szczegółowe porównanie średnich wykonano testem Tukeya przy poziomie istotności $\alpha = 0,05$.

Publikacja 2: Analizę statystyczną przeprowadzono przy użyciu dwuczynnikowej analizy wariancji (ANOVA). Szczegółowe porównanie średnich przeprowadzono przy użyciu testu Tukeya przy poziomie istotności $\alpha = 0,05$. Analizę statystyczną dla oceny struktury liści papryki przeprowadzono w STATGRAPHICS Plus 5.1, stosując analizę wariancji (ANOVA). Do opracowania wyników analizy sensorycznej owoców papryki wykorzystano program ANALSENS wersja 6, służący do przygotowania testów, rejestracji wyników i analizy statystycznej.

Publikacja 3: Analizę statystyczną przeprowadzono z wykorzystaniem jednoczynnikowej i dwuczynnikowej analizy wariancji (ANOVA) w programie Statistica, wersja 13 (Warszawa, Polska). Porównania szczegółowe średnich wykonano za pomocą testu Tukeya przy poziomie istotności $\alpha = 0,05$. Do opracowania wyników analizy sensorycznej owoców papryki wykorzystano program ANALSENS wersja 6.

Publikacja 4: Wykorzystano jednoczynnikową, dwuczynnikową i trójczynnikową analizę wariancji (ANOVA), przeprowadzoną w programie Statistica, wersja 13 (Warszawa, Polska). Szczegółowe porównanie średnich zrealizowano przy użyciu testu Tukeya ($\alpha = 0,05$). W celu opracowania wyników oceny jakości sensorycznej papryki, zastosowano program ANALSENS ver. 6.

Publikacja 5: W celu zredukowania liczby zmiennych i identyfikacji głównych źródeł wariancji przeprowadzono wielowymiarową analizę czynnikową z zastosowaniem analizy głównych składowych (PCA). Rotacja Varimax pozwoliła na maksymalizację wariancji ładunków między czynnikami przy jednoczesnej minimalizacji wariancji w ich obrębie. Wyniki przedstawiono w formie biplotu, ilustrującego współczynniki korelacji zmiennych ze składowymi oraz powiązania między obiektami czynnikowymi z uwzględnieniem odmian papryki. Obliczenia wykonano w programie IBM SPSS Statistics, wersja 29, w Katedrze Biometrii, w Instytucie Rolnictwa SGGW w Warszawie.

4. WYNIKI I DYSKUSJA

Wyniki przeprowadzonych badań wskazują na istotny wpływ rodzaju zastosowanych zabiegów agrotechnicznych na wzrost i aktywność metaboliczną, strukturę anatomiczną liści oraz plonowanie roślin papryki. Szczególnie ważny efekt proekologiczny uzyskano przy produkcji rozsady papryki do upraw hydroponicznych, w związku z użyciem energooszczędnego sztucznego źródła światła LED zamiast tradycyjnie wykorzystywanych lamp sodowych. Doświetlanie lampami LED korzystnie wpłynęło na wzrost i jakość rozsady papryki w porównaniu do tradycyjnie stosowanych lamp sodowych.

Pozytywny wpływ na rozwój systemu korzeniowego papryki oraz efektywność przyswajania składników pokarmowych w uprawie hydroponicznej zaobserwowano w przypadku zastosowania fosforu w formie polifosforanów w pożywce. Z kolei aplikacja dolistna kwasu salicylowego w uprawie hydroponicznej papryki miała wpływ głównie na mechanizmy obronne roślin oraz ich reakcję na stres środowiskowy. W badaniach wykazano także zróżnicowaną odpowiedź odmian 'Aifos' i 'Palermo' na analizowane czynniki środowiskowe i agrotechniczne.

4.1. Wpływ światła na morfologię i wydajność fotosyntezy

Zgodnie z wynikami przedstawionymi w publikacji 2, rozsada papryki odmiany 'Aifos' produkowana pod lampami LED wykazywała silniejszy wzrost oraz większą liczbę liści w porównaniu z roślinami rosnącymi pod lampami HPS. Co istotne, efekt ten nie został zaobserwowany u odmiany 'Palermo', co sugeruje odmienną wrażliwość genotypową papryki na spektrum światła. Wynik ten jest zgodny z obserwacjami Hernández i Kubota [2016], którzy również wykazali, że odpowiednio dobrane spektrum światła LED może korzystnie wpływać na wzrost biomasy warzyw szklarniowych, jednak efekty te mogą być silnie uzależnione od genotypu. Podobne zróżnicowanie genotypowe zaobserwowali Massa i in. [2008] oraz Su i in. [2024], którzy stwierdzili, że nie wszystkie odmiany reagują w ten sam sposób na jednakowe spektrum świetlne. Wyniki pomiaru indeksu SPAD w liściach roślin doświetlanych światłem LED wskazują na zwiększoną zawartość chlorofilu, co potwierdza przewagę spektrum emitowanego przez lampy LED nad spektrum HPS w kontekście efektywności fotosyntetycznej. Wyższe wartości SPAD przy oświetleniu LED potwierdzają wpływ tego typu światła (z zakresu czerwono-niebieskiego) w zakresie syntezy chlorofilu, co zostało wcześniej odnotowane m.in. przez Johkan i in. [2012], którzy wskazali,

że światło czerwono-niebieskie sprzyja zwiększeniu zawartości chlorofilu w liściach sałaty, a Gao i in. [2020] wykazali, że niebieskie światło znacząco poprawia wydajność fotosyntezy u czosnku pospolitego.

Pomimo, iż wybrane parametry fluorescencji chlorofilu *a*, takie jak efektywna wydajność kwantowa PSII (φPSII) i maksymalna wydajność kwantowa PSII (Fv/Fm), były niższe u roślin doświetlanych LED niż u roślin doświetlanych HPS, zaobserwowano wzrost wskaźnika wydajności fotosystemu (PI) u roślin doświetlanych LED o odpowiednio 45% i 30% dla odmian 'Aifos' i 'Palermo'. Wskazuje to, że PI może stanowić bardziej czuły wskaźnik ogólnej kondycji fotosyntetycznej niż tradycyjne parametry związane z PSII. To spostrzeżenie jest zgodne z wynikami badań Kalaji i in. [2014], którzy podkreślali, że wskaźnik wydajności PI uwzględnia szerszy zakres aspektów funkcjonowania fotosystemu i może pełnić rolę bardziej kompleksowego wskaźnika kondycji fotosyntetycznej. Dodatkowo, badania Živčák i in. [2008] potwierdzają, że PI jest bardziej wrażliwy na zmiany środowiskowe niż klasyczne parametry PSII, co czyni go użytecznym narzędziem w ocenie stresu środowiskowego oraz zdolności adaptacyjnej roślin [Kalaji i in. 2018, Chen i in. 2023].

4.2. Anatomia i ultrastruktura liści w zależności od spektrum światła

Analiza mikroskopowa wykazała, że zastosowanie oświetlenia LED wpływało na wzrost grubości liści, głównie poprzez pogrubienie miękiszu palisadowego i gąbczastego, a także na zwiększenie liczby aparatów szparkowych. Zmiany te mogą stanowić adaptację anatomiczną ukierunkowaną na zwiększenie absorpcji światła oraz efektywniejszą wymianę gazową, co w konsekwencji przekłada się na wyższą wydajność fotosyntezy. Podobne rezultaty odnotowano w badaniach nad eustomą (*Eustoma grandiflorum* (Hook.) G. Don ex Sweet), w których wykazano, że liście roślin oświetlanych niebieskim światłem LED charakteryzowały się grubszymi warstwami epidermy oraz bardziej cylindrycznym kształtem komórek palisadowych, co sprzyjało intensyfikacji procesu fotosyntezy. Ponadto, w przypadku eustomy odnotowano zwiększoną liczbę aparatów szparkowych oraz ich szersze otwarcie, co skutkowało wyższym przewodnictwem szparkowym i intensywniejszą fotosyntezą [Roni i in. 2017]. Obserwacje ultrastrukturalne ujawniły, że chloroplasty roślin doświetlanych światłem LED były większe, zawierały więcej ziaren skrobi i charakteryzowały się grubszą strukturą grana, co może wskazywać na lepszą organizację wewnętrzną aparatu fotosyntetycznego. Analogiczne zmiany zaobserwowano w badaniach nad

tytoniem (*Nicotiana tabacum* L.), w których wykazano, że światło czerwone zwiększało zarówno liczbę, jak i rozmiar ziaren skrobi w chloroplastach oraz wpływało na strukturę grana, co również sugeruje poprawę organizacji strukturalnej chloroplastów [Kasperbauer i Hamilton 1984, Liu i in. 2022, Kim i in. 2024].

4.3. Wydajność fotosyntezy i plonowania w zależności od nawożenia i warunków stresowych

Zastosowanie zróżnicowanych form nawożenia – zarówno dokorzeniowego, jak i dolistnego – miało istotny wpływ na wzrost i rozwój roślin w badanych doświadczeniach. Nawożenie dokorzeniowe zapewniło roślinom dostępność podstawowych makro- i mikroskładników mineralnych bezpośrednio w strefie korzeniowej, co sprzyjało efektywnemu pobieraniu składników pokarmowych i prowadziło do intensyfikacji przyrostu biomasy. Uzyskane wyniki potwierdzają, że takie podejście sprzyjało równomiernemu rozwojowi zarówno systemu korzeniowego, jak i części nadziemnych, zwłaszcza w początkowych etapach wegetacji, gdy formowanie struktury rośliny jest szczególnie wrażliwe na niedobory pokarmowe. Uzupełnieniem nawożenia były zabiegi dolistne, których celem było nie tylko szybkie wyrównanie ewentualnych niedoborów składników mineralnych, ale także poprawa kondycji fizjologicznej roślin w okresach zwiększonego zapotrzebowania metabolicznego oraz występowania czynników stresowych. Zabiegi dolistne z wykorzystaniem soli wapnia oraz kombinacji kwasu salicylowego z wapniem (SA + Ca) wskazują, że te składniki mogły pozytywnie wpływać na integralność tkanek poprzez wzrost zawartości pektynianów wapnia w ścianach komórkowych, co prowadziło do ich usztywnienia i większej odporności mechanicznej. Tego typu modyfikacje strukturalne mają istotne znaczenie w kontekście poprawy jakości plonu oraz jego zdolności do przetrwania w warunkach stresu [Farhangi-Abriz i Ghassemi-Golezani 2023, Chen i in. 2025]. Kwas salicylowy, jako naturalny związek sygnałowy zaangażowany w reakcje odpornościowe roślin, mógł dodatkowo stymulować mechanizmy odporności systemicznej nabytej (SAR), zwiększając odporność roślin na działanie stresów abiotycznych, w tym suszę i ekstremalną temperaturę. Potwierdzają to wcześniejsze doniesienia naukowe, wskazujące na rolę kwasu salicylowego w aktywacji genów związanych z tolerancją na stres oksydacyjny oraz w stabilizacji struktury błon komórkowych [El-Sherif 2022, Urban i in. 2022].

W publikacjach 1 i 3 wykazano, że zastosowanie w uprawie hydroponicznej papryki polifosforanów oraz kwasu salicylowego może modyfikować parametry fotosyntetyczne roślin oraz ograniczać negatywne skutki stresu środowiskowego, takiego jak podwyższone EC pożywki. Kwas salicylowy, stosowany zarówno dolistnie, jak i poprzez system korzeniowy, skutecznie redukował objawy BER, szczególnie u odmiany 'Palermo' – bardziej podatnej na ten rodzaj zaburzeń fizjologicznych niż 'Aifos'. U papryki w kombinacji z SA zaobserwowano jednocześnie istotny wzrost aktywności enzymów antyoksydacyjnych, takich jak dysmutaza ponadtlenkowa oraz katalaza, co wskazuje na aktywację mechanizmów obronnych roślin w odpowiedzi na aplikację kwasu salicylowego. Działanie SA w łagodzeniu skutków stresu solnego oraz w poprawie parametrów fotosyntetycznych zostało opisane w literaturze przez Khan i in. [2015] oraz Xu i in. [2022], którzy odnotowali także zwiększenie aktywności enzymów antyoksydacyjnych (SOD, CAT) po zastosowaniu SA m.in. u *Vigna radiata* L., *Zea mays* L., *Salvia officinalis* L. Podobne efekty uzyskano w badaniach Naeem i in. [2020] oraz Aires i in. [2022], gdzie dolistna aplikacja kwasu salicylowego ograniczała fizjologiczne objawy uszkodzeń owoców *Solanum lycopersicum*, analogicznie do obserwowanej redukcji BER u odmiany 'Palermo'. W odniesieniu do zastosowania polifosforanów, mimo że dostępna literatura w tym zakresie jest mniej obszerna, to badania Yassen i in. [2011] oraz Shah i Chu [2021] wykazały, że nawożenie polifosforanami (w dawkach porównywalnych z konwencjonalnymi zaleceniami) może przyczyniać się do poprawy efektywności fotosyntezy oraz łagodzenia skutków stresów abiotycznych, co jest zgodne z wynikami przedstawionymi w publikacji 1. Skuteczność kwasu salicylowego może być istotnie zależna od zastosowanego stężenia oraz sposobu aplikacji. Zbyt wysokie dawki mogą prowadzić do efektów fitotoksycznych, co zostało odnotowane m.in. w badaniach Gharbi i in. [2018], Senaratna i in. [2000] oraz Kowalczyk i in. [2025]. W kontekście omawianych publikacji nie zaobserwowano jednak takich efektów, co może świadczyć o odpowiednim doborze dawek i metod aplikacji SA, zapewniających skuteczność przy jednoczesnym braku negatywnego wpływu na rośliny.

4.4. Wpływ kwasu salicylowego na jakość i cechy sensoryczne owoców

Zdolność związków bioaktywnych do neutralizacji wolnych rodników tlenowych oraz reaktywnych form azotu określana jest mianem aktywności antyoksydacyjnej. W kontekście biologii i medycyny, właściwości antyoksydacyjne mają kluczowe znaczenie dla utrzymania homeostazy redoks w organizmach żywych, przeciwdziałania uszkodzeniom komórkowym oraz opóźniania procesów patologicznych związanych ze stresem oksydacyjnym [Mishra i in. 2023]. Do głównych grup związków o potwierdzonym działaniu antyoksydacyjnym należą przede wszystkim polifenole (w tym flawonoidy, kwasy fenolowe, stilbeny czy lignany), witaminy antyoksydacyjne (głównie witaminy C i E), karotenoidy (np. β-karoten, likopen, luteina) oraz związki mineralne będące kofaktorami enzymów redoksowych (m.in. cynk, mangan, selen). Związki te działają poprzez różnorodne mechanizmy, m.in. bezpośrednie wygaszanie wolnych rodników, chelatowanie jonów metali przejściowych katalizujących reakcje rodnikowe (np. Fe^{2+}, Cu^{2+}), regenerację innych antyoksydantów, a także modulację ekspresji genów związanych z odpowiedzią oksydacyjną i stanem zapalnym. Istotną rolę pełnią również endogenne enzymy antyoksydacyjne, takie jak dysmutaza ponadtlenkowa, katalaza czy peroksydaza glutationowa, które stanowią pierwszą linię obrony przed działaniem ROS w obrębie komórek [Chibisov i in. 2022, Lakshminarayana i Paul 2022]. Z perspektywy zdrowia publicznego, obecność związków antyoksydacyjnych w diecie człowieka jest nie do przecenienia. Promowanie spożycia produktów naturalnych bogatych w antyoksydanty, takich jak warzywa, owoce, pełnoziarniste produkty zbożowe, zioła, herbata czy przyprawy, przyczynia się do zmniejszenia obciążenia populacyjnego chorobami przewlekłymi, a tym samym może prowadzić do wydłużenia i poprawy jakości życia. Z tego względu badania nad bioaktywnością substancji o potencjale antyoksydacyjnym mają istotne znaczenie nie tylko poznawcze, lecz również aplikacyjne, ukierunkowane na poprawę zdrowia jednostki i społeczeństwa [Verghese i in. 2021].

W badaniach przedstawionych w publikacjach 4 i 5 wykazano, że dolistne aplikacje wapnia oraz kwasu salicylowego wpłynęły korzystnie na ograniczenie występowania BER, a także przyczyniły się do poprawy cech sensorycznych owoców papryki, takich jak twardość, jędrność oraz smak słodki. Zaobserwowano wyraźne różnice pomiędzy badanymi odmianami – owoce odmiany 'Palermo' charakteryzowały się wyższą zawartością suchej masy i cukrów, co znalazło odzwierciedlenie w wyższej ocenie sensorycznej. Z kolei owoce odmiany 'Aifos' wyróżniały się wyższą zawartością

związków bioaktywnych, w tym karotenoidów i witaminy C. Zhang i in. [2020b] wykazali, że dolistne stosowanie wapnia znacząco ograniczało występowanie BER u pomidora, co przypisano wzmocnieniu ścian komórkowych oraz poprawie stabilności błon komórkowych. El-Sherif [2022] wskazał, że kwas salicylowy nie tylko zwiększał odporność roślin na stresy abiotyczne, ale również redukował objawy BER poprzez poprawę efektywności gospodarki wapniem w roślinie. Natomiast Sharma i in. [2022] w badaniach nad papryką stwierdzili, że SA wpływał pozytywnie na jędrność owoców oraz ich trwałość pozbiorczą, co było związane z opóźnieniem procesów dojrzewania i degradacji ścian komórkowych. Podobne rezultaty uzyskali Dobón-Suárez i in. [2025], którzy wykazali, że zastosowanie dolistne i dokorzeniowe SA w uprawie gruntowej papryki przyczyniało się do wzrostu zawartości cukrów oraz poprawy walorów smakowych – co potwierdza otrzymane wyniki dotyczące odmiany 'Palermo'. Równocześnie wyniki badań Mamedov i in. [2017] podkreślają znaczenie genotypu w kontekście akumulacji związków bioaktywnych – odmiany o ciemniejszym zabarwieniu skórki, takie jak 'Aifos', wykazywały wyższą zawartość karotenoidów oraz witaminy C. Z kolei Atmini i in. [2022] zwracają uwagę, że zawartość cukrów i suchej masy jest silnie uwarunkowana genotypowo i niekoniecznie koreluje z poziomem związków bioaktywnych, co pozostaje w zgodzie z obserwacjami uzyskanymi dla odmiany 'Palermo'.

Wyniki przeprowadzonych badań wykazały istotny wpływ egzogennej aplikacji kwasu salicylowego na zwiększenie aktywności antyoksydacyjnej u papryki słodkiej uprawianej w systemie aeroponicznym, w warunkach stresu abiotycznego wywołanego podwyższoną przewodnością elektryczną pożywki (EC). Zastosowanie SA, zarówno w formie opryskiwania dolistnego (5 mmol), jak i aplikacji do strefy korzeniowej (100 ppm), w warunkach wysokiego EC (7 $dS \cdot m^{-1}$), prowadziło do istotnego zwiększenia aktywności enzymów antyoksydacyjnych – katalazy oraz dysmutazy ponadtlenkowej. Zaobserwowane zmiany wskazują na aktywację mechanizmów obronnych roślin w odpowiedzi na stres oksydacyjny wywołany nadmiarem soli. Dodatkowo, odnotowano wzrost zawartości nadtlenku wodoru, co może sugerować udział SA w mechanizmach sygnalizacji stresowej, prowadzących do indukcji odpowiedzi obronnej. Wyniki te potwierdzają badania przeprowadzone przez Tahjib-Ul-Arif i in. [2018], Rekhter i in. [2019], Ding i Ding [2020], a także Farhadi i Ghassemi-Golezani [2020].

W odrębnych badaniach przeprowadzonych w warunkach hydroponicznych z wykorzystaniem podłoża z mat wełny mineralnej, stwierdzono, iż dolistna aplikacja SA w stężeniu 0,03% istotnie wpłynęła na poprawę właściwości prozdrowotnych owoców papryki. Zastosowanie SA skutkowało zwiększeniem zawartości związków karotenoidowych w owocach papryki. Wykazano w owocach badanych odmian wysoką zawartość przede wszystkim kapsantyny, β-karotenu i luteiny oraz α-karotenu (odpowiednio: około 1226, 736, 210 i 168 $\mu g \cdot 100\ g^{-1}$ świeżej masy, średnio dla odmian). Badania przeprowadzone przez Wang i in. [2024] oraz Dantas i in. [2025] potwierdzają korzystny wpływ SA na syntezę karotenoidów i zdrowotność roślin w systemach hydroponicznych. Dla obu odmian papryki stwierdzono dodatnią korelację pomiędzy zawartością cukrów ogółem i stosunkiem cukrów do kwasów w owocach w przypadku zastosowania opryskiwania roślin papryki roztworem 0,03% kwasu salicylowego razem z 0,7% roztworem wapnia.

Owoce pochodzące z roślin traktowanych SA charakteryzowały się również wysoką aktywnością antyoksydacyjną, ocenianą przy zastosowaniu trzech niezależnych metod: zdolność zmiatania wolnych rodników w teście DPPH (>86%), zdolność redukcji rodników ABTS (>78% RSC) oraz całkowita zawartość związków fenolowych (ok. 54 mg CE·100 g^{-1} św. m.). Uzyskane wyniki są zgodne z doniesieniami Hamed i in. [2019], Chilczuk i in. [2021] oraz Papathanasiou i in. [2021].

5. WNIOSKI

Na podstawie przedstawionych w niniejszej pracy wyników badań sformułowano następujące wnioski, które potwierdzają postawione hipotezy badawcze:

1. Doświetlanie lampami LED przyspiesza wzrost oraz wpływa korzystnie na rozwój i aktywność aparatu asymilacyjnego rozsady papryki, produkowanej z przeznaczeniem do upraw hydroponicznych, w porównaniu do tradycyjnego doświetlania lampami sodowymi.
2. Zastosowanie polifosforanów do fertygacji w uprawach hydroponicznych wpływa na zwiększenie aktywności fotosyntetycznej liści oraz udział plonu handlowego w plonie całkowitym owoców papryki, szczególnie w przypadku odmian o większej podatności na BER.
3. Dolistne lub dokorzeniowe zastosowanie kwasu salicylowego w warunkach stresu wysokiego EC pożywki w uprawie aeroponicznej papryki aktywuje mechanizmy obronne związane z metabolizmem antyoksydacyjnym i wpływa na ograniczenie występowania objawów BER.
4. Dolistne opryskiwanie kwasem salicylowym zwiększa odporność papryki na niekorzystne warunki środowiskowe w uprawie hydroponicznej i poprawia jakość plonu, szczególnie u odmian podatnych na BER, ograniczając jego występowanie, a także podwyższając twardość, jędrność i smak słodki owoców w plonie handlowym.
5. Dolistne stosowanie kwasu salicylowego w uprawie hydroponicznej papryki wpływa na zwiększenie zawartości składników odżywczych, w tym karotenoidów, w owocach, zwiększenie potencjału antyoksydacyjnego i poprawę jakości sensorycznej owoców.

6. SPIS LITERATURY

1. Aamer M., Chattha M.U., Hassan M.U., Ahmed H.A.I., Haiying T., Rasheed A., Shahzad B. 2022. Regulation of photosynthesis by salicylic acid under optimal and suboptimal conditions. W: Sharma A., Bhardwaj R., Kumar V., Zheng B., Tripathi D.K. (red.) Managing Plant Stress Using Salicylic Acid: Physiological and Molecular Aspects. John Wiley & Sons, New Jersey, USA: 258–269.
2. Aasim M., Akgür, Ö., Yıldırım B. 2022. An overview on boron and pollen germination, tube growth and development under in vitro and in vivo conditions. W: Araniti F., Landi M., Brown P.H., Papadakis I.E., Aftab T. (red.) Boron in Plants and Agriculture: Exploring the Physiology of Boron and Its Impact on Plant Growth. Academic Press, Nowy Jork, USA: 293–310.
3. Aires E.S., Ferraz A.K.L., Carvalho B.L., Teixeira F.P., Rodrigues J.D., Ono E.O. 2022. Foliar application of salicylic acid intensifies antioxidant system and photosynthetic efficiency in tomato plants. Bragantia 81: e1522.
4. Al Meselmani M.A. 2024. Hydroponics: The future of sustainable farming. W: Kumar N. (red.) Hydroponics: The Future of Sustainable Farming. Springer, New York: 101–122.
5. Anani P.Y., Danso A.B., Danquah E.Y., Annor C., Asibuo J.Y. 2024. Exploring morphological variation and stability in hot pepper (*Capsicum annuum*) germplasm collection from the northern region of Ghana. Scientia Horticulturae 337: 113509.
6. Arikan B., Yildiztugay E., Ozfidan-Konakci C. 2023. Responses of salicylic acid encapsulation on growth, photosynthetic attributes and ROS scavenging system in *Lactuca sativa* exposed to polycyclic aromatic hydrocarbon pollution. Plant Physiology and Biochemistry 203: 108026.
7. Atmini K.D., Diantina S., Sabda M., Koswanudin D. 2022. Screening of beta carotene and its correlation with tuber flesh color in sweet potato. AIP Conference Proceedings 2462(1): 020031.
8. Azab A. 2020. Solanaceae plants of Israel and Palestine – rich source of medicinally active natural products. European Chemical Bulletin 9(8): 199–261.

9. Barceló-Muñoz A., Barceló-Muñoz M., Gago-Calderon A. 2021. Effect of LED lighting on physical environment and microenvironment on in vitro plant growth and morphogenesis: the need to standardize lighting conditions and their description. Plants 11(1): 60.
10. Batiha G.E.S., Alqahtani A., Ojo O.A., Shaheen H.M., Wasef L., Elzeiny M., Hetta H.F. 2020. Biological properties, bioactive constituents, and pharmacokinetics of some *Capsicum* spp. and capsaicinoids. International Journal of Molecular Sciences 21(15): 5179.
11. Ben Youssef R., Jelali N., Acosta-Motos J.R., Abdelly C., Albacete A. 2025. Salicylic acid seed priming: A key frontier in conferring salt stress tolerance in barley seed germination and seedling growth. Agronomy 15(1): 154.
12. Berde C.P., Rawool P., Berde V.B. 2021. Phosphate-solubilizing bacteria: Recent trends and applications in agriculture. W: De Mandal S., Passari A.K. (red.) Recent Advancement in Microbial Biotechnology: Agricultural and Industrial Approach. Academic Press, Nowy Jork, USA: 27–47.
13. Bradford M.M. 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Analytical Biochemistry 72(1–2): 248–254.
14. Cebula S., Jakubas A., Sekara A., Kalisz A., Pohl A. 2015. The relationship between morphological features and nutritive value of sweet pepper fruits. Acta Scientiarum Polonorum. Hortorum Cultus 14(4): 3–14.
15. Chen G., Cai T., Zhang J., Wang J., Ren L., Wang Y., Shi S. 2025. Optimizing water–nitrogen productivity in rain-fed summer maize production in semi-humid and drought-prone area: Sustainable approach by integrating straw mulching and suitable fertilization depth. Field Crops Research 327: 109918.
16. Chen Y., Lin Y., Zhou X., Zhang J., Yang C., Zhang Y. 2023. Effects of drought treatment on photosystem II activity in the ephemeral plant *Erodium oxyrhinchum*. Journal of Arid Land 15(6): 724–739.
17. Chibisov S., Kharlitskaya E., Singh R.B., Itharat A., On-Saard E., Park H.R., Smail M.M. 2022. Polyphenolics and flavonoids in health and diseases. W: Singh R.B., Isaza A.A., Watanabe S. (red.) Functional Foods and Nutraceuticals in Metabolic and Non-communicable Diseases. Academic Press, New York, USA: 671–689.

18. Chilczuk B., Marciniak B., Kontek R., Materska M. 2021. Diversity of the chemical profile and biological activity of *Capsicum annuum* L. extracts in relation to their lipophilicity. Molecules 26(17): 5215.
19. Claypool N.B., Lieth J.H. 2021. Modeling morphological adaptations of bell pepper (*Capsicum annuum*) to light spectra. Scientia Horticulturae 285: 110135.
20. Cruz J.G., Silveira T., Barbieri R.L., Neitzke R.S. 2024. Pre-breeding of a *Capsicum annuum* accession with ornamental potential. Revista Caatinga 38: e12278.
21. Dantas M.V., Sá V.K.D., Lima G.S.D., Soares L.A.D.A., Gheyi H.R., Silva L.D.A., Azevedo C.A.D. 2025. Morphophysiology of cucumber under saline nutrient solutions and salicylic acid application in hydroponic system. Revista Brasileira de Engenharia Agrícola e Ambiental 29(5): e287640.
22. de Freitas S.T., Handa A.K., Wu Q., Park S., Mitcham E.J. 2012. Role of pectin methylesterases in cellular calcium distribution and blossom-end rot development in tomato fruit. The Plant Journal 71(5): 824–835.
23. de Freitas S.T., Martinelli F., Feng B., Reitz N.F., Mitcham E.J. 2018. Transcriptome approach to understand the potential mechanisms inhibiting or triggering blossom-end rot development in tomato fruit in response to plant growth regulators. Journal of Plant Growth Regulation 37(1): 183–198.
24. de Freitas S.T., Shackel K.A., Mitcham E.J. 2011. Abscisic acid triggers whole-plant and fruit-specific mechanisms to increase fruit calcium uptake and prevent blossom end rot development in tomato fruit. Journal of Experimental Botany 62(8): 2645–2656.
25. de Sá Mendes N., de Branco É.C.B. 2020. The role of bioactive components found in peppers. Trends in Food Science Technology 99: 229–243.
26. Devi K., Bakshi P., Kour J., Dhiman S., Ibrahim M., Bhardwaj T., Bhardwaj R. 2023. Role of salicylic acid in the regulation of physiological and molecular aspects of plants under abiotic stress. W: Tripathi D.K., Sharma A., Bhardwaj R., Zheng B., Pandey S. (red.) The Role of Growth Regulators and Phytohormones in Overcoming Environmental Stress. Academic Press, New Jork, USA: 175–196.
27. Didaran F., Kordrostami M., Ghasemi-Soloklui A.A., Pashkovskiy P., Kreslavski V., Kuznetsov V., Allakhverdiev S.I. 2024. The mechanisms of photoinhibition and repair in plants under high light conditions and interplay with abiotic stressors. Journal of Photochemistry and Photobiology B: Biology 259: 113004.

28. Ding L.N., Li Y.T., Wu Y.Z., Li T., Geng R., Cao J., Tan X.L. 2022. Plant disease resistance-related signaling pathways: recent progress and future prospects. International Journal of Molecular Sciences 23(24): 16200.
29. Ding P., Ding Y. 2020. Stories of salicylic acid: a plant defense hormone. Trends in Plant Science 25(6): 549–565.
30. Dixit S., Shukla A., Singh D.K. 2021. Methods for detection and measurement of calcium in plants. W: Upadhyay S.K. (red.) Calcium transport elements in plants. Academic Press, New York, USA: 411–426.
31. Dobón-Suárez A., Gutiérrez-Pozo M., Serna-Escolano V., Giménez M.J., Valero D., Serrano M., Zapata P.J. 2025. Antioxidant metabolism insights into ripening and senescence delay of green pepper fruit through the salicylic acid preharvest treatment. Frontiers in Plant Science 16: 1475068.
32. Dong S.J., Ge S.B., Li L., He L.Q., Fan F.J., Qi Z.Y., Zhou Y.H. 2022. Effects of supplemental lighting on growth, root colonization by arbuscular mycorrhizal fungi and phosphorus uptake in pepper seedlings. Acta Horticulturae Sinica 8: 1699–1712.
33. El-Sherif N.A. 2022. Salicylic acid and its crosstalk with other plant hormones under stressful environments. W: Sharma A., Bhardwaj R., Kumar V., Zheng B., Tripathi D.K. (red.) Managing Plant Stress Using Salicylic Acid: Physiological and Molecular Aspects, John Wiley & Sons, New Jersey, USA: 304–317.
34. Engel D.C.H., Feltrim D., Rodrigues M., Baptistella J.L.C., Mazzafera P. 2024. Application of protein hydrolysate improved the productivity of soybean under greenhouse cultivation. Agriculture 14(8): 1205.
35. Erel R., Yalin D., Kushmaro-Bier A., Li Q., Gérard F., Toren N. 2023. Soil properties and growing duration determine phosphorus phyto-availability dynamics of polyphosphate versus orthophosphate fertilizers. Plant and Soil 485(1): 299–315.
36. Farhadi N., Ghassemi-Golezani K. 2020. Physiological changes of *Mentha pulegium* in response to exogenous salicylic acid under salinity. Scientia Horticulturae 267: 109325.
37. Farhangi-Abriz S., Ghassemi-Golezani K. 2023. Nutrient availability regulates root system behavior. W: Singh V.P., Siddiqui M.H. (red.) Plant Ionomics: Sensing, Signaling, and Regulation. Springer, Berlin, Niemcy: 96–119.

38. Gai W.X., Ma X., Qiao Y.M., Shi B.H., ul Haq S., Li Q.H., Wei A.M., Liu K.K., Gong Z.H. 2020. Characterization of the bZIP transcription factor family in pepper (*Capsicum annuum* L.): CabZIP25 positively modulates the salt tolerance. Frontiers in Plant Science 11: 139.
39. Gao S., Liu X., Liu Y., Cao B., Chen Z., Xu K. 2020. Photosynthetic characteristics and chloroplast ultrastructure of welsh onion (*Allium fistulosum* L.) grown under different LED wavelengths. BMC Plant Biology 20(1): 1–12.
40. Gharbi E., Lutts S., Dailly H., Quinet M. 2018. Comparison between the impacts of two different modes of salicylic acid application on tomato (*Solanum lycopersicum*) responses to salinity. Plant Signaling and Behavior 13(5): e1469361.
41. Giannopolitis C.N., Ries S.K. 1977. Superoxide dismutases: I. Occurrence in higher plants. Plant Physiology 59(2): 309–314.
42. Główny Urząd Statystyczny. 2024. Rolnictwo w 2023 roku. https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2023-roku,3,21.html (dostęp 3 czerwca 2025).
43. Góth L. 1991. A simple method for determination of serum catalase activity and revision of reference range. Clinica Chimica Acta 196(2–3): 143–152.
44. Hamed M., Kalita D., Bartolo M.E., Jayanty S.S. 2019. Capsaicinoids, polyphenols, and antioxidant activities of *Capsicum annuum*: Comparative study of the effect of ripening stage and cooking methods. Antioxidants 8(9): 364.
45. Hernández R., Kubota C. 2016. Physiological responses of cucumber seedlings under different blue and red photon flux ratios using LEDs. Environmental and Experimental Botany 121: 66–74.
46. Ho L.C., White P.J. 2005. A cellular hypothesis for the induction of blossom-end rot in tomato fruit. Annals of Botany 95(4): 571–581.
47. Hu Y., Zhi L., Li P., Hancock J., Hu X. 2022. The role of salicylic acid signal in plant growth, development and abiotic stress. Phyton 91(12): 2591–2605.
48. Hui D., Chun D.X., Hui C.Z. 2015. Effect of exogenous salicylic acid on salt tolerance in perennial ryegrass. Journal of Beijing Forestry University 37(2): 128–135.
49. Jassim E., Jasem B., Djavanroodi F. 2024. CFD analysis to optimize air quality in aeroponic tower garden. WSEAS Transactions on Environment and Development 20: 473–477.

50. Jimoh M.O., Adeoye J.P., Senjobi C.T., Ahmed K.A., Salami S.O., Laubscher C.P. 2024. Sustainable food production and prospects: a fundamental guide to hydroponic agriculture. W: Bvenura C., Kambizi L. (red.) Food Security and Nutrition. CRC Press, Floryda, USA: 399–417.
51. Johkan M., Shoji K., Goto F., Hahida S.N., Yoshihara T. 2012. Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in *Lactuca sativa*. Environmental and Experimental Botany 75: 128–133.
52. Kalaji H.M., Oukarroum A., Alexandrov V., Kouzmanova M., Brestic M., Zivcak M., Goltsev V. 2014. Identification of nutrient deficiency in maize and tomato plants by in vivo chlorophyll *a* fluorescence measurements. Plant Physiology and Biochemistry 81: 16–25.
53. Kalaji H.M., Rastogi A., Živčák M., Brestic M., Daszkowska-Golec A., Sitko K., Cetner M.D. 2018. Prompt chlorophyll fluorescence as a tool for crop phenotyping: an example of barley landraces exposed to various abiotic stress factors. Photosynthetica 56(3): 953–961.
54. Kasperbauer M.J., Hamilton J.L. 1984. Chloroplast structure and starch grain accumulation in leaves that received different red and far-red levels during development. Plant Physiology 74(4): 967–970.
55. Kaya C., Ugurlar F., Ashraf M., Ahmad P. 2023. Salicylic acid interacts with other plant growth regulators and signal molecules in response to stressful environments in plants. Plant Physiology and Biochemistry 196: 431–443.
56. Khan M.I.R., Fatma M., Per T.S., Anjum N.A., Khan N.A. 2015. Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. Frontiers in Plant Science 6: 462.
57. Kim D., Moon T., Kwon S., Hwang I., Son J.E. 2023. Supplemental inter-lighting with additional far-red to red and blue light increases the growth and yield of greenhouse sweet peppers (*Capsicum annuum* L.) in winter. Horticulture, Environment, and Biotechnology 64(1): 83–95.
58. Kim J., Park H., Seo C., Kim H., Choi G., Kim M., Lee W. 2024. Sustainable and inflatable aeroponics smart farm system for water efficiency and high-value crop production. Applied Sciences 14(11): 4931.
59. Kim Y., Castroverde C.D.M., Kim J.H. 2024. Natural allelic diversity of the calcium signaling regulators in plants. Molecules and Cells 47(9): 100104.

60. Kowalczyk K., Sobczak-Samburska A., Pióro-Jabrucka E., Mirgos M., Swoczyna T., Cecelska B. 2025. Wpływ kwasu salicylowego i gęstości sadzenia roślin w podłożu z wełny mineralnej na plon i jakość owoców papryki (*Capsicum annuum* L.) w uprawie z doświetlaniem LED. Konferencja Naukowa, Wyzwania Współczesnego Ogrodnictwa, Lublin, 4–6 czerwca 2025.
61. Kozub B. 2024. Mineral wool: composites and applications. W: Rangappa S.M., Ayyappan V., Manik G., Siengchin S. (red.) Synthetic and Mineral Fibers, Their Composites and Applications. Woodhead Publishing, Sawston, Wielka Brytania: 321–336.
62. Krasniqi K., Drvoshanova B. 2024. Effect of grafting and growing environment on yield performance of two bell pepper cultivars. Agriculturae Conspectus Scientificus 89(4): 383–389.
63. Kudoyarova G., Veselov D., Yemelyanov V., Shishova M. 2022. The role of aquaporins in plant growth under conditions of oxygen deficiency. International Journal of Molecular Sciences 23(17): 10159.
64. Kundal A., Sharma T.P. 2024. Detection of plant diseases in hydroponics farming using deep learning techniques. W: International Conference on Smart Systems for Applications in Electrical Sciences (ICSSES). IEEE, New York, USA: 1–6.
65. Lakshminarayana R., Paul B. 2022. Free radical chemistry of carotenoids and oxidative stress physiology of cancer. W: Chakraborti S. (red.) Handbook of Oxidative Stress in Cancer: Therapeutic Aspects. Springer, Singapore, Azja: 1–22.
66. Leng Z., Zhong B., Wu H., Liu Z., Rauf A., Bawazeer S., Suleria H.A.R. 2022. Identification of phenolic compounds in Australian-grown bell peppers by liquid chromatography coupled with electrospray ionization-quadrupole-time-of-flight-mass spectrometry and estimation of their antioxidant potential. ACS Omega 7(5): 4563–4576.
67. Licastro A., Salomone R., Mondello G., Calabrò G. 2024. Assessing the environmental impacts of soilless systems: a comprehensive literature review of Life Cycle Assessment studies. The International Journal of Life Cycle Assessment 29(6): 1053–1074.
68. Liu X., Shi R., Gao M., He R., Li Y., Liu H. 2022. Effects of LED light quality on the growth of pepper (*Capsicum* spp.) seedlings and the development after transplanting. Agronomy 12(10): 2269.

69. Lorenzo-Orts L., Couto D., Hothorn M. 2020. Identity and functions of inorganic and inositol polyphosphates in plants. New Phytologist 225(2): 637–652.
70. Lu C., Liu X., Tang Y., Fu Y., Zhang J., Yang L., Dong P. 2024. A comprehensive review of TGA transcription factors in plant growth, stress responses, and beyond. International Journal of Biological Macromolecules 258: 128880.
71. Mahouachi J., Gómez-Cadenas A., Primo-Millo E., Talon M. 2005. Antagonistic changes between abscisic acid and gibberellins in citrus fruits subjected to a series of different water conditions. Plant Growth Regulation 24(3): 179–187.
72. Mamedov M.I., Pishnaya O.N., Baikov A.A., Pivovarov V.F., Dzhos E.A., Matykina A.A., Gins M.S. 2017. Antioxidant contents of pepper *Capsicum* spp. for use in biofortification. Agricultural Biology 52(5): 1021–1029.
73. Marson P., Pasero G. 2006. The Italian contributions to the history of salicylates. Reumatismo 58(1): 66–75.
74. Martínez-Ispizua E., Martínez-Cuenca M.R., Marsal J.I., Díez M.J., Soler S., Valcárcel J.V., Calatayud Á. 2021. Bioactive compounds and antioxidant capacity of Valencian pepper landraces. Molecules 26(4): 1031.
75. Massa G.D., Kim H., Wheeler R.M., Mitchell C.A. 2008. Plant productivity in response to LED lighting. HortScience 43(7): 1951–1956.
76. Méndez-Guzmán H.A., Padilla-Medina J.A., Martínez-Nolasco C., Martinez-Nolasco J.J., Barranco-Gutiérrez A.I., Contreras-Medina L. M., Leon-Rodriguez M. 2022. IoT-based monitoring system applied to aeroponics greenhouse. Sensors 22(15): 5646.
77. Miao C., Zhang Y., Cui J., Zhang H., Wang H., Jin H., Ding X. 2024. An enhanced interaction of graft and exogenous SA on photosynthesis, phytohormone, and transcriptome analysis in tomato under salinity stress. International Journal of Molecular Sciences 25(19): 10799.
78. Mishra A.K., Baek K.H. 2021. Salicylic acid biosynthesis and metabolism: a divergent pathway for plants and bacteria. Biomolecules 11(5): 705.
79. Mishra U.N., Dey P., Singhal R.K., Sahu C., Jena D., Nanda S.P., Chauhan J. 2023. Plant phenolics: as antioxidants and potent compounds under multiple stresses. W: Lone R., Khan S., Al-Sadi A.M. (red.) Plant Phenolics in Abiotic Stress Management. Springer, Singapore, Azja: 215–234.

80. Mittler R., Zandalinas S.I., Fichman Y., Van Breusegem F. 2022. Reactive oxygen species signalling in plant stress responses. Nature Reviews Molecular Cell Biology 23(10): 663–679.
81. Mohamed H.I., El-Shazly H.H., Badr A. 2020. Role of salicylic acid in biotic and abiotic stress tolerance in plants. W: Lone R., Shuab R., Kamili A.N. (red.) Plant Phenolics in Sustainable Agriculture. Springer, Singapore, Azja: 533–554.
82. Monisha K., Kalai Selvi H., Sivanandhini P., Sona Nachammai A., Anuradha C.T., Rama Devi S., Kavitha Sri A., Neya N.R., Vaitheeswari M., Hikku G.S. 2023. Hydroponics agriculture as a modern agriculture technique. Journal of Achievements in Materials and Manufacturing Engineering 116(1): 26–32.
83. Mu T., Luo S., Li L., Zhang R., Wang P., Zhang G. 2025. A review of the interaction mechanisms between jasmonic acid (JA) and various plant hormones, as well as the core regulatory role of MYC2. Plant Science 353: 112407.
84. Mukhametzyanov T.A., Fatkhutdinova A.A., Sedov I.A., Yakimova L.S., Klimovitskii A.E. 2021. Calorimetric observation of lysozyme degradation at elevated temperature in water and DMSO-water mixtures. Thermochimica Acta 695: 178826.
85. Naciri R., Chtouki M., Oukarroum A. 2024. Mechanisms of cadmium mitigation in tomato plants under orthophosphate and polyphosphate fertilization regimes. Ecotoxicology and Environmental Safety 274: 116219.
86. Naeem M., Basit A., Ahmad I., Mohamed H. I., Wasila H. 2020. Effect of salicylic acid and salinity stress on the performance of tomato plants. Gesunde Pflanzen 72(4): 393–402.
87. Nosecka B. (red.) 2024. Rynek owoców i warzyw. Stan i perspektywy. 65. https://ierigz.waw.pl/download/25776ol3ts8rphv084dbkc7b094eu26_owoce_65_24.pdf (dostęp 3 czerwca 2025).
88. Olatunji T.L., Afolayan A.J. 2020. Comparison of nutritional, antioxidant vitamins and capsaicin contents in *Capsicum annuum* and *C. frutescens*. International Journal of Vegetable Science 26(2): 190–207.
89. Orellana-Escobedo L., Garcia-Amezquita L.E., Olivas G.I., Ornelas-Paz J.J., Sepulveda D.R. 2013. Capsaicinoids content and proximate composition of Mexican chili peppers (*Capsicum* spp.) cultivated in the State of Chihuahua. CyTA-Journal of Food 11(2): 179–184.

90. Özden E., Kulak M. 2023. Salicylic acid biosynthesis for hormone crosstalk and plant development. W: Husen A., Zhang W. (red.) Hormonal Cross-Talk, Plant Defense and Development. Academic Press, New York, USA: 61–74.
91. Papathanasiou T., Gougoulias N., Karayannis V.G., Kamvoukou C.A. 2021. Investigation of the total phenolic content and antioxidant capacity of three sweet pepper cultivars (*Capsicum annuum* L.) at different development and maturation stages. Periodica Polytechnica Chemical Engineering 65(2): 219–228.
92. Paradiso R., Proietti S. 2022. Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. Journal of Plant Growth Regulation 41(2): 742–780.
93. Paredes-Andrade N.J., Monteros-Altamirano A., Tapia Bastidas C.G., Sørensen M. 2020. Morphological, sensorial and chemical characterization of chilli peppers (*Capsicum* spp.) from the CATIE genebank. Agronomy 10(11): 1732.
94. Piekut J., Krasowska M., Kowczyk-Sadowy M., Polewko K., Dec D. 2018. Impact of heat treatment and freezing on vitamin C content in selected vegetables and fruits. Carpathian Journal of Food Science and Technology: 10(5): 136–141.
95. PN-A-75101-07:1990. Przetwory owocowe i warzywne, Przygotowanie próbek i metody badań fizykochemicznych, Oznaczanie zawartości cukrów i ekstraktu bezcukrowego.
96. PN-R-04022:1996. Analiza chemiczna gleb. Oznaczanie przyswajalnego potasu metodą fotometrii płomieniowej.
97. PN-R-04023:1996. Analiza chemiczna gleb. Oznaczanie przyswajalnego fosforu metodą kolorymetryczną (metoda z molibdenianem i wanadanem amonu).
98. Rainsford K. 2007. Anti-inflammatory drugs in the 21st century. W: Harris R.E., Bittman R., Dasgupta D., Engelhardt E., Flohe L., Herrmann H., Holzenburg A., Nasheuer H.P., Rottem S., Wyss M., Zwickl P. (red.) Inflammation in the Pathogenesis of Chronic Diseases: The COX-2 Controversy. Springer Dordrecht, Holandia: 3–27.
99. Rajametov S.N., Lee K., Jeong H.B., Cho M.C., Nam C.W., Yang E.Y. 2021. The effect of night low temperature on agronomical traits of thirty-nine pepper accessions (*Capsicum annuum* L.). Agronomy 11(10): 1986.

100. Rajametov S.N., Lee K., Jeong H.B., Cho M.C., Nam C.W., Yang E.Y. 2021. The effect of night low temperature on agronomical traits of thirty-nine pepper accessions (*Capsicum annuum* L.). Agronomy 11(10): 1986.
101. Reitz N.F., Shackel K.A., Mitcham E.J. 2021. Differential effects of excess calcium applied to whole plants vs. excised fruit tissue on blossom-end rot in tomato. Scientia Horticulturae 290: 110514.
102. Rekhter D., Lüdke D., Ding Y., Feussner K., Zienkiewicz K., Lipka V., Wiermer M., Zhang Y., Petit-Houdenot Y. 2019. Isochorismate-derived biosynthesis of the plant stress hormone salicylic acid. Science 365(6452): 498–502.
103. Rodriguez-Amaya D.B. 2001. A guide to carotenoid analysis in foods (Vol.71). ILSI Press Washington, DC, USA.
104. Roni M.Z.K., Islam M.S., Shimasaki K. 2017. Response of *Eustoma* leaf phenotype and photosynthetic performance to LED light quality. Horticulturae 3(4): 50.
105. Roy Z., Bansal R., Siddiqui L., Chaudhary N. 2023. Understanding the role of free radicals and antioxidant enzymes in human diseases. Current Pharmaceutical Biotechnology 24(10): 1265–1276.
106. Saha B., Fatima A., Saha S., Sahoo S. K., Poddar P. 2024. Environmental pollution due to improper use of chemical fertilizers and their remediation. W: Ganguly P., Mandal J., Paramsivam M., Patra S. (red.) Environmental Contaminants Impact, Assessment, and Remediation. Apple Academic Press, New Jersey, USA: 203–219.
107. Saleem M., Fariduddin Q., Castroverde C.D.M. 2021. Salicylic acid: A key regulator of redox signalling and plant immunity. Plant Physiology and Biochemistry 168: 381–397.
108. Sattler T., Pomberger R., Schimek J., Vollprecht D. 2020. Mineral wool waste in Austria, associated health aspects and recycling options. Detritus 9: 174–180.
109. Schoefs B. 2002. Chlorophyll and carotenoid analysis in food products. Properties of the pigments and methods of analysis. Trends in Food Science and Technology 13(11): 361–371.
110. Senaratna T., Touchell D., Bunn E., Dixon K. 2000. Acetyl salicylic acid (aspirin) and salicylic acid induce multiple stress tolerance in bean and tomato plants. Plant Growth Regulation 30(2): 157–161.

111. Sethi K., Dhaka S. S., Bari V. K. 2024. Insights into blossom end-rot disorder in tomato (*Solanum lycopersicum*). Plant Molecular Biology Reporter 42(3): 492–514.
112. Shah J. A., Chu G. 2021. Short-chain soluble polyphosphate fertilizers increased soil P availability and mobility by reducing P fixation in two contrasting calcareous soils. PeerJ 9: e11493.
113. Sharma N., Sharma V., Sharma V., Bhardwaj R. 2022. Salicylic acid: A regulator of plant growth and development. W: Sharma A., Bhardwaj R., Kumar V., Zheng B., Tripathi D.K. (red.) Managing Plant Stress Using Salicylic Acid: Physiological and Molecular Aspects. John Wiley & Sons, New Jersey, USA: 1–15.
114. Sharma P., Sharma P., Arora P., Verma V., Khanna K., Saini P., Bhardwaj R. 2019. Role and regulation of ROS and antioxidants as signaling molecules in response to abiotic stresses. W: Khan M.I.R., Reddy P.S., Ferrante A., Khan N.A. (red.) Plant Signaling Molecules: Role and Regulation under Stressful Environments. Woodhead Publishing, Sawston, Wielka Brytania: 141–156.
115. Sindhu S. 2023. Organic food products: Potential and challenges globally. W: Kumar D., Ravisankar N., Panghal A. (red.) Transforming Organic Agri-Produce into Processed Food Products. Apple Academic Press, New Jersey, USA: 57–76.
116. Sleighter R.L., Hanson T., Holden D., Richards K.M. 2023. Abiotic stress mitigation: A case study from 21 trials using a natural organic matter based biostimulant across multiple geographies. Agronomy 13(3): 728.
117. Sousa V.F.O., Santos A.S., Sales W.S., Silva A.J., Gomes F.A.L., Dias T.J., Araújo J.R.E.S. 2022. Exogenous application of salicylic acid induces salinity tolerance in eggplant seedlings. Brazilian Journal of Biology 84: e257739.
118. Sran T.S., Jindal S.K. 2022. Assessment of heterotic and combining ability effects along with genotype × environment factors influencing the variation of yield and quality components in pepper. Scientia Horticulturae 299: 111040.
119. Su P., Ding S., Wang D., Kan W., Yuan M., Chen X., Wu L. 2024. Plant morphology, secondary metabolites and chlorophyll fluorescence of *Artemisia argyi* under different LED environments. Photosynthesis Research 159(2): 153–164.
120. Tahjib-Ul-Arif M., Siddiqui M.N., Sohag A.A.M., Sakil M.A., Rahman M.M., Polash M.A.S., Mostofa M.G., Tran L.S.P. 2018. Salicylic acid-mediated

enhancement of photosynthesis attributes and antioxidant capacity contributes to yield improvement of maize plants under salt stress. Journal of Plant Growth Regulation 37(4): 1318–1330.

121. Tran D.M., Nguyen T.H., Huynh T.U., Do T.O., Nguyen Q.V., Nguyen A.D. 2022. Analysis of endophytic microbiome dataset from roots of black pepper (*Piper nigrum* L.) cultivated in the Central Highlands region, Vietnam using 16S rRNA gene metagenomic next-generation sequencing. Data in Brief 42: 108108.
122. Tucuch-Haas C. J., Dzib-Ek M. A., Vergara-Yoisura S., Larqué-Saavedra A. 2021. Salicylic acid increases root size that favours the absorption and accumulation of macro and micronutrients that contribute to biomass production. W: Tucuch-Haas C.J., Dzib-Ek M.A., Vergara-Yoisura S., Larqué-Saavedra A. (red.) Salicylic acid – a versatile plant growth regulator. Springer International Publishing, Berlin, Niemcy: 17–33.
123. Tzortzakis N., Massa D., Vandecasteele B.J.A. 2022. The tripartite of soilless systems, growing media, and plants through an intensive crop production scheme. Agronomy 12(8): 1896.
124. Urban L., Lauri F., Ben Hdech D., Aarrouf J. 2022. Prospects for increasing the efficacy of plant resistance inducers stimulating salicylic acid. Agronomy 12(12): 3151.
125. Verghese M., Willis S., Boateng J., Gomaa A., Kaur R. 2021. Effect of food processing on antioxidant potential, availability, and bioavailability. Annual Review of Food Science and Technology 12(1): 307–329.
126. Wang F., Xu H., He W., Lu Y., Luo H., Guo Q., Zhang Z. 2024. Exogenous salicylic acid promotes carotenoid accumulation and antioxidant capacity in germinated maize kernels by regulating carotenoid biosynthetic pathway. Food Bioscience 59: 103990.
127. Wilmowicz E., Frankowski K., Glazinska P., Kesy J., Kopcewicz J. 2011. Involvement of ABA in flower induction of *Pharbitis nil*. Acta Societatis Botanicorum Poloniae 80(1): 21–26.
128. Xu L., Chen H., Zhang T., Deng Y., Yan J., Wang L. 2022. Salicylic acid improves the salt tolerance capacity of *Saponaria officinalis* by modulating its photosynthetic rate, osmoprotectants, antioxidant levels, and ion homeostasis. Agronomy 12(6): 1443.

129. Xue Q., Zhang Q., Zhang A., Li D., Liu Y., Xu H., Yang Q., Liu F., Han T., Tang X., Zhang X. 2024. Integrated metabolome and transcriptome analysis provides clues to fruit color formation of yellow, orange, and red bell pepper. Scientific Reports 14(1): 29737.
130. Yassen A.A., Safia M.A., Sahar M.Z. 2011. Impact of nitrogen fertilizer and foliar spray of selenium on growth, yield and chemical constituents of potato plants. Australian Journal of Basic and Applied Sciences 5(11): 1296–1303.
131. Zhan X., Yang Q., Wang S., Wang Y., Fan X., Bian Z. 2023. The responses of sucrose metabolism and carbon translocation in tomato seedlings under different light spectra. International Journal of Molecular Sciences 24(20): 15054.
132. Zhang C., Li X., Yan H., Ullah I., Zuo Z., Li L., Yu J. 2020b. Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and and quality of greenhouse tomato. Agricultural Water Management 241: 106263.
133. Zhang Z., Lan M., Han X., Wu J., Wang-Pruski G. 2020a. Response of ornamental pepper to high-temperature stress and role of exogenous salicylic acid in mitigating high temperature. Journal of Plant Growth Regulation 39(1): 133–146.
134. Zhou H., Ge H., Chen J., Li X., Yang L., Zhang H., Wang Y. 2022. Salicylic acid regulates root gravitropic growth via clathrin-independent endocytic trafficking of PIN2 auxin transporter in *Arabidopsis thaliana*. International Journal of Molecular Sciences 23(16): 9379.
135. Živčák M., Brestič, M., Olšovská K., Slamka P. 2008. Performance index as a sensitive indicator of water stress in *Triticum aestivum* L. Plant, Soil and Environment 54(4): 133–139.

7. ARTYKUŁY NAUKOWE I OŚWIADCZENIA WSPÓŁAUTORÓW

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Growth, Yield and Quality of Sweet Pepper Fruits Fertilized with Polyphosphates in Hydroponic Cultivation with LED Lighting

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Abstract: The aim of this study was to investigate the effect of phosphorus application in the form of polyphosphates on the yield and quality of sweet pepper fruits grown with LED (light-emitting diodes) assimilation lighting. Phosphorus is absorbed by the root system of plants mainly in the form of orthophosphates ions. The availability of phosphorus depends, among other things, on the pH of the substrate and the temperature. Two cultivars of sweet pepper with red fruits were tested in hydroponic cultivation on a mineral wool substrate. The plants were fertilized with one of three schedules, each of the same concentration of components, but differing only in the form of the applied phosphorus: polyphosphates (PP) and orthophosphates (OP). In the experiment, stem length extensions and number of leaves, chlorophyll concentration in leaves and fluorescence of the chlorophyll in a leaf were measured. The number and weight of fruits in total as well as marketable and non-commercial fruits with symptoms of dry rot (BER—blossom end rot) were studied. The concentration of dry matter and selected chemical components in fruits were examined and the sensory quality of fruits was evaluated using the QDA (Quantitative Description Analysis) method. The nutrient status of the pepper plants was also examined. Polyphosphates used in the medium increase the activity of photosynthetic apparatus of leaves and have a positive effect on the share of marketable yield of the total yield in the cultivar susceptible to BER. Fertigation in hydroponic cultivation with medium containing 30% phosphorus in the form of polyphosphates increased the uptake of calcium in pepper plants growing with LED lighting. The pepper cultivars tested differ in, among other things, the susceptibility to BER and the quality attributes of the fruit.

Keywords: SPAD; chlorophyll fluorescence; fruit quality; sensory quality

1. Introduction

Sweet pepper (*Capsicum annuum* L.) is a plant with a long growing period and requires good quality soil or substrate and adequate light, temperature and water [1,2]. The pepper fruit is highly valued for its taste and health-promoting qualities. Sweet pepper fruit provides vitamin C and vitamin A, flavonoids and antioxidants as well [3–5]. The demand for the fruit is high all year round. Growing plants in year-round greenhouses requires effective assimilation lighting.

Light is an important environmental factor with a significant role in plant life processes [6]. Plants use light as a source of energy for photosynthesis as well as for growth and development

processes. There is a strong correlation between light availability and plant productivity. Insufficient light supplied to the plants can reduce the size and quality of the yield [7]. In practice, in the northern part of the globe, year-round greenhouse cultivation under natural light is only possible in latitudes below the 40th parallel. In moderate-climate countries, in latitudes above the 50th north parallel, in the autumn–winter period and early spring, due to the low solar radiation and shortage of natural sunlight, it is necessary to use assimilation lighting in plant production. At this time, HPS (High-Pressure Sodium) lamps are traditionally used most for supplementary lighting of plants, while solid-state light sources (LED) are being increasingly used [8]. LED technology allows to optimize the light spectrum to the requirements of individual plant species, provides a more energy-efficient way of lighting than HPS and improves yield and quality [9–11]. Environmental factors in pepper cultivation, such as light, temperature, humidity and fertilization, influence water and nutrient uptake, yield and fruit quality [12].

One of the most important macroelements in nucleic acids, high-energy compounds cell membranes, which participates in the process of photosynthesis and respiration, influences gene expression and activates or causes inhibition of enzymes by phosphorylation, is phosphorus [13,14].

The world's main source of phosphorus is phosphate rock. Global demand for phosphorus is expected to increase but it is a non-renewable resource [15]. The use of the traditional form of orthophosphates forces the application of higher doses of fertilizer than is normal for the plant, due to the tendency to make it unavailable to plants at both high- and low-substrate pH. Phosphorus application in the form of polyphosphates makes it more efficient and requires smaller doses of fertilizer, mainly in soil. This makes it possible to reduce phosphorus consumption in mineral form when fertilizing plants and thus slow down the exploitation of its resources. In addition, hydroponic crops provide the opportunity to control and optimize plant fertilization, contributing to the reduction of phosphorus fertilizer consumption.

The deficiency of phosphorus available to plants causes inhibition of shoot and root growth, reduction of leaf blade area and reduction of plant weight [16]. Plants absorb phosphorus in the form of $H_2\ PO_4^-$ and HPO_4^{2-} ions, the so-called orthophosphates [17]. However, a popular form is several combined water-soluble phosphorus molecules identified as polyphosphates (PP). Polyphosphates are an anionic linear polymer of orthophosphate residues joined by hydrogen phosphate bonds similar to those found in ATP. They can affect the transcription and translation of specific genes, modulate several stress responses, provide an alternative source of energy and act as a metabolic regulator [18,19]. The presence of polyphosphates in plant systems has been known for a long time but their role in cellular processes has only begun to be studied relatively recently [20,21].

The use of polyphosphates in the nutrient solution has a significant effect on strong root system development, plant growth and earlier flowering [22]. The use of PP in plant production does not cause the formation of sludge in irrigation systems, which often results in irregular substrate moisture in hydroponic crops [23,24]. Reduced nutrient solution flow in the drip system, especially in the period of high temperature under covers, may be the cause of increased share of fruit with dry BER rot in such vegetables as tomato or pepper [25].

The aim of the study was to evaluate the effect of polyphosphates on the growth, yield and quality of pepper fruits in the cultivation with LED assimilation lighting.

2. Materials and Methods

The study was carried out in the greenhouse of the Department of Vegetable and Medicinal Plants at the Warsaw University of Life Sciences WULS—SGGW (longitude 21° E, latitude 51°15′ N) in the winter cycle of 2018. Two cultivars of sweet peppers with red fruits were taken into consideration: 'Aifos'—block type by Seminis (Bayer) and 'Palermo'—longer type by Rijk Zwaan. The transplants were produced in rockwool cubes, day/night temperature 22 °C/20 °C, air humidity RH (relative humidity) 60–70%, and average CO_2 concentration 800 ppm. Sweet pepper transplants were grown under 16 h a day photosynthetic photon flux density (PPFD) at 170 μmol m^{-2} s^{-1} provided by HPS lamps.

Sweet pepper was planted on mineral wool slabs type Grotop Master 100 × 20 × 10 cm (2 plants on each slab) on 6 December 2018 and the production was completed in July 2019. In the experimental chamber, with a useful area of about 40 m^2, the plants were grown on three beds. The plant density was about 2.5 per m^2 (the plants were pruned to have two main stems and staked individually in the shape of a "V."). Plants growing in each of the beds were fertilized with a nutrient solution differing in the form of applied phosphorus. Polyphosphates were applied using Antibloc Mineral (Yara). Fertilizer combinations: (1) P-15, where the nutrient solution contained 15% phosphorus in the form of polyphosphates and 85% phosphorus in the form of orthophosphates, (2) P-30, the nutrient solution containing 30% phosphorus in the form of polyphosphates and 70% phosphorus in the form of orthophosphates and (3) C, the nutrient solution in control containing 100% phosphorus in the form of orthophosphates. Nutrient concentration in the solution, EC (electro-conductivity) and pH were continuously controlled and kept at uniform levels for all experimental objects. The average pH and EC were respectively about 5.5–5.8 and 2.8–3.3 dS m^{-1} of drop solution. The concentration of nutrients (in $mg.dm^{-3}$) was in each combination as follows: N – NO_3—195, P—57, K—273, Mg—47, Ca—187, Fe—2, Mn—0.6, B—0.3, Cu—0.15, Zn—0.3, Mo—0.05. The experiment was established with the randomized blocks method in three replications, with 4 plants in each. In the experiment, top lighting with Green Power LED (Philips) top lighting units (DR/W–LB, 195 W) and inter-row 1-line of LEDs (module 2.5 m HO DR/B 100 W) (Philips) were applied. A daily light exposure equaled 16 h. The top lighting units switched off automatically when the solar radiation was higher than 250 W m^{-2}. Light conditions in terms of PAR (Photosynthetically Active Radiation) were closest to ~185 $\mu mol \cdot m^{-2}$ s^{-1} (PPFD). Light intensity was measured with a Li-Cor Light meter LI-250A, quantum sensor LI-190. Microclimate parameters were controlled by the Synopta Climate Computer and were as follows: temperature was 22–25 °C/18–20 °C during day/night respectively, CO_2 was supplied up to 800 ppm level and RH was approximately 75%. In each combination, weekly increments in stem length were measured by determining the total plant height and number of leaves. Twice during the vegetation period of the plants (8 and 16 weeks after planting: term 1 and term 2), in fully mature leaves, located on three levels of the plant: upper leaf, middle leaf and bottom leaf, a relative concentration of chlorophyll $a + b$ was measured with Minolta SPAD-502 apparatus. Relative SPAD meter values are proportional to the amount of chlorophyll present in the leaf [26]. The result was averaged from five unit measurements made on each examined leaf. Chlorophyll fluorescence was measured in the same leaves of pepper plants with the use of the FMS-2 Field Portable Pulse Modulated Chlorophyll Fluorescence Monitoring System (Hansatech Instruments Ltd., King's Lynn, Norfolk, England) and the following parameters were measured: Fs—steady-state fluorescence yield, Fm'—light-adapted fluorescence maximum and φPSII (Fv'/Fm')—quantum efficiency of photosystem II (PSII). The Pocket PEA fluorescence meter (Hansatech Instruments Ltd., King's Lynn, Norfolk, England) was used to measure direct fluorescence, obtaining a measurement of the maximum efficiency of the plant's photosynthetic camera after an earlier 30 min of adapting the leaves to darkness (using special clips). The following parameters were analyzed: maximum efficiency of PS II photosystem in the dark (Fv/Fm) and PI—PS II vitality index.

The nutrient status of the pepper plants fertilized with three kinds of medium, differing in the form of the applied phosphorus, was determined by leaf sample analysis. The samples were gathered in term 1 and term 2 where the analysis was performed for fully mature leaves, as above. The samples were dried at the temperature of 60 °C, in a forced-air oven, then ground in a Wiley stainless-steel mill. The samples were microwave digested in HNO_3, using closed Teflon vessels. The elements (P, K, Mg, Na, Ca, Fe, Mn, Cu, Zn, B) were determined by an inductively-coupled plasma spectrometer (ICP, Model OPTIMA 2000DV, PerkinElmer, Boston, USA). For total N determining, the plant material was mineralized after drying in concentrated sulfuric acid in the presence of copper-potassium catalyst. The N content was determined using the Kjeldahl apparatus (Vapodest, Königswinter, Germany). After distillation of nitrogen in the form of NH_3, the N content was determined by titration methods [27].

The fruit was harvested in the full color phase. The number and weight of fruit in the total, as well as marketable and non-marketable fruit with symptoms of dry rot (BER—blossom end rot),

were determined. The quality of pepper fruit was tested twice (term 1 and term 2). For this purpose, fully colored fruit were randomly collected from each combination, in which, in one part, in three repetitions, the dry matter was determined by drying method at 105 °C, the concentration of ascorbic acid (AA) was determined using the Tillmans' method (Polish Standard PN-A-04019) [28] and total soluble solids (TSS) concentration (in °Brix) with digital refractometer (Atago CO.,LTD.) and total sugars (TS) were analyzed according to the Luff-Schoorl method (Polish Standard PN-90/A-75101/07) [29]. Nitrate (NO_3) concentration was determined spectrophotometrically, with the FIAstar device (Foss Tecator AB, Sweden), using the wavelength of 440 nm, and the concentration of P was determined with the colorimetric test. The concentration of K and Ca was determined with the flame method. Other parts of fruits served for sensory analysis. The sensory quality of fruits was evaluated using the QDA (Quantitative Description Analysis) method. This was achieved by a team of 20 trained panelists in two duplicates. The odor, texture and taste quality attributes were evaluated. Each panelist marked his evaluation of the investigated sample on a scale—a segment of a straight line with border marks. The marked notes were converted to numerical values in the stipulated units from 0 to 10. Also, overall sensory quality impression was taken into account as a separate descriptor. Overall quality is a general sensory quality impression and anchoring points from low quality to high quality (from 0 to 10). A semi-consumer test of pepper cultivars liking was also performed alongside the QDA procedure. For this evaluation, a non-structural scale was also used, with anchoring points: 'I do not like it'—'I like it very much'.

Statistical analysis was performed using two-way analysis of variance, ANOVA (Statistica, Version 13, Warsaw, Poland). Detailed comparison of means was performed by the Tukey's test at the significance level of $\alpha = 0.05$.

3. Results

The results of biometric measurements showed no effect of polyphosphates used in the nutrient solution for pepper fertigation in hydroponic cultivation with LED lighting on plant height, weekly shoot growth on the length and number of leaves in both studied pepper cultivars. Plant height depended on the cultivar. Plants of 'Palermo' were taller than 'Aifos', achieving an average height of 92.77 cm, and plants of 'Aifos'—64.45 cm (Table 1).

Table 1. Effect of fertilizer with polyphosphates in hydroponic cultivation on the height of pepper plant, number of leaves on the plant and weekly growth of stem depending on cultivar (average of two terms).

	Cultivar	Treatment		
		Control	P-15	P-30
Weekly growth of stem (cm)	'Aifos'	5.23 a	5.03 a	4.57 a
	'Palermo'	5.97 a	4.63 a	6.70 a
Plant height (cm)	'Aifos'	63.40 b *	66.07 b	63.87 b
	'Palermo'	89.10 a	90.70 a	98.50 a
Number of leaves (No.)	'Aifos'	24.90 a	29.47 a	25.97 a
	'Palermo'	28.87 a	29.90 a	33.03 a

* The mean values marked with the same letters do not differ significantly according to the Tukey HSD (honestly significant difference) test at $\alpha = 0.05$.

Pulse amplitude modulation (PAM) measurement of chlorophyll fluorescence allows to measure fluorescence under current light intensity conditions. One of the parameters measured by this technique is Fs, or stationary fluorescence. The influence of the use of polyphosphates in pepper hydroponic cultivation on Fs was observed. Fs value was the highest in peppers fed with P-15 medium in relation to control, regardless of the cultivar. For 'Aifos' cultivar, the fluorescence parameter such as Fs in P-30 combination was also higher than in the control (Table 2). Fm' maximum fluorescence

of chlorophyll *a* in the leaves adapted to light, which is lower than the maximum fluorescence of chlorophyll achieved after adaptation to darkness (Fm), was also the highest in the P-15 combination (Table 2). However, no effect of polyphosphates' application on the current quantum yield of PSII, φPSII (Fv'/Fm'), was found in the examined pepper cultivars (Table 2). The maximum photochemical yield of PSII (Fv/Fm) determines the photochemical activity of the plant's photosynthetic apparatus. It is determined for plants adapted to darkness. The analysis of the obtained results showed lower maximum photochemical yield of PSII in 'Palermo' fed with P-15 medium, and lower vitality of PSII (PI inst.) in 'Palermo' than 'Aifos', whereas no positive effect of polyphosphates on the maximum yield of pepper photosynthetic apparatus was found (Table 2). The value of PI inst. was significantly lower in 'Palermo' than 'Aifos', although in the P-15 combination, PI inst. for cultivars did not differ significantly (Table 2). A significant dependence of the leaf chlorophyll index on the sweet pepper cultivar was found. The cultivar 'Aifos' had higher SPAD index in leaves than cultivar 'Palermo'. Whereas, no significant effect of polyphosphates application in the medium on chlorophyll concentration in pepper leaves was found (Figure 1).

Table 2. Effect of fertilizer with polyphosphates in hydroponic cultivation on the photosynthetic activity of pepper leaves depending on the cultivar (average of two terms).

Chlorophyll Fluorescence Parameters	Cultivar	Control	P-15	P-30
Fs	'Aifos'	305 d *	385 ab	374 abc
	'Palermo'	312 cd	401 a	326 bcd
	Average	301 C	393 A	350 B
Fm'	'Aifos'	1289 b	1608 a	1468 ab
	'Palermo'	1276 b	1596 a	1289 b
	Average	1283 B	1602 A	1379 B
φPSII	'Aifos'	0.76 a	0.75 a	0.74 a
	'Palermo'	0.75 a	0.75 a	0.74 a
	Average	0.75 A	0.75 A	0.74 AB
Fv/Fm	'Aifos'	0.81 a	0.81 a	0.81 a
	'Palermo'	0.80 a	0.79 b	0.81 a
	Average	0.81 A	0.80 A	0.79 B
PI inst.	'Aifos'	11.72 a	10.86 ab	10.65 abc
	'Palermo'	8.81 cd	9.53 bcd	8.20 d
	Average	10.27 A	10.20 A	9.43 A

* The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The small letters indicate the differences in the interaction of cultivar x treatment, the capital letters indicate the differences in the treatment.

The highest total yield was obtained in combination P-15, on average from cultivars of 2.74 kg per one stem, that is 5.48 kg per one plant (pepper plants were cultivated with 2 stems), and in control and combination P-30, 2.37 kg and 2.26 kg per one stem, that is 4.74 kg and 4.52 kg per plant, respectively. A similar trend was found in the marketable yield for both pepper cultivars (Figure 2). The share of marketable yield in the total yield depended on the pepper cultivar and phosphorus source. 'Aifos' had from 13% to 16% lower marketable yield than total yield regardless of the phosphorus source used. On the other hand, the cultivar 'Palermo' which is more susceptible to BER had in the control combination as much as 42% lower marketable yield than the total one, mainly due to BER, but in combinations with polyphosphate use in concentrations P-15 and P-30, it had 28% and 29%, respectively. Differences in yielding were found between the examined pepper cultivars. 'Palermo' obtained a low share of marketable yield in the total yield, which was not observed in 'Aifos' (Figure 2). The reason was the higher susceptibility of 'Palermo' to BER (Figures 2 and 3). In this cultivar, the use of polyphosphates decreased the share of fruits with BER symptoms as compared to the control

combination (Figure 3). In both investigated cultivars, the average weight of marketable fruit in combination with phosphorus in the form of polyphosphates was higher than in the control, although the differences were not statistically significant (Figure 4).

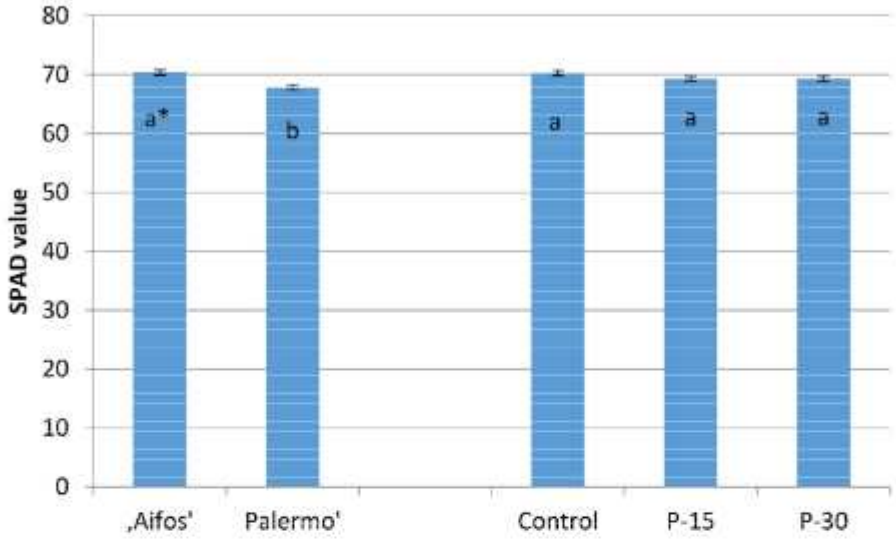

Figure 1. Effect of fertilizer with polyphosphates in hydroponic cultivation and cultivar of pepper on the chlorophyll index in pepper leaves (average of two terms). * The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

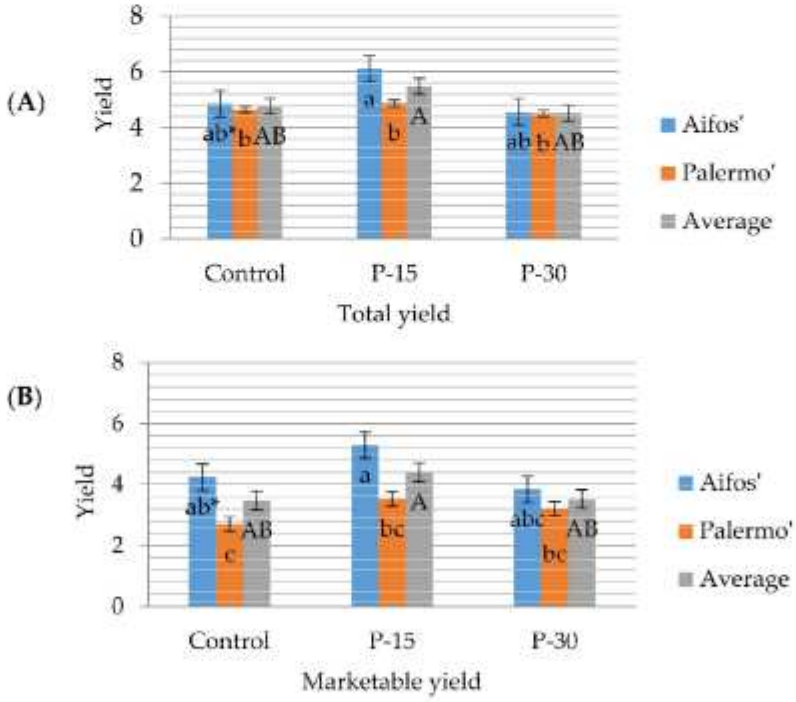

Figure 2. (**A**, **B**) Effect of fertilizer with polyphosphates in hydroponic cultivation on the total (**A**) and marketable (**B**) yield depending on the sweet pepper cultivar (kg plant^{-1}). * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

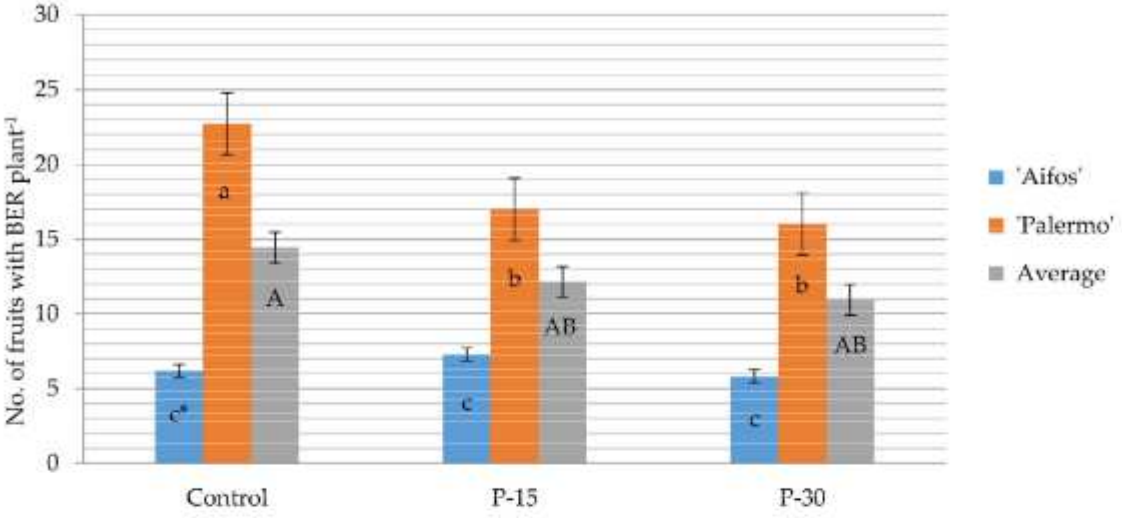

Figure 3. Effect of fertilizer with polyphosphates in hydroponic cultivation on the number of BER (blossom end rot) fruit depending on the sweet pepper cultivar. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

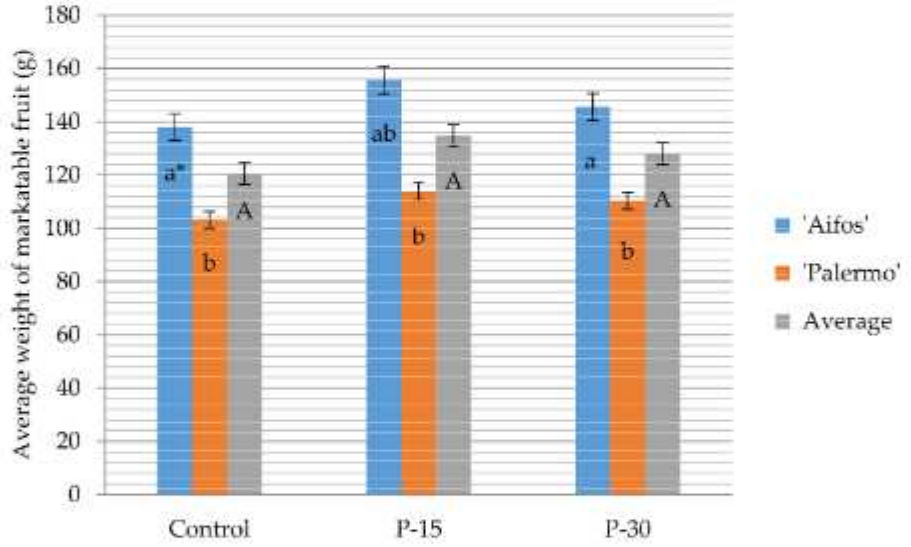

Figure 4. Effect of fertilizer with polyphosphates in hydroponic cultivation on the average weight of marketable fruit depending on the sweet pepper cultivar. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

Calcium concentration in the drip nutrient solution for plant fertigation, on average for the growing period of pepper, was about 187 mg dm^{-3} for each combination (See Section 2). In the case of pepper fertilization with PP medium in the substrate, a lower accumulation of Ca was found in P-30 than in the P-15 combination and in the control (Figure 5). Probably in the combination P-30, the pepper plants taken up more calcium than when fertilized with medium at P-15 and with the nutrient solution containing 100% phosphorus in the form of orthophosphates.

The concentration of mineral components in pepper leaves, on average of the two measurement dates and combinations, was the following for macronutrients in % of dry matter: N—4.80, P—0.24, K—6.60, Ca—3.42, Mg—0.62, S—0.57, and for micronutrients in mg kg^{-1} of dry matter: Fe—171.0, Mn—194.9, Cu—4.6, Zn—151.1, B—43.0. There were no significant differences between the cultivars in the mineral content of leaves. In comparison to the control, the content of especially P as well as K, Zn, S and Ca in pepper leaves, was higher when PP was applied in nutrient solution at a concentration of

15%, and when PP was applied at a concentration of 30%, the content of Ca and Mg in leaves was higher than in the control plants (Figure 6).

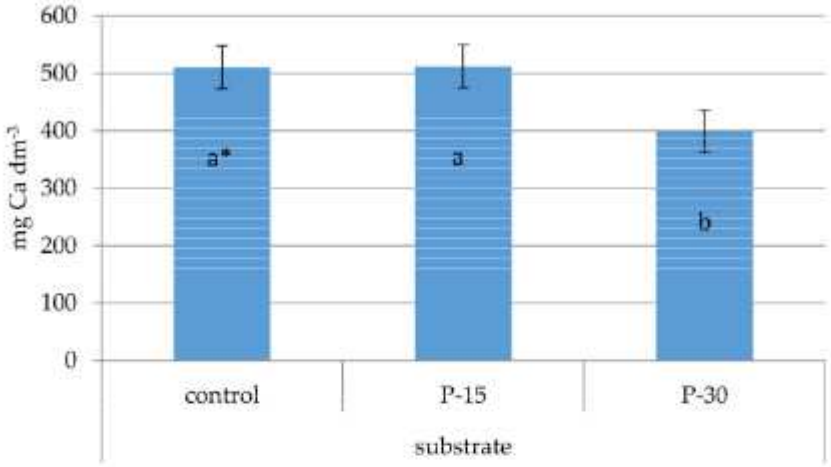

Figure 5. Calcium concentration in the substrate depending on the level of PP (polyphosphates) applied in the drip nutrient solution, on average for the growing period of pepper. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

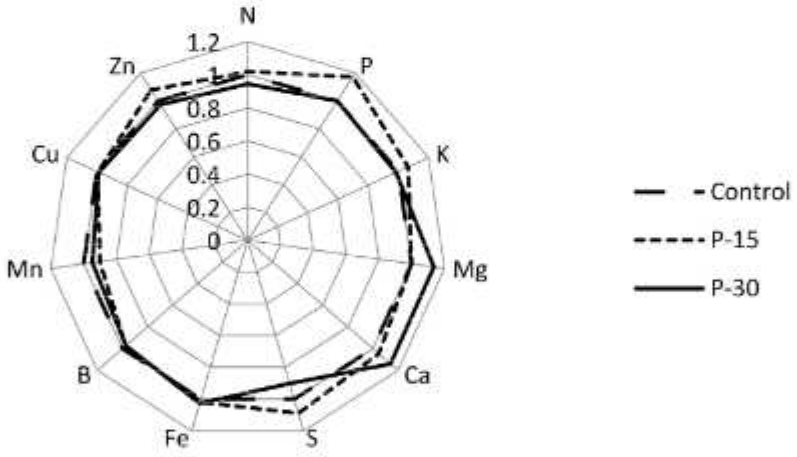

Figure 6. The concentration of mineral components in pepper leaves normalized to the values in control content as radar plots under different PP combinations (average of two terms).

The analysis of chosen quality features of pepper fruits did not show any influence of polyphosphates on the concentration of such components in pepper fruits as dry matter, TSS (total soluble solids), ascorbic acid, TS, P, NO_3, K and Ca (Table 3). The concentration of these components in the fruit depended mainly on the cultivar. The 'Palermo' fruit contained more dry matter, TSS and total sugars (TS). The fruits of the 'Palermo' had a higher TSS content in combination P-15 and a higher TS content in combination P-30 than in the control. Nitrates contained the most fruits fertilized with PP in the P-15 combination and potassium contained the most fruits from the P-30 combination. In the control combination, without applied polyphosphates in the nutrient solution, there was less calcium in 'Palermo' than in 'Aifos' (Table 3). In this combination, 'Palermo' was found to yield the most fruit with BER (Figure 3). Sensory analysis of pepper fruits did not show the influence of polyphosphates on attributes concerning odor, texture and flavor of pepper fruits (Table 4). On the other hand, the fruits between the cultivars differed significantly in terms of, among others, sweet taste, which correlates with sugar concentration. 'Palermo' fruits were assessed significantly higher in terms of sweet taste and 'Aifos' fruits were found to have higher flesh texture, crispier flesh and tougher skin than the

other one (Figure 7). The overall sensory quality for pepper fruits did not depend on the PP applied in fertilization. The cultivar 'Palermo' obtained a higher score than the 'Aifos' (Figure 8).

Table 3. Effects of fertilizer with polyphosphates in hydroponic cultivation on the concentration of dry weight and chosen chemical components in pepper fruit depending on the cultivar (average of two terms).

Component	Cultivar	Control	P-15	P-30
Dry weight (%)	'Aifos'	8.01 b *	8.08 b	8.05 b
	'Palermo'	10.14 a	10.60 a	10.34 a
	Average	9.07 A	9.19 A	9.34 A
TSS (°Brix)	'Aifos'	7.57 c	7.42 c	7.27 c
	'Palermo'	9.45 b	10.15 a	9.47 b
	Average	8.50 A	8.78 A	8.37 A
Ascorbic Acid (mg.100 g^{-1} FW)	'Aifos'	26.54 a	22.33 b	22.07 b
	'Palermo'	19.56 b	21.00 b	21.73 b
	Average	23.04 A	21.66 A	21.89 A
TS (g.100 g^{-1} FW)	'Aifos'	4.56 c	3.75 d	3.94 d
	'Palermo'	6.01 b	6.30 ab	6.45 a
	Average	5.28 A	5.03 A	5.20 A
P (mg.kg^{-1} FW)	'Aifos'	249.95 a	249.00 a	248.35 a
	'Palermo'	247.65 a	272.5 a	250.15 a
	Average	248.8 A	260.75 A	249.25 A
NO_3^- (mg.kg^{-1} FW)	'Aifos'	56.27 ab	58.04 a	56.04 abc
	'Palermo'	50.95 c	56.48 ab	52.06 bc
	Average	53.61 B	57.26 A	54.05 B
K (mg.kg^{-1} FW)	'Aifos'	2335.85 abc	2325.4 bc	2148.45 c
	'Palermo'	2384.63 ab	2523.2 a	2335.85 abc
	Average	2360.24 A	2424.3 A	2242.2 B
Ca (mg.kg^{-1} FW)	'Aifos'	26.5 a	22.65 a	20.00 a
	'Palermo'	19.9 a	22.00 a	22.65 a
	Average	23.2 A	22.33 A	21.33 A

* See Table 2.

Table 4. The results of sensory analysis concerning odor, texture and taste for pepper fruits as affected by cultivar and PP treatment, scale 0–10 (average of two terms).

Attributes of Odor, Texture and Taste	Cultivar	Control	P-15	P-30
Odor of fresh pepper	'Aifos'	5.77 a *	6.02 a	5.25 a
	'Palermo'	5.33 a	5.16 a	5.36 a
	Average	5.53 A	5.60 A	5.31 A
Skin hardness	'Aifos'	5.39 ab	5.72 a	5.38 ab
	'Palermo'	4.27 b	4.72 ab	4.54 ab
	Average	4.81 A	5.24 A	4.94 A
Flesh fibrousness	'Aifos'	6.27 ab	6.48 ab	6.98 a
	'Palermo'	5.88 ab	5.47 b	6.10 ab
	Average	6.07 A	5.99 A	6.52 A

Table 4. *Cont.*

Attributes of Odor, Texture and Taste	Cultivar	Control	P-15	P-30
Flesh juiciness	'Aifos'	5.77 a	6.04 a	5.81 a
	'Palermo'	5.98 a	5.37 a	5.86 a
	Average	5.88 A	5.72 A	5.83 A
Flesh firmness	'Aifos'	6.81 a	7.04 a	6.50 a
	'Palermo'	4.31 a	3.77 b	4.58 a
	Average	5.51 A	5.48 A	5.51 A
Typical pepper taste	'Aifos'	5.99 ab	6.01 ab	5.41 b
	'Palermo'	6.51 ab	6.29 ab	6.98 a
	Average	6.27 A	6.15 A	6.23 A
Sour taste	'Aifos'	1.82 a	1.59 a	1.74 a
	'Palermo'	1.70 a	1.74 a	1.78 a
	Average	1.75 A	1.66 A	1.76 A
Sweet taste	'Aifos'	3.16 c	3.74 bc	3.07 c
	'Palermo'	5.13 ab	5.32 a	5.69 a
	Average	4.19 A	4.49 A	4.43 A
Bitter taste	'Aifos'	1.69 a	0.78 ab	1.24 ab
	'Palermo'	0.62 b	0.76 ab	0.64 b
	Average	1.13 A	0.77 A	0.93 A
Pungent flavor	'Aifos'	0.93 a	0.70 a	0.98 a
	'Palermo'	0.76 a	0.99 a	0.85 a
	Average	0.84 A	0.84 A	0.91 A
Off-flavor	'Aifos'	0.28 a	0.21 a	0.23 a
	'Palermo'	0.28 a	0.26 a	0.28 a
	Average	0.15 A	0.11 A	0.11 A
Overall quality	'Aifos'	6.38 a	6.69 a	6.58 a
	'Palermo'	7.07 a	6.74 a	7.15 a
	Average	6.73 A	6.86 A	6.87 A

* See Table 2.

Figure 7. The results of sensory analysis concerning odor, texture and taste and overall quality for pepper fruits normalized to the values of 'Aifos' cultivar as radar plots compared to the 'Palermo' cultivar (average of two terms).

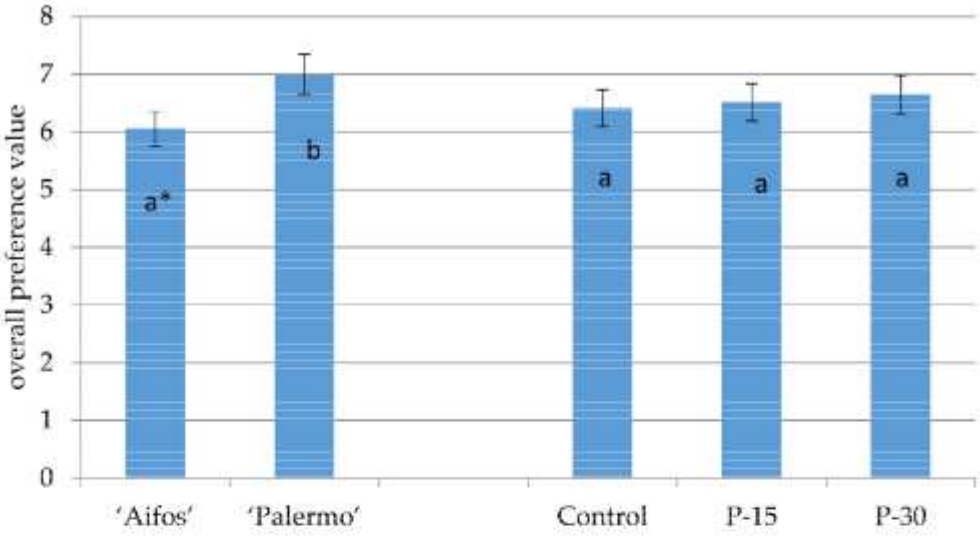

Figure 8. Overall sensory preference for pepper fruits as affected by cultivar and fertilized with polyphosphates in hydroponic cultivation (average of two terms). * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

4. Discussion

Phosphorus (P) is an essential macronutrient for plant growth and development [30]. P affects the light use efficiency of PSII and deficiency of phosphorus could cause detectable fluctuations of the kinetic parameters of photosynthetic fluorescence [31–35].

According to Kalaji [36], a decrease in chlorophyll fluorescence parameters may result from macro- and micro-elements' deficiency. The results obtained from our experiment suggest better nutrient availability in PP compared to control. Significant effects of P-15 and P-30 on Fs and of P-15 on Fm' could be due to the differences in phosphorus availability during cultivation.

Torres-Dorante et al. [22] reported that the P availability was dependent on the source of P and soil properties. Efficiency of fertilization was significantly higher for PP treatments in the silty-loam soil where the plants have produced longer roots. However, no differences were observed in the sandy soil, between OP and PP treatments [34]. Although, according to Dicklowa [35], the effectiveness of a unit amount of P taken up by ryegrass and corn plants in increasing the dry matter yield was similar among the polyphosphates and the conventional P fertilizer, orthophosphate. However, these studies concern traditional crops in different soils.

According to Flexas et al. [33], measurements of Fs—steady-state fluorescence yield is a promising tool for remote water shortage diagnosis. Effectively, it shows the effect of many reactions resulting from consequences that follow stomatal closure in response to water stress. The relationship between Fs and g (stomatal conductance) provides a new method for detection of water stress, which can cause BER in pepper fruits. Our results showed that higher values of pepper leaves' chlorophyll a fluorescence parameters in plants fertilized with polyphosphates indicate an increased yield of pepper photosynthetic apparatus in the case of pepper cultivar more susceptible to BER. In hydroponic crops, the problem of water and nutrient uptake and partitioning, and transport to particular plant parts, is more frequent than their availability in the substrate. Li and Erel [34] report that PP can function as a chelate for micronutrients and Ca. Moreover, in hydroponic crops, PP can improve the nutrient solution flow in the drip system by reducing the accumulation of insoluble salts.

Fm' maximum fluorescence of chlorophyll a in the leaves adapted to light was also the highest in the P-30 combination, with the acceptors of photosystem II (PSII) partially reduced in this case [37]. According to Borawska-Jarmułowicz et al. [38], it is temperature stress that is the key factor in any Fm' decrease. The Fv/Fm index presents the maximum quantum yield of photosystem II [39]. Graham and McDonald [40] observed a decrease in the Fv/Fm due to high temperature, a decrease in this parameter

may indicate active sun protection of the plant [41]. Baker and Rosenqvist [26] concluded in their studies that a decrease in Fv/Fm may inhibit the rate of photosynthesis and also affect plant growth and development. The PI PSII vitality index, on the other hand, shows the ability of plants to adapt to stress conditions [42].

The use of polyphosphates to fertilize pepper grown in rockwool influenced the activity of the photosynthetic apparatus. A large share of BER fruits in the control is a reaction to environmental stress conditions during the growing period. Possible reasons are a short-term increase in temperature or substrate EC (electrical conductivity), a decrease in substrate moisture or the increase in fruit load on the plant.

Differences in yield, fruit quality and susceptibility to BER were found between pepper cultivars. Plants fertilized with phosphorus in the form of polyphosphates were less susceptible to common disorders that have been associated with fruit calcium deficiency (BER), especially the cultivar which was more susceptible to BER. Many authors report [43,44] that proper nutrition of plants with calcium has a significant impact on reducing the occurrence of BER. According to Michałojć and Horodko [45], the share of fruits with BER symptoms in the total yield is lower when plants are properly supplied with calcium.

According to Selahle et al. [46], the taste of sweet peppers is determined by the sugar and organic acid concentrations. Pepper flavor is a complex trait, influenced by environmental factors during growth [47,48]. However, polyphosphates used in the nutrient solution for fertigation in hydroponic cultivation of pepper with LED lighting do not significantly change the sensory quality of pepper fruits.

5. Conclusions

The following conclusions can be drawn from the study.

The use of polyphosphates for fertigation in hydroponic cultivation increase the activity of photosynthetic apparatus of pepper leaves and has a positive effect on the share of marketable yield of the total yield in the cultivar susceptible to BER.

Pepper plants fertilized with polyphosphates are characterized by increased values of such fluorescence of chlorophyll parameters as Fs—steady-state fluorescence yield, and Fm'—maximum fluorescence of chlorophyll *a*.

Fertigation in hydroponic cultivation with medium containing 30% phosphorus in the form of polyphosphates increased the uptake of calcium in pepper plants growing with LED lighting.

The polyphosphates used in the nutrient solution do not significantly change the quality of pepper fruits.

The pepper cultivars tested differ in the yield and the susceptibility to BER and such features as the height of the plants, the dry matter and sugar concentration of the fruit, and the sensory quality characteristics of the fruit, such as sweet taste, consistency of the flesh, crispness of the flesh and hardness of skin.

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References

1. Kuczuk, A. The productive-economic results of paprika cultivation in organic farming conditions. *J. Res. App. Agric. Eng.* **2011**, *56*, 243–249.
2. Jakubas, A.; Sękara, A.; Cebula, S.; Kalisz, A. Ocena wzrostu i plonowania polskich odmian papryki słodkiej (*Capsicum annuum* L) w uprawie polowej. *Episteme* **2013**, *20*, 341–356.
3. Howard, L.R.; Talcott, S.T.; Brenes, C.H.; Villalon, B. Changes in phytochemical and antioxidant activity of selected pepper cultivars (*Capsicum* Species) as influenced by maturity. *J. Agric. Food Chem.* **2000**, *48*, 1713–1720. [CrossRef]
4. Lee, S.; Kader, A. Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biol. Technol.* **2000**, *20*, 207–220. [CrossRef]
5. Zhuang, Y.; Chen, L.; Sun, L.; Cao, J. Bioactive characteristics and antioxidant activities of nine peppers. *J. Funct. Foods.* **2012**, *4*, 331–338. [CrossRef]
6. Liu, X.Y.; Chang, T.T.; Guo, S.R.; Xu, Z.G.; Li, J. Effect of different light quality of LED on growth and photosynthetic character in cherry tomato seedling. *Acta Horticulturae* **2011**, *907*, 325–330. [CrossRef]
7. Massa, G.D.; Kim, H.-H.; Wheeler, R.M.; Mitchell, C.A. Plant productivity in response to LED lighting. *HortScience* **2008**, *43*, 1951–1956. [CrossRef]
8. Puternicki, A. Zastosowanie półprzewodnikowych źródeł światła do wspomagania wzrostu roślin. *Prace Instytutu Elektrotechniki* **2010**, *245*, 69–86.
9. Mitchell, C.A.; Both, A.J.; Bourget, M.C.; Burr, J.F.; Kubota, C.; Lopez, R.G.; Morrow, R.C.; Runkle, E.S. LEDs: The future of greenhouse lighting! *Chronica Horticulturae* **2012**, *52*, 6–12.
10. Bian, Z.H.; Yang, Q.C.; Liu, W.K. Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. *J. Sci. Food Agric.* **2015**, *95*, 869–887. [CrossRef]
11. Kalaitzoglou, P.; van Ieperen, W.; Harbinson, J.; van der Meer, M.; Martinakos, S.; Weerheim, K.; Nicole, C.C.S.; Marcelis, L.F.M. Effects of continuous or end-of-day far-red light on tomato plant growth, morphology, light absorption and fruit production. *Front. Plant Sci.* **2019**, *10*, 322. [CrossRef] [PubMed]
12. Amalfitano, C.; Del Vacchio, L.; Somma, S.; Cuciniello, A.; Caruso, G. Effects of cultural cycle and nutrient solution electrical conductivity on plant growth, yield and fruit quality of 'Friariello' pepper grown in hydroponics. *Hort. Sci.* **2017**, *44*, 91–98.
13. Ciereczko, I. Kontrola metabolizmu sacharozy u roślin w odpowiedzi na zmienne warunki środowiska. *Kosmos* **2006**, *55*, 229–241.
14. Richardson, A.E. Regulating the phosphorus nutrition of plants: Molecular biology meeting agronomic needs. *Plant Soil.* **2009**, *322*, 17–24. [CrossRef]
15. Schröder, J.J.; Cordell, D.; Smit, A.L.; Rosemarin, A. *Sustainable Use of Phosphorus*; Technical Report 357 for Plant Research International; Wageningen University and Research Centre: Wageningen, The Netherlands, 2010.
16. Rychter, A.M.; Rao, I.M. Role of phosphorus in photosynthetic carbon metabolism. In *Handbook of Photosynthesis*, 2nd ed.; Pessarakli, M., Ed.; Marcel Dekker, Inc.: New York, NY, USA, 2005; pp. 123–148.
17. Schachtman, D.P.; Shin, R. Nutrient sensing and signaling: NPKS. *Annu. Rev. Plant Biol.* **2007**, *58*, 47–69. [CrossRef] [PubMed]
18. Zhu, J.; Loubery, S.; Broger, L.; Lorenzo-Orts, L.; Utz-Pugin, A.; Chang, Y.-T.; Hothorn, M. A genetically validated approach to detect inorganic polyphosphates in plants. *BioRxiv* **2019**. [CrossRef]
19. Laha, D.; Parvin, N.; Dynowski, M.; Johnen, P.; Mao, H.; Bitters, S.T.; Zheng, N.; Schaaf, G. Inositol polyphosphate binding specificity of the jasmonate receptor complex. *Plant Physiol.* **2016**, *171*, 2364–2370. [CrossRef]
20. Seufferheld, M.; Curzi, M.J. Recent discoveries on the roles of polyphosphates in plants. *Plant Mol. Biol. Rep.* **2010**, *28*, 549–559. [CrossRef]
21. Lorenzo-Orts, L.; Couto, D.; Hothorn, M. Tansley review. Identity and functions of inorganic and inositol polyphosphates in plants. *New Phytol.* **2019**, *225*, 637–652.
22. Torres-Dorante, L.O.; Claasse, N.; Steingrobe, B.; Olfs, H.W. Fertilizer-use efficiency of different inorganic polyphosphate sources: Effects on soil P availability and plant P acquisition during early growth of corn. *J. Plant. Nutr. Soil Sci.* **2006**, *169*, 509–515. [CrossRef]

23. Ma, C.; Xiao, Y.; Puig-Bargés, J.; Shukla, M.K.; Tang, X.; Hou, P.; Li, Y. Using phosphate fertilizer to reduce emitter clogging of drip fertigation systems with high salinity water. *J. Environ. Manag.* **2020**, *263*. [CrossRef] [PubMed]
24. McBeath, T. Chemical Reactions of Polyphosphate Fertilisers in Soils and Solutions. Ph.D. Thesis, University of Adelaide, Adelaide, SA, Australia, 2006; p. 29.
25. Saure, M.C. Why calcium deficiency is not the cause of blossom-end rot in tomato and pepper fruit—A reappraisal. *Sciencia Horticulturae* **2014**, *174*, 151–154. [CrossRef]
26. Baker, N.R.; Rosenqvist, E. Applications of chlorophyll fluorescence can improve crop production strategies: An examination of future possibilities. *J. Exp. Bot.* **2004**, *55*, 1607–1621. [CrossRef] [PubMed]
27. Latimer, G., Jr. *Official Methods of Analysis*, 19th ed.; AOAC International: Gaithersburg, MD, USA, 2012.
28. Polish Standard PN-A-04019. *Determine of Vitamin C Content Using the Tillman Method*; Polish Committee for Standardization: Warsaw, Poland, 1998.
29. Polish Standard PN-90/A-75101/07. *Determine the Content of Total Sugars as well as Sacharose and Monosaccharides Using the Luff-Schoorl Method*; Polish Committee for Standardization: Warsaw, Poland, 1990.
30. Marschner, P. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK, 2012.
31. Conroy, J.P.; Smillie, R.M.; Kuppers, M.; Bevege, D.I.; Barlow, E.W. Chlorophyll *a* fluorescence and photosynthetic and growth responses of *Pinus radiate* to phosphorus deficiency, drought stress, and high CO_2. *Plant Physiol.* **1986**, *81*, 423–429. [CrossRef]
32. Carstensen, A.; Herdean, A.; Schmidt, S.B.; Sharma, A.; Spetea, C.; Pribil, M.; Husted, S. The impacts of phosphorus deficiency on the photosynthetic electron transport chain. *Plant Physiol.* **2018**, *177*, 271–284. [CrossRef] [PubMed]
33. Flexas, J.; Briantais, J.-M.; Cerovic, Z.; Medrano, H.; Moya, I. Steady-state and maximum chlorophyll fluorescence responses to water stress in grapevine leaves: A new remote sensing system. *RSE* **2000**, *73*, 283–297. [CrossRef]
34. Li, Q.; Erel, R. Availability of Polyphosphate Versus Orthophosphate on Alkaline Soil to Lettuce Plants. From Molecular Scale to Ecosystems. In Proceedings of the 6th Symposium on Phosphorus in Soils and Plants (PSPS), Leuven, Belgium, 10–13 September 2018.
35. Dick, R.P. Hydrolysis and availability to plants of polyphosphates added to soils. Paper 12054. Ph.D. Thesis, Iowa State University Capstones, Ames, IA, USA, 1985. [CrossRef]
36. Kalaji, M.H. Influence of abiotic stress factors on chlorophyll fluorescence in selected varieties of barley (*Hordeum vulgare* L.) plants. In *Treatises and Monographs*; Warsaw University of Life Sciences WULS—SGGW: Warsaw, Poland, 2011; pp. 1–176.
37. Kalaji, M.; Łoboda, T. *Fluorescencja Chlorofilu w Badaniach Stanu Fizjologicznego Roślin*, 2nd ed.; Warsaw University of Life Sciences Press: Warsaw, Poland, 2010; pp. 19–21.
38. Borawska-Jarmułowicz, B.; Mastalerczuk, G.; Pietkiewicz, S.; Kalaji, M.H. Low temperature and hardening effects on photosynthetic apparatus efficiency and survival of forage grass varieties. *PSE* **2014**, *60*, 177–183. [CrossRef]
39. Björkman, O.; Demming, B. Photon yield of O_2 evolution and chlorophyll fluorescence characteristics at 77K among vascular plants of diverse origins. *Planta* **1987**, *170*, 489–504. [CrossRef] [PubMed]
40. Graham, A.W.; McDonald, G.K. Effect of zinc on photosynthesis and yield of wheat under heat stress. In Proceedings of the 10th Australian Agronomy Conference, Hobart, Tasmania, 29 January–1 February 2001.
41. Horton, P.; Ruban, A.V.; Walters, R.G. Regulation of light harvesting in green plants. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1996**, *47*, 655–684. [CrossRef]
42. Prost, L.; Jeuffroy, M.H. Replacing the nitrogen nutrition index by the chlorophyll meter to assess wheat N status. *ASD* **2007**, *27*, 1–10. [CrossRef]
43. Errecart, P.M.; Agnusdei, M.G.; Lattanzi, F.A.; Marino, M.A. Leaf nitrogen concentration and chlorophyll meter readings as predictors of tall fescue nitrogen nutrition status. *Field Crops Res.* **2012**, *129*, 46–58. [CrossRef]
44. Giletto, C.M.; Echeverría, H.E. Chlorophyll meter for the evaluation of potato N status. *Am. J. Potato Res.* **2013**, *90*, 313–323. [CrossRef]
45. Michałojć, Z.M.; Horodko, K. Wpływ dokarmiania pozakorzeniowego wapniem na plonowanie i skład chemiczny papryki słodkiej [EN. Effect of calcium foliar nutrition on yield end chemical composition of sweet pepper]. *Acta Agrophysica* **2006**, *7*, 671–679.

46. Selahle, K.M.; Sivakumar, D.; Jifon, J.; Soundy, P. Postharvest responses of red and yellow sweet peppers grown under photo-selective nets. *Food Chem.* **2015**, *173*, 951–956. [CrossRef]
47. Eggink, P.M.; Maliepaard, C.; Tikunov, Y.; Haanstra, J.P.W.; Bovy, A.G.; Visser, R.G.F. A taste of sweet pepper: Volatile and non-volatile chemical composition of fresh sweet pepper (*Capsicum annuum*) in relation to sensory evaluation of taste. *Food Chem.* **2012**, *132*, 301–310. [CrossRef]
48. Eggink, P.M.; Maliepaard, C.; Tikunov, Y.; Haanstra, J.P.W.; Pohu-Flament, L.M.M.; de WitMaljaars, S.C.; Willeboordse-Vos, F.; Bos, S.; Benning-de Waard, C.; de Grauw-van Leeuwen, P.J.; et al. Prediction of sweet pepper (*Capsicum annuum*) flavor over different harvests. *Euphytica* **2012**, *187*, 117–131. [CrossRef]

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Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems

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Abstract: The aim of this study was to evaluate the effects of various supplemental greenhouse lighting systems, i.e., high-pressure sodium lamps and mixtures of red and blue light-emitting diodes, on the photochemical efficiency, anatomical leaf structure, and growth of the two pepper cultivars. The intensity levels of the photosynthetically active radiation were the same for both light treatments. In this study, the relative chlorophyll content was measured. Additionally, certain parameters of chlorophyll *a* fluorescence were measured under ambient light or after dark adaptation. The obtained results showed that the application of light-emitting diodes (LEDs) as supplemental lighting positively affected the anatomical leaf characteristics and plant growth. The leaves of both pepper cultivars were thicker and had larger palisade parenchyma cells under LED supplemental lighting compared to leaves grown under high-pressure sodium (HPS) lamps. Moreover, the mesophyll cells of seedlings grown under LEDs contained more chloroplasts than those growing under HPS lighting. The chlorophyll *a* fluorescence measurements of pepper seedlings grown under LEDs showed significant increases in photosynthetic apparatus performance index (PI) values compared to plants grown under HPS lamps; however, the values for this index were higher in cv. 'Aifos' as compared to cv. 'Palermo'. We recommend that supplemental lighting systems are applied with caution, as their performance appears to depend not only on the light spectrum but also on the cultivar.

Keywords: supplementary lighting; seedlings; leaf productivity; light quality; SPAD

1. Introduction

Light is one of the essential factors in a plant's growth, development, and yield [1–3]. Light affects the process and intensity of photosynthesis and regulates photomorphogenesis throughout the plant development cycle; therefore, light efficiency is considered not only in terms of intensity but also in terms of wavelength [4–6]. This is especially important when artificial light is the only light source used in indoor farming [7]. Increasing attention is being focused on the promotion of efficient artificial light sources in lighted crops cultivated during periods when there is not enough natural light for proper plant growth

and development. This applies to crops grown during winter, as well as to seedling production for the earliest crop dates [8]. Additionally, light quality can be strategically used to increase the quality and efficiency of the photosynthetic apparatus of leaves by affecting the anatomy and physiological parameters of foliage. In moderate climate zones at northern latitudes, during autumn–winter and early spring there is a deficit of the natural light required for the optimal plant growth of most plants. This is the time of year when seedlings of vegetables are usually prepared in greenhouses for the earliest cultivation dates [9]. In these periods, seedlings of vegetables destined for early cultivation are grown under covers with assimilation lighting. As the standard protocol, they are usually grown under high-pressure sodium (HPS) lamps.

As reported by Marcelis et al. [10] and Virsile, Olle, and Duchovskis [11], the levels of photosynthetically active radiation (PAR) in sodium lamps can reach approximately 1.7–1.8 μmol J^{-1}. Sodium lamps have relatively high electrical efficiency as compared to the earlier generation of lamps used for light supplementation. Additionally, sodium lamps are characterized by a long working life and a broad light spectrum, making them suitable for many plant species [12]. On the other hand, HPS lamps have many disadvantages. They lack the possibility to adjust the spectral composition. They also emit a large amount of yellow light and a small amount of blue light, which causes plant stems to elongate and decreases the quality of seedlings [13]; however, despite the above-mentioned defects, these lamps were used for a long time as artificial light sources, until the appearance of LED systems [14,15].

In greenhouse crops, light-emitting diodes (LEDs) are becoming a popular source for assimilative lighting because they are much more efficient than HPS lamps and reach an average of 2.5 μmol J^{-1} or more [16]. The effectiveness and efficiency of LED lamps depend on their spectral efficiency [17]. Proper plant development depends, among other things, on the light intensity and its spectral composition [18]. LED lamps have a spectral composition adapted to the requirements of plants, high-efficiency, and a low operating temperature. They are small in size and energy-efficient, with a long life expectancy and minimal heat emissions [19]. The spectra of LED lamps are usually close to the absorption spectrum of chlorophylls, emitting red and blue light in different proportions. According to Bagdonavičienė et al. [20], blue LED light at 470 nm used as a supplement to high-pressure sodium (HPS) lamps, showing very positive effects on the photosynthesis efficiency of pepper seedlings grown during winter in a greenhouse. According to Liu et al. [2], blue light also seems to be an important factor for cherry tomato plant growth. The spectral quality also affects the anatomical structure of the plant leaves, among other factors, by influencing the arrangement of the palisade and sponge cells, which affects the photosynthetic efficiency of the plants [21,22]. According to Zheng et al. [22], in many plant species, blue light (B) and red light with blue (RB), as compared to red light (R) and white light (W), affect the growth of the palisade parenchyma, which is correlated with the quantum yield of leaf photosynthesis (φPSII). HPS and LED lighting affect the photosynthesis and yield [23]. We hypothesized that the adaptation of chloroplasts of pepper leaves to supplementary lighting provided by HPS or LED would involve changes in the distribution of chlorophylls and carotenoids. Carotenoids can absorb light energy and transfer it to the chlorophylls, which may dissipate excess light energy, acting as antioxidants [24,25]. Artificial irradiation influences the carotenoid content in leaves and fruits [23,26]. As reported by Li et al. [27], mixed R and B light alters plant photomorphogenesis and photosynthesis, mainly by affecting the leaf anatomy, stoichiometry of photosystems I and II, photosynthetic electron transport, and the expression and activity of key Calvin cycle enzymes. It was found that when pepper seedlings were illuminated with mixed RB (red–blue) light, the leaves were thicker and the photosynthetic electron transport efficiency and photosynthetic rate increased compared to plants illuminated with white light; therefore, using LED lamps with a higher proportion of blue light can increase the supplementary light efficiency. The leaf anatomy is dependent on the above-mentioned physiological and morphological changes. Proving the beneficial effects of illuminating pepper seedlings with LED lamps

compared to sodium lamps may promote their use in commercial seedling production, among other outcomes. Pepper is a vegetable of great economic importance. Investigating the responses of pepper plants at the seedling stage to light from LED lamps, in terms of changes in the leaf anatomy and photochemical efficiency compared to plants grown under traditional sodium lamps, will allow the introduction of new, more energy-efficient solutions for the horticultural production of pepper plants.

The aim of the study was to evaluate the effects of supplementary lighting of pepper seedlings with HPS and LED lamps on the growth, photochemical efficiency, and anatomical structure of the leaves.

2. Results and Discussion

2.1. Plant Growth

Supplemental lighting affected the growth of plants and the development of leaves, depending on both the type of light source (HPS or LED) and on the cultivars. 'Aifos' plants growing under LED lighting conditions were significantly taller and had more leaves than those grown under HPS lighting. There was no significant effect of the lighting type on the seedling height or number of leaves in the 'Palermo' cultivar. On the other hand, 'Aifos' seedlings were shorter than the 'Palermo' plants, while those grown under HPS lighting also had fewer leaves (Figures 1 and 2).

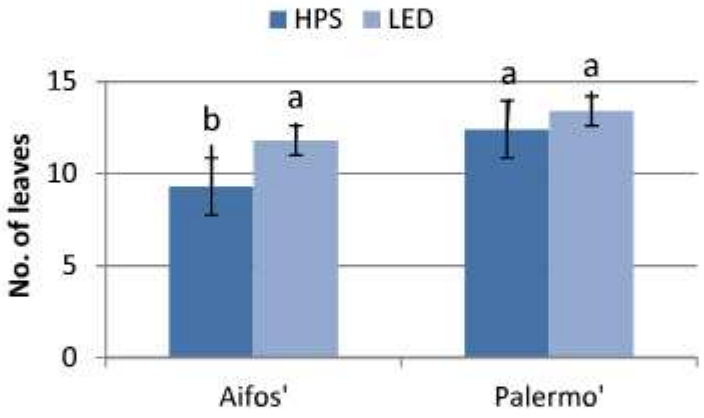

Figure 1. Effects of supplementary lighting with HPS and LED lamps on the numbers of leaves of pepper seedlings, depending on the cultivar. The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The bars represent means ± SE (Standard Error).

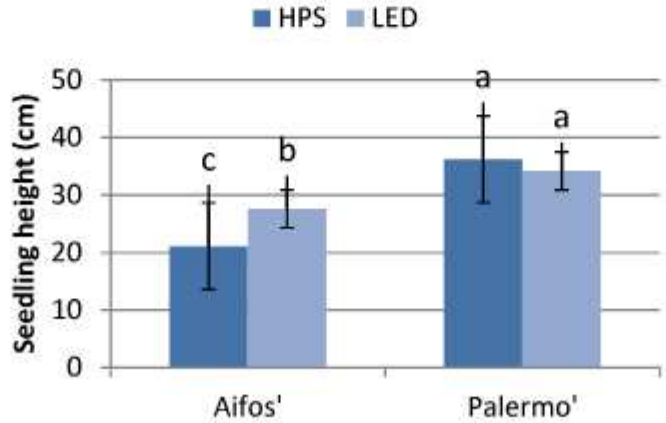

Figure 2. Effects of supplementary lighting with HPS and LED lamps on seedling height, depending on the cultivar. The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The bars represent means ± SE (Standard Error).

2.2. Photosynthetic Efficiency

SPAD index values are proportional to the amount of chlorophyll contained in a leaf [28]. The seedlings of both pepper cultivars grown under LED lamps were characterized by higher chlorophyll contents in the leaves than those grown under HPS lamps. The leaves of 'Aifos' plants were characterized by higher SPAD index values than those of 'Palermo' plants (Figure 3). This may have been because the spectra of LED lamps, which emit red and blue light, are more similar to the absorption spectra of chlorophyll molecules than those of HPS [29–31].

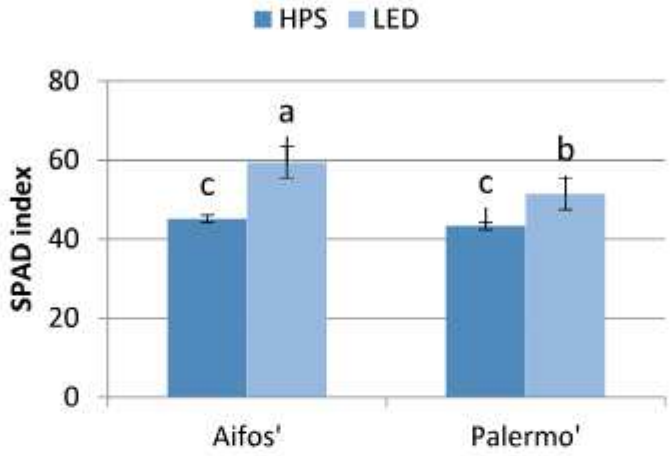

Figure 3. Effects of supplementary lighting with HPS and LED lamps on the chlorophyll index values in pepper leaves, depending on the cultivar (averages of four measurement dates). The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The bars represent means ± SE (Standard Error).

Inadequate lighting (the use of inappropriate supplemental lighting) can lead to decreases in photosynthesis intensity, and consequently in growth and yield. Signals of chlorophyll *a* fluorescence (ChlF) can be used to study the photosynthetic performance under varying growth conditions [23,32].

The values of chlorophyll *a* fluorescence parameters such as photosystem II (PSII), actual quantum efficiency (φPSII), and PSII maximum photochemical efficiency (Fv/Fm) values in pepper seedlings were significantly lower in pepper plants grown under LED lighting as compared to those grown under HPS (Table 1). This suggests that these parameters were not sensitive to light spectrum changes in our experiment. This could be explained by the results found in the stuides by Kalaji et al. [33,34], where it was reported that these two above-mentioned parameters are not sensitive to unfavorable growth conditions (stressors). We believe that more advanced measurement protocols should be applied in future experiments, e.g., the application of rapid light curves [35].

Table 1. Effects of supplementary lighting with sodium and LED lamps on the photosynthetic activity of pepper seedling leaves according to the cultivar (averages of four measurement dates).

Chlorophyll Fluorescence Parameters	Cultivar	HPS	LED
φPSII	'Aifos'	0.78 a	0.74 bc
	'Palermo'	0.77 ab	0.72 c
	Average	0.77 A	0.73 B
Fv/Fm	'Aifos'	0.83 a	0.81 b
	'Palermo'	0.82 ab	0.80 c
	Average	0.82 A	0.80 B
PI inst.	'Aifos'	4.41 bc	6.41 a (45%)
	'Palermo'	3.81 c	4.97 b (30%)
	Average	4.11 B	5.70 A (38.7%)
DIo/RC	'Aifos'	0.21 ab	0.19 b
	'Palermo'	0.23 a	0.23 a
	Average	0.22 A	0.20 A
Area	'Aifos'	773,108 ab	814,715 a
	'Palermo'	725,554 ab	697,771 b
	Average	749,331 A	756,243 A

The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The small letters indicate the differences in the interaction of cultivar x lamp type, the capital letters indicate the differences in the lamp type.

Generally, the performance index (PI) is a very sensitive parameter, providing quantitative information about the overall condition of plants and their vitality. Kalaji et al. [32] revealed that the PI is a very good biophysical indicator when measured under stress conditions. The use of integrative parameters such as the performance index (PI) can be more useful than a complex of specific biophysical parameters that require a deeper understanding of photochemical processes in order to interpret the data correctly. The Performance $\text{Index}_{\text{Instruments}}$ (PI) is taken directly from the instrument and almost exactly corresponds to the Performance $\text{Index}_{\text{Absorption}}$ (PI_{Abs}). If, however, it is recalculated by selecting Fo as F $50_{\mu s}$, then PI_{Abs} = PI inst. (where Fo is the minimal chlorophyll fluorescence at time zero or 50 μs). In our work, changes of this parameter showed that the application of LEDs caused significant and positive effects on the photosynthetic efficiency levels of both tested cultivars (increases of ca. 45% and 30% for 'Aifos' and 'Palermo' cultivars, respectively) (Table 1). Better photosynthetic efficiency was also partially shown in the case of cv. 'Aifos', as shown by the positive trend that LEDs caused in the *Area* parameter, indicating an increase in the size of the reduced plastoquinone pool. In the same cultivar, a trend of less heat dissipation was also observed (lower DIo/RC). The above results suggest that LEDs increase the photosynthetic efficiency of plants by enhancing the light absorption, trapping, and electron transport and reducing primary acceptors of photosystem I. Additionally, as it can minimize the loss of absorbed light energy (less heat dissipation), the use of light quanta is more efficient.

Hoffmann et al. [31] showed that blue light can initiate plant responses and induce morphological and physiological changes in leaf characteristics, which also develop under high irradiance conditions; however, further investigations are required to prove the physiological mechanisms of the differences induced by different supplementary lighting systems.

2.3. *Leaf Characteristic*

The cultivars of pepper showed very similar leaf anatomies under HPS lighting, while LED lighting caused changes in leaf anatomy (Figure 4). Regardless of the cultivar and lighting, the leaves show a well-developed palisade and a spongy mesophyll. The calcium oxalate crystals were observed in vacuoles of mesophyll cells in all treatments (Figure 4).

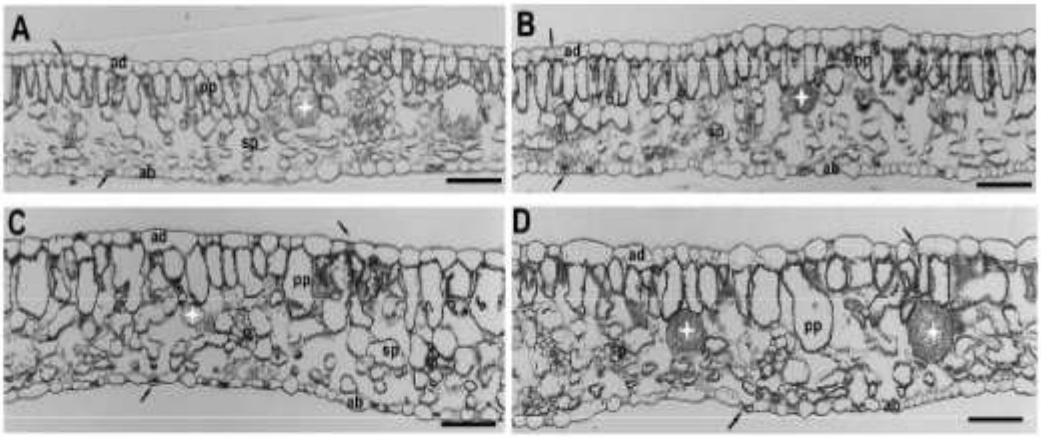

Figure 4. Effects of different lighting systems on the anatomies of the Capsicum leaves (cv. 'Aifos' or 'Palermo'): (**A**) 'Aifos' HPS; (**B**) 'Palermo' HPS; (**C**) 'Aifos' LED; (**D**) 'Palermo' LED. Abbreviations: ad—adaxial epidermis; ab—abaxial epidermis; pp—palisade parenchyma; sp—spongy parenchyma; stomata—black arrow; calcium oxalate crystals—asterisk. Scale bar—100 μm.

The microscopic measurements revealed significant variations in the anatomy of the analyzed leaves (Table 2, Figure 4). The leaf thickness and cell size were significantly different between light treatments. Plants grown under LED lighting (LED) had thicker leaves than those grown under sodium lighting (HPS), with the thicknesses ranging from 264.05 μm to 276.05 μm for LED and from 193.05 μm to 195.09 μm for HPS, respectively. The changes in leaf thickness in the LED treatment were mainly due to changes in the cell size of the palisade parenchyma cells and the thickness of the spongy mesophyll, since the number of cell layers was not significantly affected by the light treatment. Similar enhanced leaf and palisade parenchyma thickness values under LED lighting conditions were observed in ornamental plants [22,32]. Reduced or no blue light results in reduced leaf thickness, while elevated blue to red levels increase the palisade and spongy mesophyll thicknesses [22]. According to Shengxin et al. [36], thicker leaves and a thicker palisade parenchyma layer result in better light absorption, and consequently higher photosynthetic yield. The LED-treated leaves showed a greater number of stomata in the adaxial epidermis compared to the HPS leaf surface (Table 2, Figure 4). A higher stomatal density, which regulates CO_2 flux to the mesophyll, might also improve the photosynthetic efficiency [37].

Table 2. Analyzed leaf traits depending on the type of supplementary lighting and cultivar.

Analyzed Traits	'Aifos' HPS	'Palermo' HPS	'Aifos' LED	'Palermo' LED
Total thickness (μm)	195.09 ± 13.4 b	193.05 ± 12.0 b	264.05 ± 8.9 a	276.74 ± 13.2 a
Number of palisade cell layers	1	1	1	1
Length of palisade parenchyma cells (μm)	59.82 ± 6.3 b	63.44 ± 7.2 b	91.18 ± 5.2 a	109.14 ± 11.1 a
Width of palisade parenchyma cells (μm)	27 ± 0.1 b	22.79 ± 0.4 b	34.25 ± 12.2 b	75.03 ± 19.2 a
Number of spongy cell layers	3	3	3–4	3–4
Thickness of spongy layer (μm)	129.02 ± 6.2 b	122.5 ± 4.3 b	180.02 ± 12.4 a	160.6 ± 2.6 a
Length of spongy parenchyma cells (μm)	65.25 ± 5.5 b	73.77 ± 8 ab	40.45 ± 25.0 b	103.66 ± 3.2 a

Table 2. *Cont.*

Analyzed Traits	'Aifos' HPS	'Palermo' HPS	'Aifos' LED	'Palermo' LED
Width of spongy parenchyma cells (μm)	31.03 ± 5.2 b	39.23 ± 8.36 b	57.61 ± 4.7 a	36.64 ± 6.3 b
Stomata number in adaxial epidermis	2 ± 0.5 a	0 ± 0.0 b	3 ± 0.6 a	3 ± 0.6 a
Stomata number in abaxial epidermis	4 ± 0.6 b	4 ± 0.6 b	4 ± 0.0 b	6 ± 1.1 a

Mean values marked with the same letters are not significantly different according to Tukey's HSD test at $\alpha = 0.05$. Values are means ± SD of 3 plants per treatment.

2.4. Mesophyll Parenchyma and Chloroplast Ultrastructure of Pepper Leaves

The mesophyll parenchyma of the pepper plants showed significant differences with different light treatments, although significant differences were not observed between the cultivars (Figure 5). Mesophyll cells under LED lighting contained larger chloroplasts and more chloroplasts rich in starch grains than those growing under sodium lamps. The shape of chloroplasts grown under LED lighting was similar to that under HPS light; however, the chloroplasts in plants grown under LED lighting were enlarged and possessed thicker grana than those grown under sodium light treatment. Moreover, in chloroplasts in LED-grown leaves, a few small plastoglobules were observed. In this study, the denser arrangement of thylakoids in plants grown under LED lighting may have contributed to the increase in chlorophyll *a* content, since this molecule is crucial for grana formation and stabilization [38–40].

As the chlorophyll content directly influences the photosynthetic potential [41], the increased number of chloroplasts with thicker grana in the mesophyll of LED-grown leaves may have contributed to the higher photosynthetic performance of this treatment. This is consistent with the results of a study on cucumber leaves and cotton leaves grown under blue LED lighting, which also showed a greater number of chloroplasts and increased integrity of the chloroplast ultrastructure, with a clearly visible lamellar structure [42,43]. During the LED response, modifications of the thylakoid membrane system in pepper plants were accompanied by starch accumulation, which may indicate a low level of stress in those plants or indicate higher photosynthetic activity. The increased daily starch turnover resulting from induced activity of α- and β-amylases (the main starch-degrading enzymes) was unequivocally related to stress conditions [44]. Additionally, the appearance of small plastoglobules in chloroplasts under LED lighting might indicate a low level of oxidative stress, since an increased number of these structures in chloroplasts is connected with reactive oxygen species accumulation [45].

2.5. Fluorescence of Chlorophyll and Carotenoids

Images in the first column (Figure 6) show the distribution of chlorophyll (false red color) and carotenoid (false green color) fluorescence signals in the upper section of the chloroplasts. The red spots probably represent granum structures [41]. Independently of the cultivar and source of additional light, chlorophyll and carotenoid signals occur in the grana, as well as between them. It seems that under LED lighting conditions, the fluorescent signals for chlorophyll and carotenoids are stronger than under HPS sodium lighting conditions, as can be seen by comparing the images in the second column.

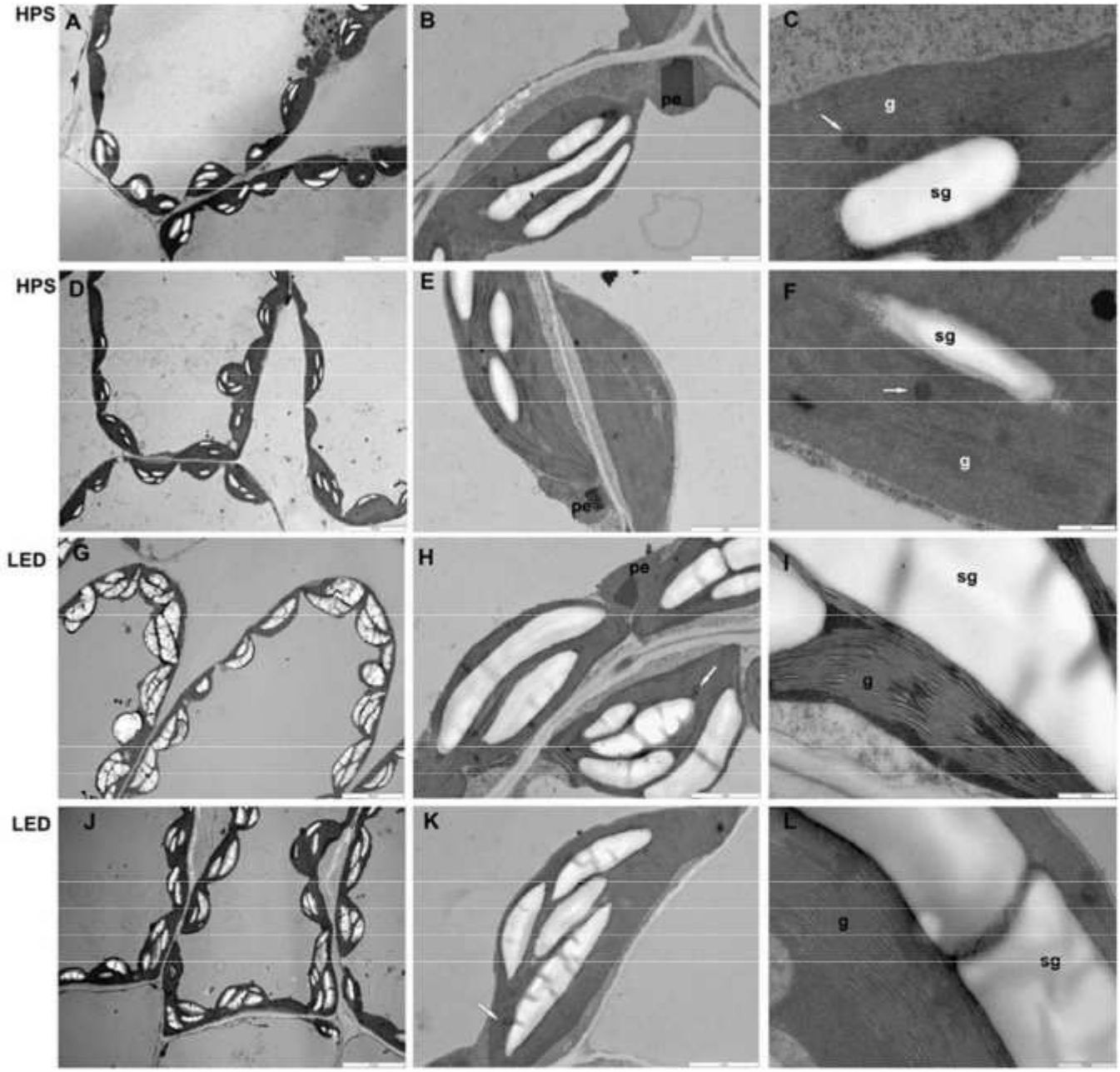

Figure 5. The effects of different lighting systems on the mesophyll parenchyma and chloroplast ultrastructures in pepper leaves (cv. 'Aifos' or 'Palermo'): (**A**–**C**) 'Aifos' HPS; (**D**–**F**) 'Palermo' HPS; (**G**–**I**) 'Aifos' LED; (**J**–**L**) 'Palermo' LED. Abbreviations: pe—peroxisome; white arrow—plastoglobule; sg—starch granule; g—granum; HPS—sodium lamp; LED—light-emitting lamp. (**A**,**B**,**D**,**E**,**G**,**H**,**J**,**K**) Scale bar—2 µm. (**C**,**F**,**I**,**L**) Scale bar—0.5 µm.

The fluorescence of chlorophyll always exceeds that of the carotenoids when starting from the 'bottom' of chloroplasts and moving to the 'top' (Figure 6, line graphs). The bottom of the chloroplast is defined as its site (often flat), which is directed toward the cell wall, while the top (usually convex shape) is directed toward the central vacuole (Figure 6). Compared to LED lighting, the increase in chlorophyll fluorescence was significantly greater than for carotenoids under HPS lighting conditions. Several studies have shown the positive effect of blue light on chlorophyll content [46–49].

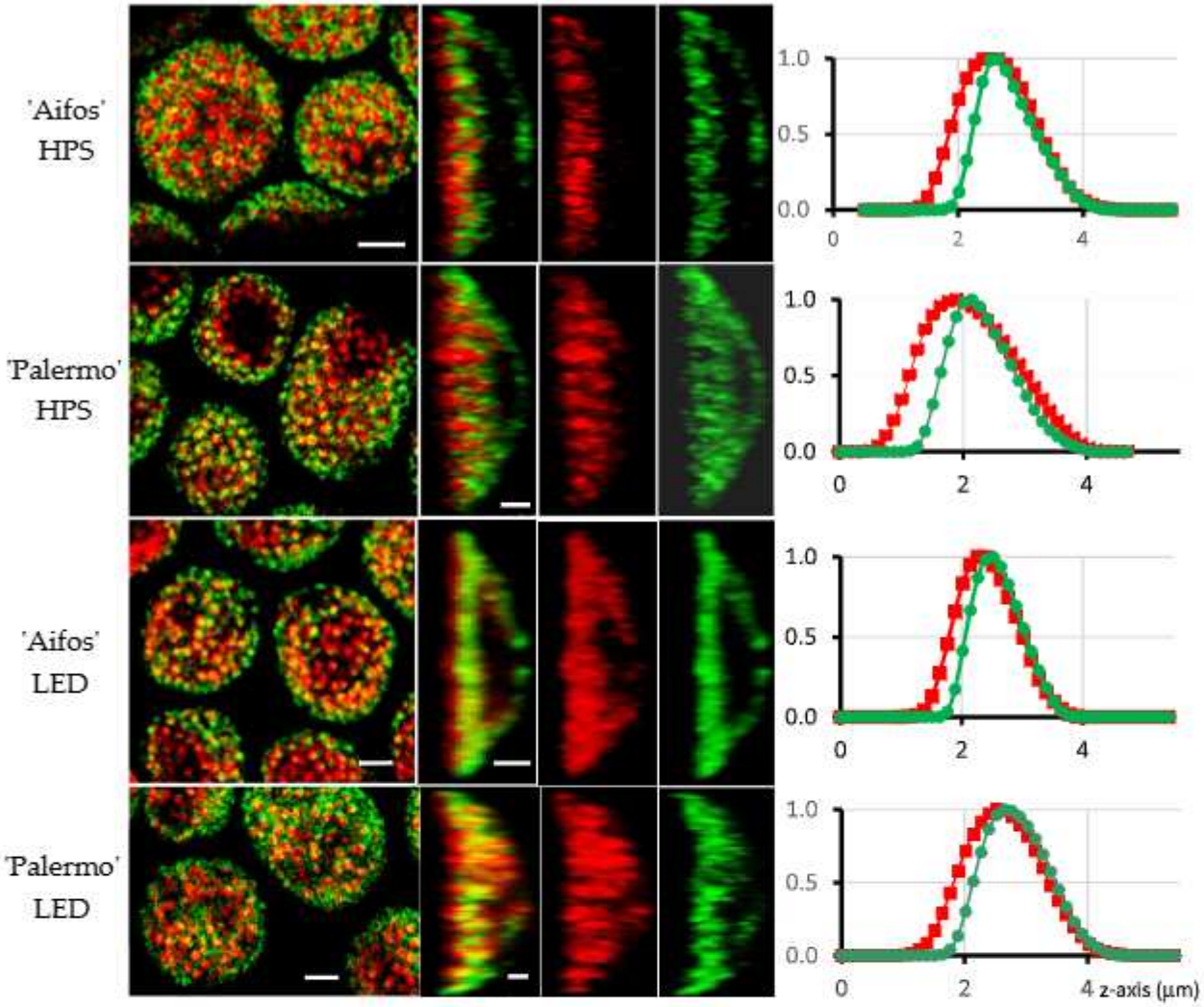

Figure 6. Fluorescence of chlorophyll and carotenoids (false red and green colours, respectively) in chloroplasts of pepper leaves (cv. 'Aifos' or 'Palermo'). Sun light was supplemented with sodium lamps (HPS) or diode (LED) actinic light. First (left) column: fluorescence of chlorophyll and carotenoids (merged images) in single median optical sections (x:y mode of scanning) through groups of chloroplasts. Notice that grana structures are represented by red discs. The second column represents median optical sections along z-axis of chloroplasts: fluorescence of chlorophyll and carotenoids—merged images. Last two columns: fluorescence of chlorophyll or carotenoids is shown separately. Line graphs show changes in fluorescence intensity (*y*-axis, normalized) of chlorophyll (red line) and carotenoids (green line) along z-axis (µm) of chloroplasts starting from their bottom side (value 0) to the top (value 4) of the organelles. Notice that fluorescence of chlorophyll always exceeds that of carotenoids when starting from the bottom of chloroplasts to their top. Abbreviations: star—starch granule. Scale bars—2 µm.

We found that for LED lighting, red and green channels overlap better (see Figure 6, second column). As a result, yellow light appears, indicating better colocalization of chlorophylls and carotenoids. In addition, the chlorophyll distribution (red channel) is more evenly balanced within chloroplasts grown under LED lighting. Changes in the distribution of chlorophylls and carotenoids under HPS or LED supplementary lighting may reflect adaptation of the photosynthetic apparatus toward different light spectra. These phenomena require further investigation, as the greenhouse environment may reduce the effects of specific spectra on the distribution of the photosynthetic pigments within chloroplasts.

3. Materials and Methods

3.1. Plant Materials and Growth Conditions

This study was conducted in a greenhouse located 21° E, 51°15′ N during the winter cycles of 2018 and 2020. The cultivation of bell pepper cultivars with fleshy, block-type, and red fruit is of the greatest importance in the cultivation of peppers under covers, although cultivars with very sweet and elongated fruit are also becoming increasingly important. Two red-fruited, sweet pepper cultivars were studied, namely 'Aifos F1′ (Bayer Crop Science—Seminis), with block-type fruit and soft flesh, and 'Palermo F1′ (Rijk Zwaan), with elongated fruit and thinner flesh. Two-week-old pepper seedlings were planted into rockwool cubes on 5 December in both years. Half of the plants were supplemented with light from HPS lamps (Gavita GAN 400 W Figure S1 in the Supplementary Materials) and the other half with Green Power LED lamps (DR/W–LB, 195 W, Figure S2 in the Supplementary Materials) (Philips). The LED lamp characteristics were as follows: 87.5% red light in the wavelength range of 630 to 660 nm, with the highest proportion at 660 nm, and 12.5% blue light in the range of 440 to 460 nm. The daily light exposure equalled 16 h. In the experimental greenhouse where pepper seedlings were grown, the PAR (photosynthetically active radiation) light level was ~170 µmol m^{-2} s^{-1} (PPFD—photosynthetic photon flux density). The lighting lamps switched off automatically when the solar radiation was higher than 250 W m^{-2}. The average daily solar radiation during the seedling growth period was around 186.9 J cm^{-2}. In the growing compartment of the greenhouse, the temperature was maintained at 22 °C during the day and 20 °C at night, with RH kept over a range of approximately 60–70% and CO_2 at an average concentration of 800 ppm. The nutrient solution for the supply of seedlings contained the following components in mg·dm^{-3}: N–NO_3-195, P-57, K-273, Mg-47, Ca-187, Fe-2, Mn-0.6, B-0.3, Cu-0.15, Zn-0.3, Mo-0.05. The average pH and EC were respectively about 5.5 and 2.8 dS m^{-1}. The study adopted a completely randomized design. Equally sized plots containing 10 plants of each cultivar were drawn in the experimental compartment, with three replications of 10 plants in each combination. The test material consisted of 120 plants, each in identical rockwool cubes.

3.2. Morphological Characteristics

Measurements of plant height and leaf number per plant were taken weekly on five randomly selected plants from each repetition, after 7, 14, 21, and 28 days of cultivation. The plant height and leaf number results are given for each plant based on averages from the measurements taken.

3.3. Chlorophyll Fluorescence Analysis

Every week, the relative contents of chlorophyll a + b in the fully mature leaves were measured (using a Minolta SPAD-502 apparatus). Measurements were taken from 5 randomly selected plants from the combinations. The results were averaged from the five-unit measurements taken from the examined leaves. The chosen chlorophyll fluorescence was measured under ambient light and after dark adaptation with special leaf clips on the same leaves (spots) of pepper plants using the following equipment:

A. FMS-2 Field-Portable Pulse-Modulated Chlorophyll Fluorescence Monitoring System (Hansatech Instruments Ltd., King's Lynn, Norfolk, England). Measurements were taken under ambient light. The saturating light source used was a built-in halogen lamp. The pulse intensity was equal to 8000 µmol·m^{-2} s^{-1} and the pulse duration was 1 s. The following parameters were measured: Fs—steady-state fluorescence yield; Fm′—light-adapted fluorescence maximum; ΦPSII—quantum efficiency of PSII;

B. A Pocket PEA fluorimeter (Hansatech Instruments Ltd., King's Lynn, Norfolk, England) was used to measure prompt fluorescence, obtaining measurements of the maximum efficiency of the plant's photosynthetic rate after 30 min of dark adaption of the leaves (using special clips). The following parameters were analyzed, where

Fv/Fm is the maximum efficiency of the PSII photochemistry (Fv/Fm) and the performance index (PI) is displayed as PI_{Abs} or PI_{Ins}. The latter is calculated on the basis of the following formula:

$$PI_{ABS} = \frac{RC}{ABS} \cdot \frac{\phi_{po}}{1-\phi_{po}} \cdot \frac{\psi_o}{1-\psi_o} \quad (1)$$

where RC is the reaction center; ABS is the absorption; $\phi_{po} = F_V/F_M$, which is the maximum quantum yield of the primary photochemical reactions (at $t = 0$), which proves the probability of trapping the energy of absorbed photons (i.e., excitons migrating along an antenna) by PSII reaction centers; ψ_o is the probability (at $t = 0$) of electron transport outside Q_A^-, i.e., that an RC trapped exciton moves an electron into the electron transport chain outside Q_A^-.

3.4. Light and Transmission Electron Microscope

For the anatomical observations, after the 28th day of cultivation, ten fragments from 10 fully expanded leaves (counting from the tip) collected from 3 seedlings of pepper from two cultivars grown in the greenhouses under different lighting systems were fixed for 3 h in Karnovsky [50] medium, then afterwards treated with 1% osmium tetraoxide for 3 h, dehydrated in an ethanol series containing propylene oxide and embedded in epoxy resin (Serva, Heidelberg, Germany). After being embedded in resin, leaf samples were then cut on a Jung microtome (RM 2065) into semithin sections (3 µm) and stained with 1% toluidine blue prior to examination under a light microscope (Olympus-Provis). Taking five leaves for each ecotype, the total thickness, number, thicknesses of the palisade and spongy cell layers, sizes of the parenchyma and spongy cells, and stomata number per 600 µm of leaf surface were measured with the Olympus-Provis cellSens Standard program at 10× magnification. Statistical analysis was performed in STATGRAPHICS Plus 5.1. For parametric tests, ANOVA was used. For chloroplast analysis, ultra-thin (80 nm thick) leaf sections were taken from epoxy-resin-embedded samples using a Leica UCT ultramicrotome (Leica Microsystems, Nussloch, Germany) and collected on formvar-coated grids, which were short-stained with uranyl acetate and lead citrate and examined under an FEI 268D 'Morgagni' (FEI Comp., Hillsboro, OR, USA) transmission electron microscope (TEM) equipped with a 10 MPix Olympus-SIS 'Morada' digital camera (Olympus-SIS, Münster, Germany). Digital images were saved as jpg files and were adjusted using Photoshop CS 8.0 (Adobe Systems, San Francisco, CA, USA) software using non-destructive tools (contrast or levels) if necessary.

3.5. Confocal Laser Scanning Microscope

A confocal laser scanning microscope (Leica TCS SP5II, Leica Microsystems CMS, Wetzlar, Germany) was used to examine groups of chloroplasts located in palisade cells of the mesophyll of pepper leaves. Fluorescence imaging of chlorophyll and carotenoids was performed on freshly prepared cross-sections through the leaf, which were prepared using razor blades. Tiny slices were embedded in distilled water. Carotenoid and chlorophyll fluorescence was excited at 488/633 nm and recorded at 520–580/660–705 nm at room temperature. Sequential scanning was performed in order to avoid bleed-through fluorescent signals between channels. In total, 29 images were acquired at intervals of 0.18 µm along the *z*-axis. All image series were deconvoluted to remove background noise and improve image quality. To show the distribution of the chlorophyll and carotenoids, red and green colors were digitally separated. The intensity levels of chlorophyll and carotenoid fluorescence were recorded separately in the central parts (the region of interest was a circle measuring 1 µm in dimeter) of chloroplasts while avoiding the starch granules.

3.6. Statistical Analysis

Statistical analysis was performed using two-way analysis of variance (ANOVA). Detailed comparison of the means was performed using Tukey's test at a significance level of $\alpha = 0.05$.

4. Conclusions

Regarding pepper seedling growth, our study revealed that LEDs delivered a better blue-to-red (R/B) ratio than HPS lamps. This better supplemental lighting (LEDs) indirectly enhanced plant growth by increasing the height of the seedlings and the number of leaves; however, we found that this effect is cultivar-dependent.

We believe that behind the above-mentioned growth enhancement were many anatomical and physiological changes that resulted in better photosynthetic performance and biomass production, such as thicker leaves, longer palisade parenchyma cells, larger mesophyll cells, increased chloroplast and chlorophyll contents, and better photosynthetic efficiency.

We recommend the use of the performance index (PI) parameter to monitor the physiological statuses of plants while testing new supplemental lighting. Further studies should investigate the responses of plants to sunlight alone and also to a combination of sunlight and different artificial light sources with different R/B ratios.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/plants10101975/s1, Figure S1: The spectrum of HPS lamps measured during cultivation with the Gigahertz-Optik apparatus, Figure S2: The spectrum of LED lamps measured during cultivation with the Gigahertz-Optik apparatus.

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References

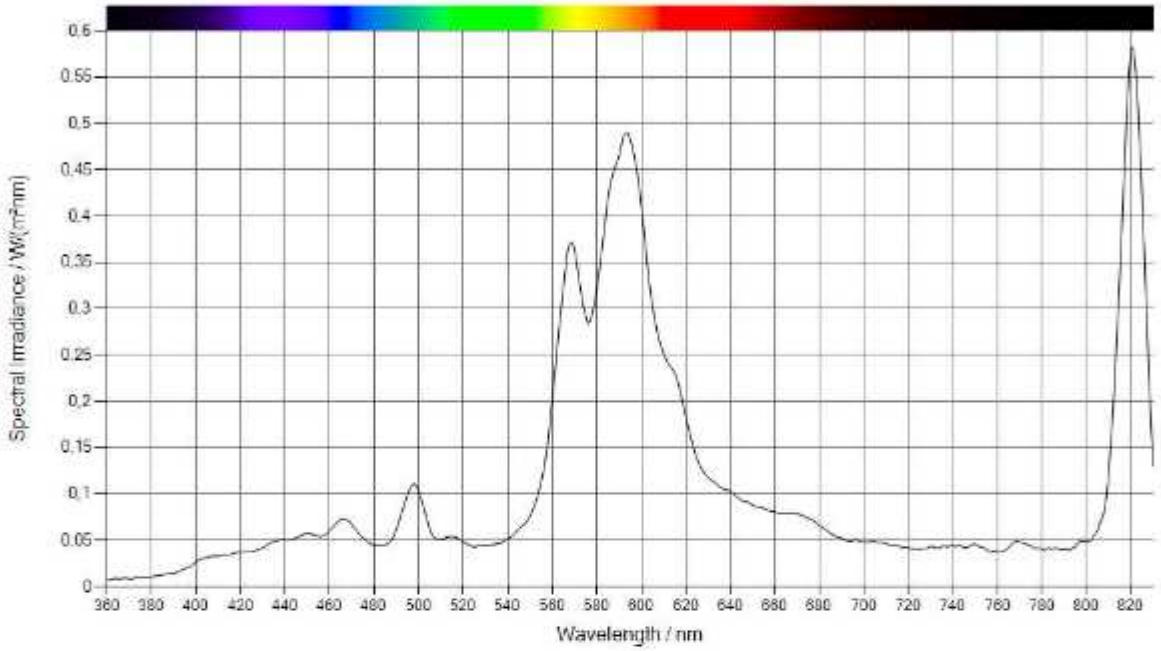
1. Massa, G.D.; Kim, H.-H.; Wheeler, R.M.; Mitchell, C.A. Plant productivity in response to LED lighting. *HortScience* **2008**, *43*, 1951–1956. [CrossRef]
2. Liu, X.Y.; Guo, S.R.; Xu, Z.G.; Jiao, X.L.; Takafumi, T. Regulation of chloroplast ultrastructure, cross-section anatomy of leaves and morphology of stomata of cherry tomato by different light irradiations of LEDs. *HortScience* **2011**, *46*, 217–221. [CrossRef]
3. Liu, X.Y.; Chang, T.T.; Guo, S.R.; Xu, Z.G.; Li, J. Effect of different light quality of LED on growth and photosynthetic character in cherry tomato seedling. *Acta Hortic.* **2011**, *907*, 325–330. [CrossRef]
4. Lau, O.S.; Deng, X.W. Plant hormone signaling lightens up: Integrators of light and hormones. *Curr. Opin. Plant Biol.* **2010**, *13*, 571–577. [CrossRef] [PubMed]
5. Van Ieperen, W. Plant morphological and developmental responses to light quality in a horticultural context. *VII Int. Symp. Light Hortic. Syst.* **2012**, *956*, 131–139. [CrossRef]
6. Ballaré, C.L. Light regulation of plant defense. *Plant Biol.* **2014**, *65*, 335. [CrossRef] [PubMed]
7. Hernández, R.; Kubota, C. Tomato seedling growth and morphological responses to supplemental LED lighting red: Blue ratios under varied daily solar light integrals. *Acta Hortic.* **2012**, *956*, 187–194. [CrossRef]
8. Wenke, L. Light environmental management for artificial protected horticulture. *Agrotechnology* **2012**, *1*, 101. [CrossRef]
9. Brazaitytė, A.; Kasiulevičiūtė, A. The effects of HPS lamp supplementation with blue light-emitting diodes on the growth of two tomato hybrid transplants. *Rural. Dev.* **2013**, *6*, 49–53.

10. Marcelis, L.; Costa, J.M.; Heuvelink, E. Achieving sustainable greenhouse production: Present status, recent advances and future developments. In *Achieving Sustainable Greenhouse Cultivation*, 1st ed.; Marcelis, L., Heuvelink, E., Eds.; Burleigh Dodds Science Publishing Limited: Sawston, UK, 2019; pp. 1–14. [CrossRef]
11. Viršilė, A.; Olle, M.; Duchovskis, P. LED lighting in horticulture. In *Light Emitting Diodes for Agriculture*; Dutta Gupta, S., Ed.; Springer Nature Singapore: Singapore, 2017; pp. 113–147.
12. Wheeler, R.M. A historical background of plant lighting: An introduction to the workshop. *HortScience* **2008**, *43*, 1942–1943. [CrossRef]
13. Randall, W.C.; Lopez, R.G. Comparison of supplemental lighting from high-pressure sodium lamps and light-emitting diodes during bedding plant seedling production. *HortScience* **2014**, *49*, 589–595. [CrossRef]
14. Brazaitytė, A.; Duchovskis, P.; Urbonavičiūtė, A.; Samuolienė, G.; Jankauskienė, J.; Sakalauskaitė, J.; Šabajevienė, G.; Sirtautas, R.; Novičkovas, A. The effect of light-emitting diodes lighting on the growth of tomato transplants. *Zemdirbyste-Agriculture* **2010**, *97*, 89–98.
15. Kowalczyk, K.; Gajc-Wolska, J.; Bujalski, D.; Mirgos, M.; Niedzińska, M.; Mazur, K.; Żołnierczyk, P.; Szatkowski, D.; Cichoń, M.; Łęczycka, N. The effect of supplemental assimilation lighting with HPS and LED lamps on the cucumber yielding and fruit quality in autumn crop. *Acta Sci. Pol.* **2018**, *17*, 193–200. [CrossRef]
16. Bugbee, B. Economics of LED lighting. In *Light Emitting Diodes for Agriculture*; Dutta Gupta, S., Ed.; Springer Nature Singapore: Singapore, 2017; pp. 81–99.
17. Pattison, P.M.; Hansen, M.; Tsao, J.Y. LED lighting efficacy: Status and directions. *Comptes Rendus Phys.* **2018**, *19*, 134–145. [CrossRef]
18. Runkle, E. Supplemental lighting guidelines for young plants. *Greenh. Prod. News* **2010**, *10*, 50. [CrossRef]
19. Kalaitzoglou, P.; van Ieperen, W.; Harbinson, J.; van der Meer, M.; Martinakos, S.; Weerheim, K.; Nicole, C.C.S.; Marcelis, L.F.M. Effects of continuous or end-of-day far-red light on tomato plant growth, morphology, light absorption and fruit production. *Front. Plant Sci.* **2019**, *10*, 322. [CrossRef]
20. Bagdonavičienė, A.; Brazaitytė, A.; Viršilė, A.; Samuolienė, G.; Jankauskienė, J.; Sirtautas, R.; Sakalauskienė, S.; Miliauskienė, J.; Maročkienė, N.; Duchovskis, P. Cultivation of sweet pepper (*Capsicum annuum* L.) transplants under high pressure sodium lamps supplemented by light-emitting diodes of various wavelengths. *Acta Sci. Pol. Hortorum Cultus* **2015**, *14*, 3–14.
21. Boardman, N.K. Comparative photosynthesis of sun and shade plants. *Annu. Rev. Plant Physiol.* **1977**, *28*, 355–377. [CrossRef]
22. Zheng, L.; Van Labeke, M.C. Long-term effects of red- and bluelight emitting diodes on leaf anatomy and photosynthetic efficiency of three ornamental pot plants. *Front. Plant Sci.* **2017**, *8*, 1–12. [CrossRef]
23. Särkkä, L.E.; Jokinen, K.; Ottosen, C.-O.; Kaukoranta, T. Effects of HPS and LED lighting on cucumber leaf photosynthesis, light quality penetration and temperature in the canopy, plant morphology and yield. *Agric. Food Sci.* **2017**, *26*, 101–109. [CrossRef]
24. Ouzounis, T.; Rosenqvist, E.; Ottosen, C.-O. Spectral Effects of Artificial Light on Plant Physiology and Secondary Metabolism: A Review. *Hortscience* **2015**, *50*, 1128–1135. [CrossRef]
25. Bramley, P.M. Regulation of carotenoid formation during tomato fruit ripening and development. *J. Exp. Bot.* **2002**, *53*, 2107–2113. [CrossRef]
26. Dannehl, D.; Schwend, T.; Veit, D.; Schmidt, U. Increase of Yield, Lycopene, and Lutein Content in Tomatoes Grown Under Continuous PAR Spectrum LED Lighting. *Front. Plant Sci.* **2021**, *12*, 611236. [CrossRef] [PubMed]
27. Li, Y.; Xin, G.; Liu, C.; Shi, Q.; Yang, F.; Wei, M. Effects of red and blue light on leaf anatomy, CO_2 assimilation and the photosynthetic electron transport capacity of sweet pepper (*Capsicum annuum* L.) seedlings. *BMC Plant Biol.* **2020**, *20*, 318. [CrossRef] [PubMed]
28. Baker, N.R.; Rosenqvist, E. Applications of chlorophyll fluorescence can improve crop production strategies: An examination of future possibilities. *J. Exp. Bot.* **2004**, *55*, 1607–1621. [CrossRef]
29. Menard, C.; Dorais, M.; Hovi, T.; Gosselin, A. Developmental and physiological responses of tomato and cucumber to additional blue light. *Acta Hort.* **2006**, *711*, 291–296. [CrossRef]
30. Brazaitytė, A.; Duchovskis, P.; Urbonavičiūtė, A.; Samuolienė, G.; Jankauskienė, J.; Kasiulevičiūtė-Bonakėrė, A.; Bliznikas, Z.; Novičkovas, A.; Breivė, K.; Žukauskas, A. The effect of light-emitting diodes lighting on cucumber transplants and after-effect on yield. *Zemdirbyste–Agriculture* **2009**, *96*, 102–118.
31. Hoffmann, A.M.; Noga, G.; Hunsche, M. High blue light improves acclimation and photosynthetic recovery of pepper plants exposed to UV stress. *Environ. Exp. Bot.* **2015**, *109*, 254–263. [CrossRef]
32. Kalaji, H.M.; Jajoo, A.; Oukarroum, A.; Brestic, M.; Zivcak, M.; Samborska, I.A.; Cetner, M.D.; Lukasik, I.; Goltsev, V.; Ladle, R.J. Chlorophyll a fluorescence as a tool to monitor physiological status of plants under abiotic stress conditions. *Acta Physiol. Plant.* **2016**, *38*, 102. [CrossRef]
33. Kalaji, H.M.; Schansker, G.; Ladle, R.J.; Goltsev, V.; Bosa, K.; Allakhverdiev, S.I.; Brestic, M.; Bussotti, F.; Calatayud, A.; Dąbrowski, P.; et al. Frequently asked questions about in vivo chlorophyll fluorescence: Practical issues. *Photosynth. Res.* **2014**, *122*, 121–158. [CrossRef] [PubMed]
34. Kalaji, H.M.; Schansker, G.; Brestic, M.; Bussotti, F.; Calatayud, A.; Ferroni, L.; Goltsev, V.; Guidi, L.; Jajoo, A.; Li, P.; et al. Frequently asked questions about chlorophyll fluorescence, the sequel. *Photosynth. Res.* **2017**, *132*, 13–66. [CrossRef]
35. Yousef, A.F.; Ali, M.M.; Rizwan, H.M.; Ahmed, M.A.A.; Ali, W.M.; Kalaji, H.M.; Elsheery, N.; Wróbel, J.; Xu, Y.; Chen, F. Effects of light spectrum on morphophysiological traits of grafted tomato seedlings. *PLoS ONE* **2021**, *16*, e0250210. [CrossRef]

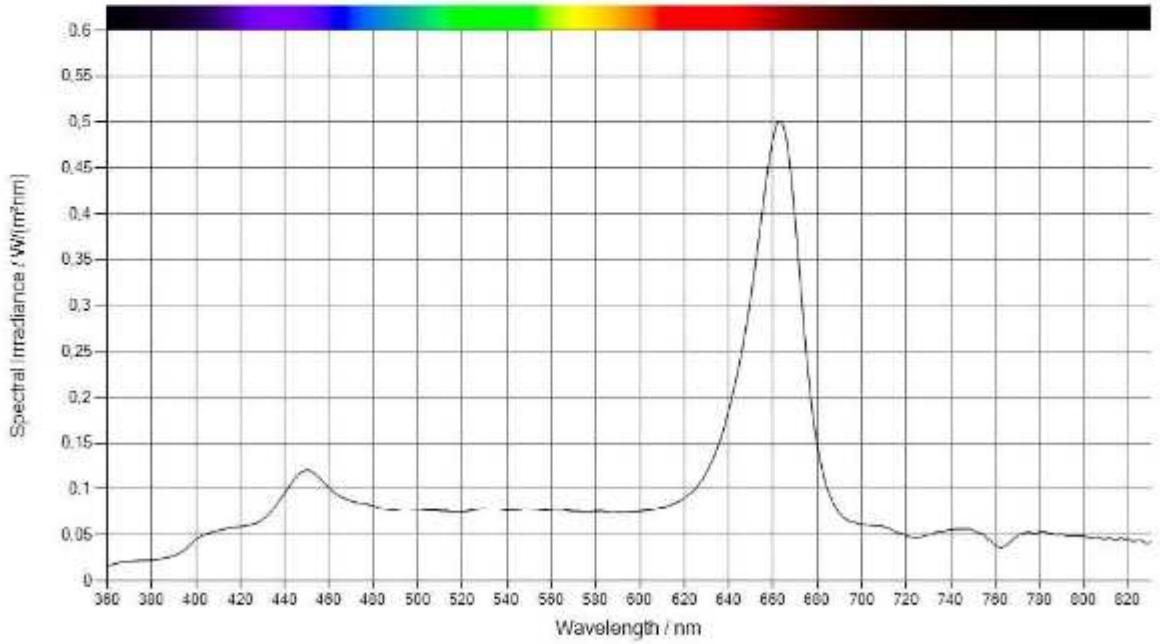
36. Shengxin, C.; Chunxia, L.; Xuyang, Y.; Song, C.; Xuelei, J.; Xiaoying, L. Morphological, photosynthetic, and physiological responses of rapeseed leaf to different combinations of red and blue lights at the rosette stage. *Front. Plant Sci.* **2016**, *7*, 1144. [CrossRef]
37. Sakoda, K.; Yamori, W.; Shimada, T.; Sugano, S.S.; Hara-Nishimura, I.; Tanaka, Y. Higher Stomatal Density Improves Photosynthetic Induction and Biomass Production in Arabidopsis Under Fluctuating Light. *Front. Plant Sci.* **2020**, *11*, 1609. [CrossRef] [PubMed]
38. Zhang, F.J.; Zhang, K.K.; Du, C.Z.; Li, J.; Xing, Y.X.; Yang, L.T.; Li, Y.R. Effect of drought stress on anatomical structure and chloroplast ultrastructure in leaves of sugarcane. *Sugar Tech* **2015**, *17*, 41–48. [CrossRef]
39. Bondada, B.R.; Syvertsen, J.P. Leaf chlorophyll, net gas exchange and chloroplast ultrastructure in citrus leaves of different nitrogen status. *Tree Physiol.* **2003**, *23*, 553–559. [CrossRef]
40. Anderson, J.M.; Goodchild, D.J.; Boardman, N.K. Composition of the photosystems and chloroplast structure in extreme shade plants. *Biochim. Biophys. Acta (BBA)-Bioenerg.* **1973**, *325*, 573–585. [CrossRef]
41. Gitelson, A.A.; Gritz, Y.; Merzlyak, M.N. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *J. Plant Physiol.* **2003**, *160*, 271–282. [CrossRef] [PubMed]
42. Wang, X.Y.; Xu, X.M.; Cui, J. The importance of blue light for leaf area expansion, development of photosynthetic apparatus, and chloroplast ultrastructure of Cucumis sativus grown under weak light. *Photosynthetica* **2014**, *53*, 213–222. [CrossRef]
43. Li, H.; Tang, C.; Xu, Z. Effects of different light quality on growth, photosynthetic characteristic and chloroplast ultrastructure of upland cotton (*Gossypium hirsutum* L.) seedlings. *Emir. J. Food Agric.* **2017**, *29*, 104–113. [CrossRef]
44. Paul, M.J.; Loos, K.; Stitt, M.; Ziegler, P. Starch-degrading enzymes during the induction of CAM in Mesembryan-themum crystallinum. *Plant Cell Environ.* **1993**, *16*, 531–538. [CrossRef]
45. Otsubo, M.; Ikoma, C.; Ueda, M.; Ishii, Y.; Tamura, N. Functional role offibrillin5 in acclimation to photooxidative stress. *Plant Cell Physiol.* **2018**, *59*, 1670–1682. [CrossRef] [PubMed]
46. Kamiya, A.; Ikegami, I.; Hase, E. Effects of light on chlorophyll formation in cultured tobacco cells, I.I. blue light effect on 5-aminolevulinic acid formation. *Plant Cell Physiol.* **1983**, *24*, 799–809. [CrossRef]
47. Sæbø, A.; Krekling, T.; Appelgren, M. Light quality affects photosynthesis and leaf anatomy of birch plantlets in vitro. *Plant Cell Tissue Organ Cult.* **1995**, *41*, 177–185. [CrossRef]
48. Holleboom, C.-P.; Walla, P.J. The back and forth of energy transfer between carotenoids and chlorophylls and its role in the regulation of light harvesting. *Photosynth. Res.* **2014**, *119*, 215–221. [CrossRef] [PubMed]
49. Darko, E.; Heydarizadeh, P.; Schoefs, B.; Sabzalian, M.R. Photosynthesis under artificial light: The shift in primary and secondary metabolism. *Philos. Trans. R. Soc. B: Biol. Sci.* **2014**, *369*. [CrossRef]
50. Karnovsky, M.J. A formaldehyde-glutaraldehyde fixative of high osmolality for use in electron-microscopy. *J. Cell Biol.* **1965**, *27*, 137A–138A.

Supplementary to :

Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems



Supplementary Figure S1. The spectrum of HPS lamps measured during cultivation with the Gigahertz-Optik apparatus



Supplementary Figure S2. The spectrum of LED lamps measured during cultivation with the Gigahertz-Optik apparatus

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Article

Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation

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Abstract: High electrical conductivity (EC) in cultivation systems with the recirculating nutrient solutions can affect plant growth and development. This study aimed to investigate the effect of salicylic acid (SA) on the selected physiological and biochemical parameters of sweet pepper (*Capsicum annum* L.) growing aeroponically at standard and high concentrations of nutritive solutions. Four experimental variants were tested: (1) plants cultivated under low EC conditions, (2) plants cultivated under low EC conditions and treated with foliar SA, (3) plants cultivated under high EC conditions, (4) plants cultivated under high EC conditions and treated with SA on leaves and roots. The obtained results revealed that exogenous SA, regardless of EC, reduced the formation of fruits with calcium deficiency symptoms. Furthermore, SA helps plants to cope with high EC nutrient stress through an increase in leaf SPAD index, maximum light-adapted chlorophyll fluorescence and PSII viability. Exogenous SA reduced the number of soluble proteins both under low and high EC; however, increased H_2O_2 content induced a defence mechanism reflected by the upregulation of antioxidant enzyme activity. The results of the study provide valuable information on the role of SA in the alleviation of the harmful effect of salinity under aeroponic cultivation.

Keywords: *osmotic stress*; *physiological disorder*; reactive oxygen species (ROS); photosynthetic activity

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1. Introduction

Sweet pepper (*Capsicum annuum* L.) is economically important for the worldwide vegetable industry. World production of pepper in 2020 was over 36 million tonnes and is still growing; European production was over 3.5 million tonnes, while in Poland, the annual harvest is approximately 159,000 tonnes [1–3]. Pepper fruits are a source of natural pigments and antioxidants, including vitamin C, flavonoids, phenolic acids, as well as carotenoids. Given the nutraceutical and anticancer properties of pepper compounds, they are important preventive factors against many diseases, e.g., cardiovascular disease, type II diabetes, and other aging-associated disorders [4–6]. Global demand for food, especially high-quality products, is increasing rapidly. However, agricultural areas and water resources are decreasing, mainly due to climate change. That is why any agronomic treatments with elicitors, including salicylic acid (SA), can positively influence the yielding of many species and reduce negative environmental impacts. However, appropriate concentrations and methods of elicitor application need to be determined to improve the effectiveness of this practice under different growing conditions [7,8].

A significant problem for pepper cultivation is the sensitivity of plants to environmental stresses, such as drought, salinity, oxygen deficit, low/high temperature, or excessive

radiation. Various unfavourable factors decrease yield and lead to the formation of non-commercial fruits. In the case of peppers, a major problem is a physiological disorder caused by a calcium deficiency in the pericarp cells, known as dry pepper fruit rot, or BER (blossom-end rot). BER significantly affects crop production also in tomatoes and watermelons [9]. It is often associated with calcium deficiency in the whole plant or in the fruit only. Calcium is an essential plant macronutrient. The plants evolved a mechanism involving interactions between the cell wall and the cytoplasm, where Ca^{2+} acts as an agent. The regulation of Ca^{2+} ions concentration in the cytoplasm, apoplast, and organelles of the cell is used by the plant as a signalling mechanism [10]. In addition, calcium stabilizes cell membrane components and pectins in the cell wall. Water uptake and transport play a crucial role in the uptake and distribution of calcium, which is supplied to the fruit mainly through the xylem [11]. Various abiotic stresses can cause a physiological BER disorder in fruits, through reduced calcium uptake by the roots and disturbed regulation of cellular calcium distribution.

In hydroponic and aeroponic cultivation, especially when the nutrient solution is recirculated, a common problem is an increase in the concentration of ions in the nutrient solution. Such manipulation can evoke abiotic stress. More specifically, higher ion concentration limits nutrient uptake and reduces crop production by increasing osmotic pressure [12]. In pepper, high electrical conductivity (EC) of nutrients in the medium was shown to reduce plant growth and net leaf photosynthesis [13]. According to Pérez-Vazquez et al. [14], EC of 3 dS m^{-1} or higher improves nutraceutical quality but decreases bell pepper yield.

According to Hagassou et al. [9], abiotic stress induces the production of reactive oxygen species (ROS) in the plant, leading to membrane breakdown and loss of cellular turgor. As reported by Rekhter et al. [15] and Ding and Ding [16], plant hormones (phytohormones) play an important role in the plant's response to biotic and abiotic stresses.

It was found that the treatment of pepper plants with salicylic acid (SA) reduced oxidative damage caused by salinity stress [17] and increased pepper fruit yield and quality [18]. SA is a plant hormone that controls growth and promotes seedlings' root formation, delays leaf senescence, induces flowering, and interacts with abscisic acid and jasmonates. In addition, it has a positive effect on photosynthesis [19]. Exogenous SA affects various processes, including stomatal closure, ion uptake and transport [20], cell membrane permeability, and intensity of photosynthesis, as well as plant growth [21]. Many studies indicated the positive effects of this hormone in stimulating plant growth under abiotic stress conditions. Furthermore, SA has been found to act as a key signalling molecule under drought, high temperature, and salinity stress conditions [22,23]. Its activity is essential for basal immunity and systemic acquired resistance [24,25] and, by regulating gene expression, SA leads to the synthesis of proteins affecting a number of metabolic processes [26]. However, the specific mechanism of action of SA is still not well understood. Additionally, SA may interact with several different stress-linked compounds, and so, its role in the regulation of plant responses is much more complex [27,28].

The aim of this study was to evaluate the effect of exogenous SA on fruit growth and quality of pepper cultivated in aeroponic conditions under standard and high nutrient solutions.

2. Materials and Methods

2.1. Location of Research

The study was conducted in the experimental greenhouses of the Warsaw University of Life Sciences in the Department of Vegetable and Medicinal Plants in the Institute of Horticultural Science (longitude 21° E, latitude 51°15′ N).

2.2. Plant Material and Growing Conditions

2.2.1. SA Concentration Optimized for Foliar and Root Treatment

In the first part, a test experiment was carried out to determine the appropriate concentration of SA for spray treatment (foliar) and by watering (root treatment). For this purpose,

pepper ('Palermo F1' cultivar) seeds, the same that was used in further studies, were sown on 25 August 2020 into 25 mm × 25 mm × 4 mm rockwool plugs soaked in nutrient solution with an EC of 1.4 dS m^{-1} and covered with expanded clay. Pepper seedlings were transplanted 14 days after sowing (DAS) into 100 mm × 100 mm × 65 mm rockwool seedling cubes soaked in nutrient solution with EC 2.5 dS m^{-1}, pH 5.5. The concentration of nutrients (mg L^{-1}) was as follows: N-NO_3-195, P-57, K-273, Mg-47, Ca-187, Fe-2, Mn-0.6, B-0.3, Cu-0.15, Zn-0.3, Mo-0.05. The day/night temperature averaged 22 °C/20 °C, RH (relative humidity) was 60–70%, and the average CO_2 concentration was 800 ppm.

Pepper plants were sprayed with SA (foliar) at four concentrations (1; 2; 5; 10 mmol SA), while the control plants were sprayed with water only (0 SA-f). SA was also applied at four concentrations (100; 150; 500; 1000 ppm SA) to the roots with a nutrient solution, and the control plants were watered with nutrient solution without salicylic acid (0 SA-r). There were 10 plants in each combination and 3 plants for each replicate. The first treatment of plants with salicylic acid was carried out on 21 DAS, followed by 24 and 27 DAS. Solutions for spray (1; 2; 5; 10 mmol SA) were supplemented with Tween 20 (0.05% (*v*/*v*), while for root application, 100; 150; 500; 1000 ppm SA was provided with the standard nutrient solution for pepper seedlings. Each plant was watered with SA-supplemented nutrient solution at the appropriate concentration for each combination as the plants in the control when a reduction of approximately 35% WC (water content) in the rockwool pot was recorded. In each combination, 30 DAS plants were tested. The height of the plant and the diameter of the shoot at 1 cm above the root neck were measured. The number of leaves and the fresh weight (d = 0.1 g) of the plant (leaves and stems) were also determined. The SPAD index of the relative chlorophyll content of the leaves was measured with a Minolta SPAD-502 apparatus. Based on the results obtained in this part, SA concentrations appropriate for pepper for foliar and root application were selected for further studies.

2.2.2. Aeroponic Growing System

Studies on the effect of SA on pepper fruit growth and quality under standard and high EC medium conditions in aeroponic cultivation were carried out on two terms. The sweet pepper cultivar 'Palermo F1' from Rijk Zwaan, with elongated and red-coloured fruit, was used for the study. Seed sowing on the first date (Term 1) was carried out on 7 April 2021 and on the second date (Term 2) on 14 July 2021. The seedling quilting treatment was performed on 14 DAS on both test terms. Seedlings were produced in 50 mm × 50 mm × 65 mm rockwool cubes and plants were fed with a standard nutrient solution for pepper seedlings with EC 2.5 dS m^{-1} pH 5.5. The concentration of nutrients and cultivation conditions were the same as in the section *SA concentration optimized for foliar and root treatment*.

Pepper seedlings were planted into the aeroponic system on both date 1 and date 2, on day 28 after sowing the seeds (28 DAS). The same method of pepper cultivation was used on both experimental dates. In the experimental growing chamber, microclimatic conditions were computer-controlled. The temperature was maintained at 20–23 °C during the day and 17–19 °C at night. Relative humidity was approximately 70–75%. The experiment was completed with 70 DAS on both terms (date 1–16 June 2021, date 2–22 September 2021). Plants with a properly developed root system, 4–5 fully developed leaves, free from diseases and pests were selected. The pepper plants were placed in openwork pots, which were then inserted into holes made on the top of special bottomless containers of 0.28 m × 0.36 m × 0.27 m in size. The containers had a capillary fed into the side wall ending in an atomizing nozzle, so that when the fertilization computer was activated, the nutrient solution was sprayed onto the plant roots. The nutrient solution then flowed down to the bottom of the bed and on to the collection container, where, when topped up with a new nutrient solution, it fed back into the pepper's root system. The containers were kept out of the sunlight and, in addition, were all covered with double-sided black and white plastic sheeting (Photo S1, Graph S1). Plants were grown in the growing chamber at a density of 2.5 plants per 1 m^2 of growing area.

2.3. Experimental Design and Treatments

The experimental design was completely randomized. The treatments included four different EC combinations and different treatments of the plants with SA.

Combinations tested:

(1) Low EC—plants were fed a standard nutrient solution for peppers with an EC of 3.3 dS m^{-1};
(2) Low EC + SA-f—plants were fed with a standard nutrient solution as in combination (1) and treated with foliar SA (SA-f);
(3) High EC—plants were fed with a nutrient solution 2 × concentrated compared to Low EC, with an EC of 7 dS m^{-1};
(4) High EC + SA-f + SA-r—plants were supplied with a nutrient solution as in the High EC combination (3), treated with foliar SA (SA-f) as in the combination (2), and SA was also applied to the roots (SA-r).

There were 20 plants in each of the four independent beds, fed with the nutrient solution in an aeroponic growing system. The nutrient concentration of the solution, EC, and pH were controlled and maintained at a uniform level suitable for the combination. Plants were cut and managed on two shoots. Immediately after planting the peppers into the aeroponic system, the plants were fed with a standard nutrient solution for peppers with the composition (mg L^{-1}): N-NO_3-195, P-57, K-273, Mg-47, Ca-187, Fe-2, Mn-0.6, B-0.3, Cu-0.15, Zn-0.3, Mo-0.05. The EC of the standard medium feeding the plants in the aeroponic system was 3.3 dS m^{-1}, and the pH was 6.2. The following fertilizers were used to prepare the concentrated media: $Ca(NO_3)_2 \times 4H_2O$; KNO_3; $MgSO_4 \times 7H_2O$, KH_2PO_4, $K_2SO_4 \times 2H_2O$, HNO_3, and Superba/Micromix from Yara International ASA.

Subsequently, on 35 DAS (0 DAT—0 days after treatment with high EC), the nutrient solution in the two combinations tested was changed, increasing the EC by adding twice as much concentrated nutrient solution as in the standard one. The EC of the nutrient solution in the combinations labelled High EC was about 7 dS m^{-1} (High EC and High EC + SA-f + SA-r). In the High EC + SA-f + SA-r combination, 100 ppm SA was added to the nutrient solution. The nutrient solution in each bed was circulated in a closed system (nutrient solution recirculation), the nutrient solution taken up by the plants was replenished daily with a new nutrient solution to a volume of 90 L^{-1}/bed, while once a week, the entire nutrient solution in each bed was replaced with a new nutrient solution. Plants in the combinations Low EC + SA-f and High EC + SA-f + SA-r (38 DAS) were sprayed with SA at a concentration of 5 mmol every 3 days (38–68 DAS). All plants were cut and managed on two fruiting shoots. The shoots left on the plant were wrapped with twine tied to wires stretched on each side of the bed. The first pruning treatment, clearing the plants of side shoots, oldest leaves, and excess flowers and fruit sets, was carried out on 42 DAS, and was repeated weekly thereafter, throughout the growing season, up to 70 DAS. During pruning, buds were removed from the plants, so that there was 1 bud in each internode. An equal number of buds were left on each plant and, for proper fruit nutrition, 2 leaves were left per bud. Eight test plants per combination were randomly selected for all analyses. All removed leaves, side shoots, and fruit set from the test plants were weighed on laboratory scales (d = 0.001 g). The results obtained were used to calculate the total plant weight produced during the 70 DAS period. At the termination of the experiment (70 DAS), the test plants were weighed. The green parts of the test plants (leaves and shoots), all fruit sets, and roots were weighed separately.

2.4. Evaluated Parameters

2.4.1. Morphological Characteristics

Morphological measurements were taken once a week for five weeks. The first plant measurements were taken on 35 DAS (0 DAT), followed by 42 DAS (7 DAT), 49 DAS (14 DAT), 56 DAS (21 DAT), and 63 DAS (28 DAT). Total plant height was measured and the number of fully developed leaves was counted. Up to 70 DAS (35 DAT), the number and

weight of pepper fruit set, and fruit set from the BER, as well as total plant mass produced (leaves, shoots and fruit) and root mass were determined. The ratio of plant weight to pepper root weight depending on the combination was calculated.

2.4.2. Chlorophyll Fluorescence and Chlorophyll Content (SPAD)

The effect of SA on the photosynthetic activity of peppers under high EC nutrient solution conditions was studied by measuring the chlorophyll *a* fluorescence of pepper leaves and the SPAD leaf greenness index, which is correlated with leaf chlorophyll content [29]. Measurements were made on three test plants, on the upper (5th) and lower (10th) fully developed leaf, counting from the top of the fruiting shoot of the plant.

Chlorophyll *a* fluorescence was measured with an PMS-2 fluorimeter (Hansatech Instruments Ltd., King's Lynn, Norfolk, England). Measurements were made in the current light. The saturating light source used was a built-in halogen lamp. The pulse intensity was 8000 µmol m^{-2} s^{-1}, and the pulse duration was 1 s. The following parameters were measured: Fs—steady-state fluorescence yield; Fm'—light-adapted fluorescence maximum; ΦPSII—PSII quantum yield. At the same locations on the pepper leaf after 30 min of leaf acclimatization to darkness by applying special clips, the leaves were illuminated with red light (3500 µmol m^{-2} s^{-1}), and the fluorescence of chlorophyll *a* was measured using a Pocket PEA chlorophyll fluorimeter (Hansatech Instruments Ltd., Pentney, UK). After leaf adaptation to darkness, the following chlorophyll fluorescence parameters were measured: Fv/Fm—maximum photochemical yield of PSII and PI (performance index) plant vitality concerning photosystem I and II [30,31]. The results of chlorophyll fluorescence measurements from the 5th and 10th leaves of the test plant were averaged.

SPAD chlorophyll content was measured using a Minolta SPAD 502 Plus portable meter (Konica Minolta Sensing, Inc., Osaka, Japan), at the same locations on the leaves as chlorophyll fluorescence. Five individual measurements were taken for each leaf and the results were averaged. Measurements were taken on each experimental date: 42 DAS, 49 DAS, 56 DAS, 63 DAS, 70 DAS.

2.4.3. Soluble Protein and H_2O_2 Content

Soluble protein content was determined using the Bradford method [32] and expressed in mg per g of fresh weight (FW).

The modified methodology of Wilmowicz et al. was used for H_2O_2 analysis [33]. Material for the study was collected on 42 DAS and 63 DAS from 5 test plants from each combination (pooled sample). Leaves were taken from the plants directly into bags made of aluminium foil, immediately placed in liquid nitrogen, and then frozen at −81 °C.

Pepper leaves (200 mg) were homogenized with 1 mL of 1% trichloroacetic acid. The homogenates were then centrifuged, the supernatants were transferred to new tubes and adjusted to pH 7.5 (with KOH). The samples were then centrifuged, and 1 mL of supernatant was mixed with 250 µL 3-(dimethylamino)-benzoic acid (19.8 mM) in 0.5 M buffer phosphate (pH 6.5), 230 µL 3-methyl-2-benzothiazolinone hydrazone (0.456 mM) and 20 µL peroxidase (0.25 U). Absorbance (590 nm) was measured and the total H_2O_2 content was expressed as µmol H_2O_2 per gram of fresh weight (µmol g^{-1} FW).

2.4.4. Assays of Antioxidant Enzymes

Extracts for measuring enzymatic activity were prepared by freezing the pepper leaves in liquid nitrogen. An amount of 0.2 g of material was weighed on an analytical scale (d = 0.001 g) and then, ground with 1 mL extraction buffer (50 mM potassium phosphate buffer, pH 7.6, 0.1 mM Na-EDTA). The homogenate was centrifuged at 15,000 rpm for 15 min and the supernatant was used for analyses.

Total SOD activity (U mg^{-1} protein) was investigated by monitoring the superoxide radical-induced nitro tetrazolium blue (NBT) reduction at 560 nm according to the method described by Giannopolitis and Ries [34], with some modifications. An amount of 1 mL of the reaction mixture contained 50 mM potassium phosphate buffer, pH 7.8, 6.5 mM

methionine, 50 µM NBT, 20 µM riboflavin, 10 µM EDTA, and 55 µL enzyme extract. This mixture was mixed and then incubated in the light for 15 min.

Total CAT activity (U mg^{-1} protein) was determined according to the Góth method [35]. For this purpose, 0.2 mL of protein extract was incubated in 1.0 mL of the substrate (65 pmoles per mL hydrogen peroxide in 60 mmol/L sodium potassium phosphate buffer, pH 7.4) at 37 °C for 60 s. Serum catalase activity was linear up to 100 kU/l. If the catalase activity exceeded 100 kU/l, the serum was diluted with phosphate buffer (2- to 1-fold) and the test was repeated. Under these conditions, one unit of catalase degraded 1 pmole of hydrogen peroxide/l min. The enzymatic reaction was stopped by adding 1.0 mL of 8.5 mole/l 3-amino-1,2,4-triazole. The hydrogen peroxide content of the reaction mixture was determined by polarographic analysis and used for calculations. The enzymatic reaction was stopped with 1.0 mL of 32.4 mmol/L ammonium molybdate and the yellow complex of molybdate and hydrogen peroxide was measured at 405 nm against blank.

2.5. Statistical Analysis

Statistical analysis was performed using one-factor and two-factor analysis of variance, ANOVA (Statistica, version 13, Warsaw, Poland). A detailed comparison of means was performed using the Tukey test at a significance level of $\alpha = 0.05$.

3. Results

3.1. SA Concentration for Foliar and Root Treatment

The SA concentrations used in the study for foliar and root treatment of peppers were selected based on the results of the conducted test (Supplementary Material, Tables S1 and S2). Pepper plants sprayed with SA at concentrations of 0 to 10 mmol L^{-1} were shorter, had fewer leaves, and had a lower SPAD index value than the control. Spraying peppers at the seedling stage with SA, regardless of the concentration used for the test, resulted in a significant reduction in plant height and a number of leaves compared to the control (Table S1). SA at a concentration of 10 mmol L^{-1} was toxic to peppers since they had stunted growth, the lowest weight, and few chlorotic leaves, which correlated with the lowest SPAD index values. Based on the results, a concentration of 5 mmol L^{-1}, the highest tested SA concentration tolerated by peppers, was selected for further studies using SA as a foliar spray on pepper plants (Table S1).

Tests for pepper tolerance to the root SA application showed that this SA at concentrations of 150 ppm and lower reduced plant growth, leaf number and weight, shoot diameter, and SPAD index compared to the control. In contrast, the treatment of roots with SA at a concentration of 1000 ppm was toxic to peppers (Table S2). Based on the results, a concentration of 100 ppm SA was selected for further studies with the use of SA for root treatment in pepper cultivation.

3.2. SPAD Index

The high EC of the nutrient solution used in 35 DAS in aeroponic pepper cultivation resulted in a lower SPAD index value in pepper leaves compared to the control (Figure 1). Plants from the control and the Low EC + SA-f and High EC + SA-f + SA-r combinations had a higher relative chlorophyll content in the leaves than those grown at the high EC of the nutrient solution (High EC). High EC of the nutrient solution had a lower effect on the SPAD index, especially in the leaves of younger peppers. Foliar application of SA and, at the same time, root application of SA at High EC of the nutrient solution resulted in an inhibition of the SPAD index value reduction (Figure 1).

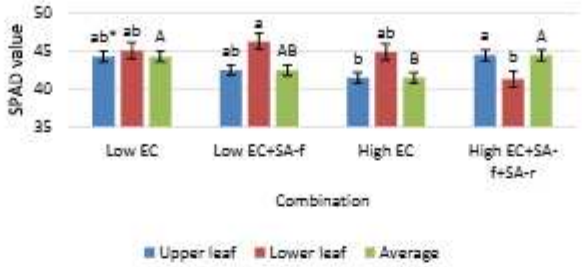

Figure 1. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on SPAD index in pepper leaves (average of two terms ± SE). * Mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. Lowercase letters indicate differences in the interaction of leaves × treatment, capital letters indicate differences between treatments (mean of two terms).

3.3. Morphological Characteristics

In the aeroponic method of cultivation, the application of a high EC nutrient solution on 35 DAS proved to be a stress factor for peppers. On the subsequent days of treatment with the high EC nutrient solution, after 21 DAT and after 28 DAT, a reduction in plant height and leaf number was observed (Figures 2 and 3). In contrast, spraying plants with SA in the combination with the high EC nutrient solution and the simultaneous addition of SA to the nutrient solution (High EC+SA-f+SA-r) did not reduce the negative effect of the high EC nutrient solution on plant height and leaf number (Figures 2 and 3). Plants cultivated under High EC and High EC + SA-f + SA-r combination were shorter and had fewer leaves than plants grown in the other experimental combinations. Peppers growing at Low EC were the highest and had most of the leaves (Figures 2 and 3).

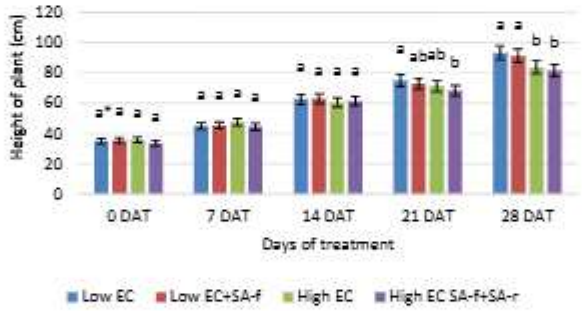

Figure 2. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on the height of plant in the following days after treating (DAT) pepper plant with high EC (average of two terms ± SE). * Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$.

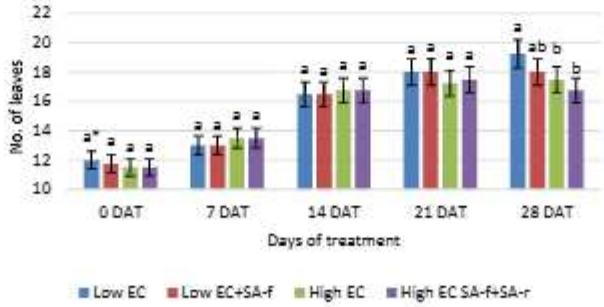

Figure 3. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on the number of leaves in the following days after treating (DAT) pepper plant with high EC (average of two terms ± SE). * Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$.

The total weight of fruit sets produced in peppers after 70 DAS using the high EC stress of 35 DAS was the highest in the Low EC and High EC combinations (Table 1). There was no effect of the applied high EC of the nutrient solution in the aeroponic cultivation of peppers on the reduction of fruit set weight after 35 DAT compared to the control. In contrast, spraying of peppers grown with the standard nutrient solution (Low EC) with SA at a concentration of 5 mmol L^{-1}, resulted in a reduction in the total fruit set weight in pepper plants on 70 DAS.

Table 1. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on biometric characteristics of the pepper plant (average of two terms ± SE).

Parameter	Measurement Dates	Combinations of EC Medium and SA Treatment			
		Low EC	Low EC + SA-f	High EC	High EC + SA-f + SA-r
Total weight of set fruits (g/plant)	Term 1. Term 2. Mean	423.75 ± 51.45 a* 713.75 ± 29.93 a 568.75 ± 42.66 A	342.50 ± 38.39 b 632.50 ± 38.39 b 487.50 ± 45.71 B	421.25 ± 40.62 a 711.25 ± 40.62 a 566.25 ± 46.60 A	362.50 ± 23.36 ab 652.50 ± 23.36 ab 507.50 ± 40.69 AB
Total number of set fruits (No./plant)	Term 1. Term 2. Mean	3.75 ± 0.61 b 6.75 ± 0.36 b 5.25 ± 0.46 B	5.25 ± 0.67 ab 8.25 ± 0.67 ab 6.75 ± 0.60 AB	6.25 ± 0.70 a 9.25 ± 0.70 a 7.75 ± 0.62 A	5.75 ± 0.37 ab 8.75 ± 0.37 ab 7.25 ± 0.46 AB
Mean weight of fruit set (g)	Term 1. Term 2. Mean	113.00 ± 4.54 a 105.74 ± 2.16 a 109.38 ± 2.64 A	65.24 ± 5.43 b 76.67 ± 8.39 b 70.96 ± 4.95 B	67.40 ± 4.63 b 76.89 ± 3.56 b 72.15 ± 3.05 B	63.04 ± 5.90 b 74.57 ± 4.03 b 68.81 ± 3.71 B
Weight of set fruits with BER (g/plant)	Term 1. Term 2. Mean	423.75 ± 30.43 a 448.75 ± 29.94 a 436.25 ± 20.70 A	146.63 ± 52.47 b 171.62 ± 52.47 b 159.13 ± 35.99 B	87.5 ± 48.51 bc 112.5 ± 48.51 bc 100.00 ± 33.30 BC	0.00 ± 0.00 c 25.00 ± 0.00 c 12.50 ± 3.20 C
Number of set fruits with BER (No./plant)	Term 1. Term 2. Mean	3.75 ± 0.43 a 4.75 ± 0.37 a 4.25 ± 0.28 A	1.88 ± 0.48 b 2.88 ± 0.48 b 2.38 ± 0.35 B	1.25 ± 0.64 bc 2.25 ± 0.64 bc 1.75 ± 0.46 BC	0.00 ± 0.00 c 1.00 ± 0.00 c 0.50 ± 0.13 C
% set fruit with BER in total weight of set fruits (%)	Term 1. Term 2. Mean	18.4 ± 3.95a ** 16.30 ± 1.85 a 17.50 ± 4.94 A	14.40 ± 11.24 b 12.90 ± 6.74 b 13.70 ± 6.54 B	12.50 ± 12.80 bc 11.50 ± 7.26 bc 12.10 ± 7.16 BC	0.00 ± 0.00 c 8.10 ± 0.14 c 6.80 ± 0.50 C
Total weight of plant (leaves, shoots, set fruits and roots) (g/plant)	Term 1. Term 2. Mean	1227.50 ± 65.14 a 1677.50 ± 56.25 a 1452.50± 69.65 A	1059.75 ± 42.59 ab 1509.75 ± 42.59 ab 1284.75 ± 64.97 AB	977.88 ± 73.71 b 1427.88 ± 73.71 b 1202.88 ± 76.88 B	969.25 ± 45.88 b 1419.25 ± 45.88 b 1194.25 ± 66.01 B
Weight of green parts of the plant (leaves, shoots and set fruits) (g/plant)	Term 1. Term 2. Mean	823.75 ± 83.19 a 1123.75 ± 51.37 a 973.75 ± 52.27 A	672.50 ± 40.17 b 972.50 ± 40.17 b 822.50 ± 47.46 B	720.63 ± 71.17 ab 1020.63 ± 71.17 ab 870.63 ± 62.16 AB	661.25 ± 43.39 b 961.25 ± 43.39 b 811.25 ± 48.77 B
Weight of roots (g/plant)	Term 1. Term 2. Mean	403.75 ± 19.58 a 553.75 ± 8.92 a 478.75 ± 20.30 A	387.25 ± 7.24 a 537.25 ± 7.24 a 462.25 ± 19.98 A	257.25 ± 31.35 b 407.25 ± 31.35 b 332.25 ± 28.80 B	308.00 ± 10.21 ab 458.00 ± 10.21 ab 383.00 ± 20.59 AB
Ratio of green parts of the plant to the weight of roots	Term 1. Term 2. Mean	2.04 ± 0.08 b 2.03 ± 0.06 ab 2.03 ± 0.06 B	1.74 ± 0.02 c 1.81 ± 0.01 b 1.77 ± 0.03 C	4.29 ± 0.68 a 2.73 ± 0.15 a 3.51 ± 0.36 A	2.15 ± 0.09 b 2.10 ± 0.06 ab 2.13 ± 0.07 B

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at α = 0.05. Lowercase letters indicate differences in the interaction of crop term × treatment, capital letters indicate differences between treatments (mean of two terms). ** data after Bliss transformation.

The number of fruit sets was lowest in the control and highest at high EC nutrient solution (Table 1). The mean weight of the pepper fruit set was highest in the control. The applied high EC of the nutrient solution (High EC) and the SA foliar (Low EC + SA-f) and foliar treatment with the simultaneous root treatment (High EC + SA-f + SA-r) reduced the average weight of pepper fruit set produced up to 70 DAS (Table 1). In contrast, the weight and number of fruits sets with BER symptoms were the highest in the control with standard Low EC of the nutrient solution. The foliar application of SA to the plants growing at Low EC of the nutrient solution up to 70 DAS, reduced the weight and number of fruit sets with BER. Additionally, the application of High EC of nutrient solution without SA resulted in lower weight and number of fruit sets with BER than in the control. Application of High EC and foliar and root application of SA at 5 mmol and 100 ppm, respectively, had the strongest effect on the reduction of the weight and number of fruit sets with BER, compared to the control. Foliar SA spraying of peppers grown at low nutrient EC decreased the number (by more than 40%) and weight (by about 60%) of fruit sets with BER symptoms compared to plants grown at low nutrient EC. At the same time, foliar and root application

of SA in plants grown at a high nutrient EC decreased the number (by about 70%) and weight (by more than 80%) of fruit sets with BER symptoms compared to plants supplied with a high nutrient EC (Table 1).

Peppers grown aeroponically at the low EC of the nutrient solution produced the highest mass of leaves, shoots, and fruit sets. The lowest values of these parameters were observed for plants from the High EC + SA-f + SA-r combination. It was found that the high EC of the nutrient solution had a negative effect on plant weight. Measurements made after 70 DAS showed that the root weight of plants growing under Low EC was the highest. The foliar application of SA in combination with the Low EC nutrient solution reduced the weight of leaves, shoots, and set fruits, but not root weight. When SA was applied by spray and to the roots in the stress combination (High EC + SA-f + SA-r), an increase in root weight was observed compared to the High EC combination. Total plant and root weights were highest in the Low EC and Low EC + SA-f combination and lowest in the High EC combination. The ratio of total aboveground weight (leaves, shoots, and fruit set) to roots was highest in the High EC combination and lowest in the Low EC + SA-f combination [Table 1].

3.4. Chlorophyll a Fluorescence

The use of high EC of the nutrient solution in pepper cultivation reduced chlorophyll *a* fluorescence parameters of pepper leaves such as Fs, Fm, and PI compared to the control and the other combinations (Table 2). On the other hand, when the nutrient solution was characterized by high EC and SA was applied to the leaves and roots, an increase in maximum light-adapted fluorescence Fm' and overall PSII—PI viability was observed, compared to plants untreated with SA (Table 2). SA-treated plants growing under optimal EC conditions also showed an increase in maximum light-adapted fluorescence Fm' compared to non-treated plants. The statistical analysis showed no significant differences between the combinations for the quantum yield of PSII—ΦPSII and the maximum photochemical yield of PSII—Fv/Fm (Table 2).

Table 2. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on chosen parameters of chlorophyll a fluorescence of pepper leaves (average of two terms ± SE).

Parameter	Combination			
	Low EC	Low EC + SA-f	High EC	High EC + SA-f + SA-r
Fs	484.66 ± 5.55 a*	493.66 ± 2.87 a	438.33 ± 4.50 b	486.00 ± 5.09 ab
Fm'	1763.66 ± 1.69 c	2003.33 ± 2.36 a	1649.67 ± 0.47 d	1835.33 ± 1.24 b
ΦPSII	0.72 ± 0.00 a	0.72 ± 0.03 a	0.74 ± 0.02 a	0.71 ± 0.01 a
Fv/Fm	0.80 ± 0.00 a	0.80 ± 0.01 a	0.79 ± 0.03 a	0.81 ± 0.00 a
PI	4.95 ± 0.17 a	4.78 ± 0.49 a	4.23 ± 1.00 b	4.67 ± 0.58 a

* Means with different lowercase letters in the same row indicate a statistically significant difference according to the Tukey test ($p \leq 0.05$).

3.5. Content of Soluble Protein and H_2O_2, the Activity of SOD and CAT

In order to precisely investigate the redox homeostasis in pepper leaves in response to different treatment combinations, the H_2O_2 content and activity of antioxidant enzymes: SOD and CAT were determined. In the first step, the soluble protein level was analysed and it was observed that it had a higher value when EC increased. The simultaneous treatment with SA to both low and high-EC-treated plants negatively influenced protein content. The foliar application of SA to the plants cultivated under low EC reduced protein level up to 14.58 mg g^{-1} FW (Figure 4A).

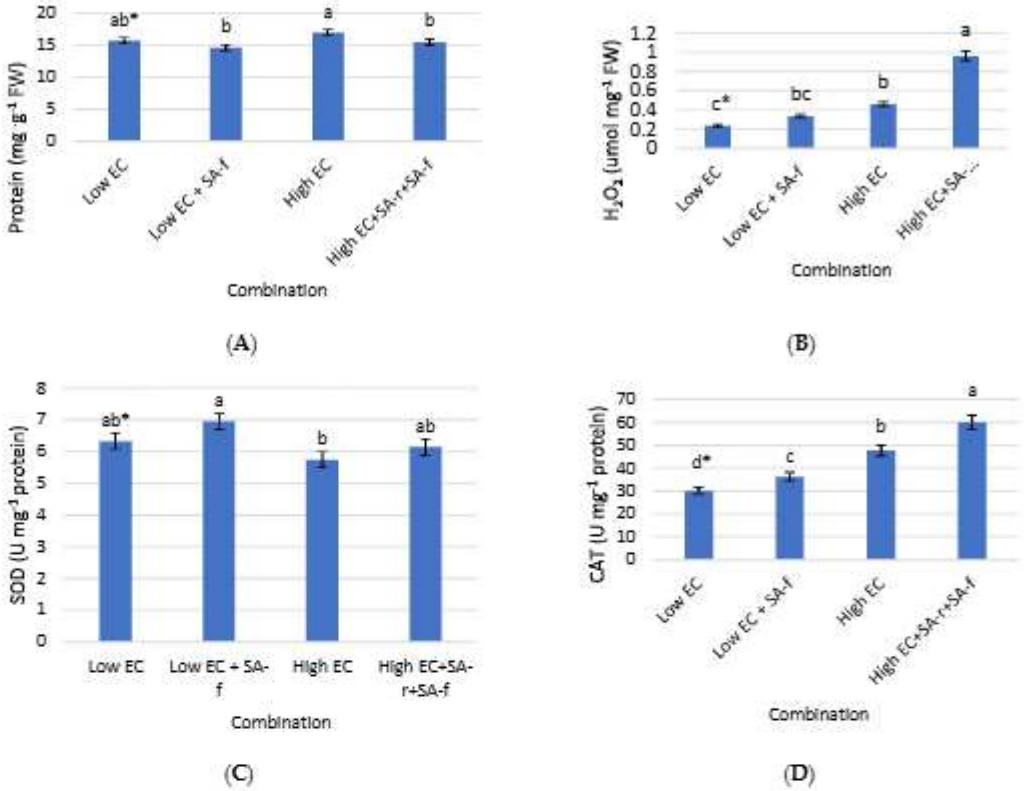

Figure 4. Effect of high EC nutrient solution and SA treatment in aeroponic cultivation on protein content (**A**), H_2O_2 level (**B**), activity of superoxide dismutase (SOD) (**C**) and catalase (CAT) (**D**) in pepper plants (average of two terms ± SE). * Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$.

The activity of one enzyme responsible for H_2O_2 formation–SOD–fluctuated among different treatments. When EC was higher, the activity of the enzyme decreased. In turn, SA application upregulated SOD activity regardless of the EC value. The maximum activity was observed when leaves were subjected to the simultaneous action of low EC and exogenous SA (Figure 4C). The next step of analyses focused on the determination of the H_2O_2 compound in pepper leaves. As Figure 4B shows, a gradual increase in H_2O_2 content was observed when EC was higher. Strong accumulation of H_2O_2 was noted in plants cultivated under high EC and treated with SA. Then, it reached 0.9 µmol mg^{-1} FW. However, foliar SA spraying on leaves under low EC did not evoke such strong stimulatory effect. One of the antioxidative enzymes dismutating H_2O_2 is CAT; thus, its activity was also determined. A similar tendency for this parameter was observed as the H_2O_2 content. The increasing salt concentration of nutrients upregulated CAT up to ~45 µmol mg^{-1} FW. Moreover, exogenous SA accelerated the activity of the enzyme, especially when it was applied to plants cultivated under high EC. Under these conditions, CAT activity was the highest reaching 60 U mg^{-1} protein (Figure 4D).

4. Discussion

4.1. Selection of a Proper SA Concentration for Foliar and Root Treatment in Peppers

Based on the obtained results, it can be concluded that 5 mmol L^{-1} SA is the most effective for foliar application to pepper plants, since a higher concentration (10 mmol L^{-1}) of this compound evoked toxic effects. On the other hand, 100 ppm SA applied with a nutrient solution in hydro or aeroponic cultivation is recommended for root treatments. A higher concentration of SA (150 ppm) affected plant growth and development and was even toxic for pepper (1000 ppm). There were several reports concerning the positive role of SA in the regulation of the development of this species in hydroponic cultivation.

Ibrahim et al. [18] sprayed pepper leaves with SA at concentrations of 0, 0.5, 1.0, and 1.5 g L^{-1} on the 20th, 40th, and 60th day after transplanting and showed that the foliar application increased vegetative growth rate compared to the control. According to this study, the application of SA at a concentration of 1.5 g L^{-1} enhanced not only growth but also fruit quality and yield. Canakci [36] treated roots of pepper seedlings with different SA concentrations (0; 0.3; 1.5; 5; and 10 mmol) and selected 1.5 mmol SA as optimal for growth improvement.

4.2. Effect of SA on the Morphology, SPAD Index, and Chlorophyll Fluorescence of Pepper Cultivated under Different EC

A study by Vicente and Plasencia [27] proves that the regulatory role of SA depends on the concentration, the plant growth conditions, and the stage of development. It was experimentally confirmed that high concentrations of SA (>1 mM) have a negative effect on plant development and growth. In the present study, there was no positive effect of foliar SA on plant growth, number of leaves, or plant and root weight of peppers grown under standard EC conditions in aeroponic cultivation. In contrast, Souri and Tohidloo [37] showed that foliar application of SA increased plant height and leaf area in tomatoes, while Yildirim and Dursun [38] observed higher growth, yield, and better quality of fruits in this species. On the other hand, Kowalska and Smoleń [39] reported no effect of salicylic acid on tomato fruit yield. Nevertheless, the most important result obtained in this study was that plants sprayed with SA formed fewer fruits with calcium deficiency symptoms (BER), which is the limiting factor for pepper productivity. Thus, this valuable data can be used to obtain high-quality products in aeroponic cultivation.

The application of a high concentration of the nutrient solution (7 dS m^{-1}) to peppers on 35 DAS under aeroponic conditions induced oxidative stress. According to Aktas et al. [40] and Ahmadi and Souri [41], high EC (5 dS m^{-1}) induced by NaCl, negatively affects pepper growth parameters. Salt stress is one of the main factors affecting plant growth and yield [42], which was confirmed by the obtained results. The exogenous SA applied as a spray and to the roots of plants growing under high EC nutrient reduced the weight and number of BERs, affected the increase in root weight of peppers, increased leaf SPAD values, maximum light-adapted fluorescence Fm' and overall PSII—PI viability compared to non-treated plants [43]. Studies by Tahjib-Ul-Arif et al. [44] and Oliveira et al. [45] showed that exogenous SA had a significant effect on cherry tomato fruit production. The authors revealed that SA optimizes plant uptake of nutrients, increases photosynthetic activity and biochemical processes, with consequent positive effects on plant growth and development under salt stress conditions. It cannot be ruled out that the SA-dependent regulation of crucial processes such as photosynthesis might contribute to the improvement of plant vitality and further better resistance to physiological disorders, such as BER. It is highly possible given the findings of Huang et al. [46], who showed that SA-treatment of *Dendrobium officinale* cultivated under stress conditions upregulated chlorophyll fluorescence parameters, including maximum photochemical PSII yield (Fv/Fm), which allowed the plant to adapt to the stress. Additionally, exogenous SA increased chlorophyll content under drought conditions [47] and salinity [48]. Osama et al. [43] suggested that the regulatory role of SA is connected to the prevention of the reduction of auxin and cytokinin levels, which leads to better cell division of the root apical meristem, thus contributing to the improvement of plant growth and yield. Furthermore, SA can alleviate salt stress by increasing water and nutrient absorption, membrane protection, as it can also interact with ROS signalling pathways and reduce oxidative stress [49].

4.3. SA-Dependent Effect on the Soluble Protein and H_2O_2 Content, SOD and CAT Activity in Pepper Cultivated under Different EC

Salinity, similarly to other stresses, stimulates the synthesis of proteins protecting plant tissues, which is a part of the defence mechanism induced in the plant to deal with adverse environments. That is why, as it was presented here, leaves of pepper cultivated under higher salt concentrations accumulate proteins. These findings are in line with

the results of Agamy et al. [50]. They show that salinity positively regulated soluble protein content in tomato leaves (~37%), even more, when SA was applied. Similarly, Ahmed et al. [51] suggested that the simultaneous action of salinity and SA increased proteins by about 5%. However, the study showed the opposite effect evoked by this plant hormone. Regardless of salt concentration, SA downregulated protein levels in pepper leaves. This is in accordance with previous studies of Shahba et al. [52] and El-Tayeb [53], indicating that SA reduced protein content under salt stress in tomato and barley. Collectively, SA treatment could exert various effects against stress in a species-dependent manner. Furthermore, it cannot be excluded that SA action in the alleviation of salinity stress could be related to the modulation of protein activity even more than their content. So, to better understand this phenomenon, the next analyses focused on the enzyme activity. Abiotic stress causes oxidative stress reflected by an imbalance in ROS generation and their scavenging, e.g., by antioxidant enzymes, such as SOD and CAT. It was not surprising that the content of H_2O_2, as one of the relatively stable ROS, increased under higher salinity. At the same time, SOD activity decreased. On the contrary, SOD activity was found to be upregulated under salt stress in tomato and wheat [54,55]. Based on the presented observations, it may be assumed that H_2O_2 could be formed in the SOD-independent pathway during salinity in pepper. The obtained results indicate that the production of H_2O_2 is stimulated by exogenous SA in pepper leaves, particularly when it was applied to the leaves and roots. Farhadi and Ghassemi-Golezani [56] observed an accumulation of H_2O_2 under salt stress in *Mentha pulegium*, but exogenous SA reversed this effect. A similar trend was noted by Alsahli et al. [55] in wheat; however, 75 mM SA upregulated H_2O_2 content. Concentration-dependent effect of exogenous SA can explain the extensive H_2O_2 production in pepper leaves. Moreover, a strong accumulation of H_2O_2 in the leaves subjected to salinity and double SA application to leaves and roots might be related to its transport from the place of application to the leaves since this molecule has the ability to diffuse across membranes [57]. Such a scenario is possible, given the enzymatic activity of CAT responsible for H_2O_2 detoxification. A high level of this kind of ROS is correlated with increasing CAT activity in every experimental variant suggesting that this enzyme is activated by salinity and exogenous SA and could detoxify such high amounts of H_2O_2 and helps the plant to alleviate stress and survive. The positive role of SA in salinity-evoked antioxidant responses was reported in tomato [58] and rice [59].

The effect of SA treatment of peppers both at low EC and under stress conditions caused by high EC of the nutrient solution in the aeroponic growing system was positive. Stress conditions cause disorders in plant metabolism, resulting in an increased production of ROS. This results in the activation of signalling cascades, leading to acclimatization to the affected conditions [60]. ROS could interact with SA during the stress response. Slight increases in ROS concentrations are thought to induce defence mechanisms, while very high concentrations induce death by cell damage [60,61]. One example of a known signalling function of ROS is the involvement of H_2O_2 in the regulation of stomatal movements [62,63], which could increase Ca transport in xylem tissues and, consequently, reduce the occurrence of BER in SA-treated plants, as was shown in SA-treated peppers.

5. Conclusions

The use of SA in aeroponic cultivation affects the growth and development of peppers. Peppers cultivated in a high concentration of the nutrient solution (EC of about 7dS m^{-1}) showed symptoms of oxidative stress. SA reduced the number and weight of fruit set with calcium deficiency symptoms. The results of the study indicate that the effect of SA in the alleviation of salinity stress in pepper is related to increasing the leaf SPAD index, a maximum light-adapted fluorescence—Fm′ and overall PSII viability—PI. Oxidative balance is disrupted by high EC, while exogenous SA activates CAT, which detoxifies high amounts of ROS and helps the plant to alleviate stress.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13030779/s1, Table S1. Effect of SA foliar spraying on chosen pepper plant parameters depending on acid concentration (mean ± SD); Table S2. Effect of SA root-applied on chosen pepper plant parameters depending on acid concentration (average of two terms ± SD); Table S3. Effect of solution with different EC and SA treatment in hydroponic cultivation on height and number of leaves (average of two terms ± SD); Photo S1. (A) Cultivation of peppers in an aeroponic system, where upside-down containers with nozzles for spraying nutrient solution (one for each plant) onto the roots were covered with black and white film, and a container for nutrient solution was installed at the beginning of each bed, which was automatically pumped into the nozzles and fed to the plants (B). A sweet pepper plant cut into two fruiting shoots; Graph S1. Diagram of the conduct of the experiment. Four growing beds, one individual aeroponic system for each combination (20 plants each). Randomly selected test plants for physiological and biochemical measurements are marked (See Photo S1).

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References

1. Sikha, S.; Sunil, P.; Arti, J.; Sujata, B. Impact of water-deficit and salinity stress on seed germination and seedling growth of *Capsicum annuum* 'Solan Bharpur'. *Int. Res. J. Biol. Sci.* **2013**, *2*, 9–15.
2. FAOSTAT. Available online: www.fao.org/faostat/en/#home (accessed on 15 December 2022).
3. Wu, L.; Yang, H.; Li, Z.; Wang, L.; Peng, Q. Effects of Salinity-Stress on Seed Germination and Growth Physiology of Quinclorac-Resistant *Echinochloa crus-galli* (L.) Beauv. *Agronomy* **2022**, *12*, 1193. [CrossRef]
4. Zhang, Y.J.; Gan, R.Y.; Li, S.; Zhou, Y.; Li, A.N.; Xu, D.P.; Li, H.B. Antioxidant phytochemicals for the prevention and treatment of chronic diseases. *Molecules* **2015**, *20*, 21138–21156. [CrossRef] [PubMed]
5. Zaki, N.; Hasib, A.; Eddine, K.C.; Dehbi, F.; El Batal, H.; Ouatmane, A. Comparative Evaluation of the Phytochemical Constituents and the Antioxidant Activities of Five Moroccan Pepper Varieties (*Capsicum Annuum* L.). *JCBPS* **2017**, *7*, 1294–1306.
6. Sanati, S.; Razavi, B.M.; Hosseinzadeh, H. A review of the e_ects of *Capsicum annuum* L. and its constituent, capsaicin, in metabolic syndrome. *Iran. J. Basic Med. Sci.* **2018**, *21*, 439–448.
7. García-Mier, L.; Guevara-González, R.G.; Mondragón-Olguín, V.M.; Del Rocío Verduzco-Cuellar, B.; Torres-Pacheco, I. Agriculture and Bioactives: Achieving Both Crop Yield and Phytochemicals. *Int. J. Mol. Sci.* **2013**, *14*, 4203–4222. [CrossRef]
8. Munshi, M.H.; Issak, H.; Kabir, K.; Hosain, M.T.; Fazle Bari, A.S.M.; Rahman, M.S.; Tamanna, M. Enhancement of growth, yield and fruit quality of sweet pepper (*Capsicum annuum* L.) by foliar application of salicylic acid. *Int. J. Biosci.* **2020**, *17*, 49–56.
9. Hagassou, D.; Francia, E.; Ronga, D.; Buti, M. Blossom end-rot in tomato (*Solanum lycopersicum* L.): A multi-disciplinary overview of inducing factors and control strategies. *Sci. Hortic.* **2019**, *249*, 49–58. [CrossRef]
10. Hepler, P.K.; Winship, L.J. Calcium at the Cell Wall-Cytoplast Interface. *J. Integr. Plant Biol.* **2010**, *52*, 147–160. [CrossRef]
11. Hocking, B.; Tyerman, S.D.; Burton, R.A.; Gilliham, M. Fruit calcium: Transport and physiology. *Front. Plant Sci.* **2016**, *7*, 569. [CrossRef]
12. Ding, X.; Jiang, Y.; Zhao, H.; Guo, D.; He, L.; Liu, F.; Zhou, Q.; Nandwani, D.; Hui, D.; Yu, J. Electrical conductivity of nutrient solution influenced photosynthesis, quality, and antioxidant enzyme activity of pakchoi (*Brassica campestris* L. ssp. Chinensis) in a hydroponic system. *PLoS ONE* **2018**, *13*, e0202090. [CrossRef]
13. Ding, X.; Zhang, H.; Qian, T.; He, L.; Jin, H.; Zhou, Q.; Yu, J. Nutrient Concentrations Induced Abiotic Stresses to Sweet Pepper Seedlings in Hydroponic Culture. *Plants* **2022**, *11*, 1098. [CrossRef]
14. Pérez-Vazquez, E.L.; Monserrat Gaucín-Delgado, J.; Ramírez-Rodríguez, S.C.; de los Ángeles Sariñana-Aldaco, M.; Zapata Sifuentes, G.; Zuñiga-Valenzuela, E. Conductividad eléctrica De La solución Nutritiva Efecto En El Rendimiento Y La Calidad nutracéutica De Pimiento morrón. *Rev. Mex. De Cienc. Agrícolas* **2020**, *11*, 1669–1675. [CrossRef]

15. Rekhter, D.; Lüdke, D.; Ding, Y.; Feussner, K.; Zienkiewicz, K.; Lipka, V.; Wiermer, M.; Zhang, Y.; Petit-Houdenot, Y. Isochorismate-derived biosynthesis of the plant stress hormone salicylic acid. *Science* **2019**, *365*, 498–502. [CrossRef]
16. Ding, P.; Ding, Y. Stories of Salicylic Acid: A Plant Defense Hormone. *Trends Plant Sci.* **2020**, *25*, 549–565. [CrossRef]
17. Veloso, L.L.A.; Lima, G.S.; Silva, A.A.R.; Souza, L.P.; Lacerda, C.N.; Silva, I.J.; Chaves, L.H.G.; Fernandes, P.D. Attenuation of salt stress on the physiology and production of bell peppers by treatment with salicylic acid. *Semin. Ciências Agrárias Londrina* **2021**, *42*, 2751–2768. [CrossRef]
18. Ibrahim, A.; Abdel-Razzak, H.; Wahb-Allah, M.; Alenazi, M.; Alsadon, A.; Dewir, Y.H. Improvement in Growth, Yield, and Fruit Quality of Three Red Sweet Pepper Cultivars by Foliar Application of Humic and Salicylic Acids. *HortTechnology* **2019**, *29*, 170–178. [CrossRef]
19. Mahdavian, K.; Ghorbanli, M.; Kalantari, K.M. Role of Salicylic Acid in Regulating Ultraviolet Radiation Induced Oxidative Stress in Pepper Leaves. *Russ. J. Plant Physiol.* **2008**, *55*, 560–563. [CrossRef]
20. Abou El-Yazied, A. Effect of foliar application of salicylic acid and chelated zinc on growth and productivity of sweet pepper (*Capsicum annuum* L.) under autumn planting. *Res. J. Agric. Biol. Sci.* **2011**, *7*, 423–433.
21. Haytova, D. A review of foliar fertilization of some vegetables crops. *Annu. Rev. Res. Biol.* **2013**, *3*, 455–465.
22. Shaar-Moshe, L.; Blumwald, E.; Peleg, Z. Unique Physiological and Transcriptional Shifts under Combinations of Salinity, Drought, and Heat. *Plant Physiol.* **2017**, *174*, 421–434. [CrossRef] [PubMed]
23. Torun, H. Time-course analysis of salicylic acid effects on ROS regulation and antioxidant defense in roots of hulled and hulless barley under combined stress of drought, heat and salinity. *Physiol. Plant.* **2018**, *165*, 169–182. [CrossRef] [PubMed]
24. Kim, D.S.; Hwang, B.K. An important role of the pepper phenylalanine ammonia-lyase gene (PAL1) in salicylic acid-dependent signalling of the defence response to microbial pathogens. *J. Exp. Bot.* **2014**, *65*, 2295–2306. [CrossRef] [PubMed]
25. Huang, W.; Wang, Y.; Li, X.; Zhang, Y. Biosynthesis and Regulation of Salicylic Acid and N-Hydroxypipecolic Acid in Plant Immunity. *Mol. Plant.* **2020**, *13*, 31–41. [CrossRef] [PubMed]
26. Janda, T.; Szalai, G.; Pál, M. Salicylic Acid Signalling in Plants. *Int. J. Mol. Sci.* **2020**, *21*, 2655. [CrossRef]
27. Vicente, M.R.S.; Plasencia, J. Salicylic acid beyond defence: Its role in plant growth and development. *J. Exp. Bot.* **2011**, *62*, 3321–3338. [CrossRef]
28. Dempsey, D.A.; Klessig, D.F. How does the multifaceted plant hormone salicylic acid combat disease in plants and are similar mechanisms utilized in humans? *BMC Biol.* **2017**, *15*, 23. [CrossRef]
29. Baker, N.R.; Rosenqvist, E. Applications of chlorophyll fluorescence can improve crop production strategies: An examination of future possibilities. *J. Exp. Bot.* **2004**, *55*, 1607–1621. [CrossRef]
30. Strasser, R.J. The Fluorescence Transient as a Tool to Characterize and Screen Photosynthetic Samples. In *Probing Photosynthesis: Mechanism, Regulation and Adaptation*; Yunus, M., Pathre, U., Mohanty, P., Eds.; CRC Press: Boca Raton, FL, USA, 2000; pp. 445–483.
31. Sieczko, L.; Dąbrowski, P.; Kowalczyk, K.; Gajc-Wolska, J.; Borucki, W.; Janaszek-Mańkowska, M.; Kowalczyk, W.; Farci, D.; Kalaji, H.M. Early detection of phosphorus deficiency stress in cucumber at the cellular level using chlorophyll fluorescence signals. *J. Water Land Dev.* **2022**, 176–186. [CrossRef]
32. Bradford, M.M. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal. Biochem.* **1976**, *72*, 248–254. [CrossRef]
33. Wilmowicz, E.; Frankowski, K.; Glazinska, P.; Kesy, J.; Kopcewicz, J. Involvement of ABA in flower induction of *Pharbitis nil*. *Acta So. Bot. Pol.* **2011**, *80*, 21–26. [CrossRef]
34. Giannopolitis, C.N.; Ries, S.K. Superoxide Dismutases: I. Occurrence in Higher Plants. *Plant Physiol.* **1977**, *59*, 309–314. [CrossRef]
35. Góth, L. A simple method for determination of serum catalase activity and revision of reference range. *Clin. Chim. Acta* **1991**, *196*, 143–152. [CrossRef]
36. Canakci, S. Effects of Salicylic Acid on Growth, Biochemical Constituents in Pepper (*Capsicum annuum* L.) Seedlings. *PJBS* **2011**, *14*, 300–304. [CrossRef]
37. Souri, M.K.; Tohidloo, G. Effectiveness of different methods of salicylic acid application on growth characteristics of tomato seedlings under salinity. *Chem. Biol. Technol. Agric.* **2019**, *6*, 26. [CrossRef]
38. Yildirim, E.; Dursun, A. Effect of foliar salicylic acid applications on plant growth and yield of tomato under greenhouse conditions. *Acta Hort.* **2009**, *807*, 395–400. [CrossRef]
39. Kowalska, I.; Smoleń, S. Effect of foliar application of salicylic acid on the response of tomato plants to oxidative stress and salinity. *J. Elem.* **2013**, *18*, 239–254. [CrossRef]
40. Aktas, H.; Abak, K.; Cakmak, I. Genotypic variation in the response of pepper to salinity. *Sci. Hortic.* **2006**, *110*, 260–266. [CrossRef]
41. Ahmadi, M.; Souri, M.K. Growth characteristics and fruit quality of chili pepper under higher electrical conductivity of nutrient solution induced by various salts. *AJAS* **2020**, *42*, 143–152. [CrossRef]
42. Kamanga, R.M.; Mndala, L. Crop abiotic stresses and nutrition of harvested food crops: A review of impacts, interventions and their effectiveness. *Afr. J. Agric. Res.* **2019**, *14*, 118–135.
43. Osama, S.; Sherei, M.; Al-Mahdy, D.A.; Bishr, M.; Salama, O. Effect of salicylic acid foliar spraying on growth parameters, γ-pyrones, phenolic content and radical scavenging activity of drought stressed *Ammi visnaga* L. plant. *Ind. Crops Prod.* **2019**, *134*, 1–10. [CrossRef]

44. Tahjib-Ul-Arif, M.; Siddiqui, M.N.; Sohag, A.A.M.; Sakil, M.A.; Rahman, M.M.; Polash, M.A.S.; Mostofa, M.G.; Tran, L.S.P. Salicylic acid-mediated enhancement of photosynthesis attributes and antioxidant capacity contributes to yield improvement of maize plants under salt stress. *J. Plant Growth Regul.* **2018**, *37*, 1318–1330. [CrossRef]
45. Oliveira, V.K.N.; Lima, G.S.; Soares, M.D.M.; Soares, L.A.A.; Gheyi, H.R.; Silva, A.A.R.; Paiva, F.J.S.; Mendonca, A.J.T.; Fernandes, P.D. Salicylic acid does not mitigate salt stress on the morphophysiology and production of hydroponic melon. *Braz. J. Biol.* **2022**, *82*, e262664. [CrossRef]
46. Huang, C.; Wang, D.; Sun, L.; Wei, L. Effects of exogenous salicylic acid on the physiological characteristics of Dendrobium officinale under chilling stress. *Plant Growth Regul.* **2016**, *79*, 199–208. [CrossRef]
47. Tang, Y.; Sun, X.; Wen, T.; Liu, M.; Yang, M.; Chen, X. Implications of terminal oxidase function in regulation of salicylic acid on soybean seedling photosynthetic performance under water stress. *Plant Physiol. Biochem.* **2017**, *112*, 19–28. [CrossRef] [PubMed]
48. Ghassemi-Golezani, K.; Farhangi-Abriz, S. Foliar sprays of salicylic acid and jasmonic acid stimulate H+-ATPase activity of tonoplast, nutrient uptake and salt tolerance of soybean. *Ecotoxicol. Environ. Saf.* **2018**, *166*, 18–25. [CrossRef]
49. Saleem, M.; Fariduddin, Q.; Castroverde, C.D.M. Salicylic acid: A key regulator of redox signalling and plant immunity. *Plant Physiol. Biochem.* **2021**, *168*, 381–397. [CrossRef]
50. Agamy, R.A.; Hafez, E.E.; Taha, T.H. Acquired resistant motivated by salicylic acid applications on salt stressed tomato (*Lycopersicum esculentum* Mill.). *Am. Eur. J. Agric. Environ. Sci.* **2013**, *13*, 50–57.
51. Ahmed, H.B.; Dhaou, N.; Wasti, S.; Mimouni, H.; Zid, E. Effects of Salicylic Acid on the Growth and Some Physiological Characters in Salt Stressed Tomato Plants (*Solanum Lycopersicum*). *J. Life Sci.* **2011**, *5*, 838–843.
52. Shahba, Z.; Baghizadeh, A.; Ali, V.S.M.; Ali, Y.; Mehdi, Y. The salicylic acid effect on the tomato (*Lycopersicon esculentum* Mill.) sugar, protein and proline contents under salinity stress (NaCl). *J. Biophy. Struct. Bio.* **2010**, *2*, 35–41.
53. El–Tayeb, M.A. Response of barley grains to the interactive effect of salinity and salicylic acid. *Plant Growth Regul.* **2005**, *45*, 215–224. [CrossRef]
54. Krantev, A.; Yordanova, R.; Janda, T.; Szalai, G.; Popova, L. Treatment with salicylic acid decreases the effect of cadmium on photosynthesis in maize plants. *J. Plant Physiol.* **2008**, *165*, 920–931. [CrossRef]
55. Alsahli, A.; Mohamed, A.K.; Alaraidh, I.; Al-Ghamdi, A.; Al-Watban, A.; El-Zaidy, M.; Alzahrani, S.M. Salicylic acid alleviates salinity stress through the modulation of biochemical attributes and some key antioxidants in wheat seedlings. *Pak. J. Bot.* **2019**, *51*, 1551–1559. [CrossRef]
56. Farhadi, N.; Ghassemi-Golezani, K. Physiological changes of Mentha pulegium in response to exogenous salicylic acid under salinity. *Sci. Hortic.* **2020**, *267*, 109325. [CrossRef]
57. Petrov, V.D.; Van Breusegem, F. Hydrogen peroxide—A central hub for information flow in plant cells. *AoB Plants* **2012**, *2012*, 1–13. [CrossRef]
58. Rodríguez-Rosales, M.; Kerkeb, L.; Bueno, P.; Donaire, J. Changes induced by NaCl in lipid content and composition, lipoxygenase, plasma membrane H+-ATPase and antioxidant enzyme activities of tomato (*Lycopersicon esculentum* Mill) calli. *Plant Sci.* **1999**, *143*, 143–150. [CrossRef]
59. Jini, D.; Joseph, B. Physiological mechanism of salicylic acid for alleviation of salt stress in rice. *Rice Sci.* **2017**, *24*, 97–108. [CrossRef]
60. Gechev, T.S.; van Breusegem, F.; Stone, J.M.; Denev, I.; Laloi, C. Reactive oxygen species as signals that modulate plant stress responses and programmed cell death. *BioEssays* **2006**, *28*, 1091–1101. [CrossRef]
61. Van Breusegem, F.; Dat, J.F. Reactive oxygen species in plant cell death. *Plant Physiol.* **2006**, *141*, 384–390. [CrossRef]
62. Bhattacharjee, S. Reactive oxygen species and oxidative burst: Roles in stress, senescence and signal transduction in plants. *Curr. Sci.* **2005**, *89*, 1113–1121.
63. Pitzschke, A.; Hirt, H. Mitogen-activated protein kinases and reactive oxygen species signaling in plants. *Plant Physiol.* **2006**, *141*, 351–356. [CrossRef] [PubMed]

SUPPLEMENTARY

Table S1. Effect of SA foliar spraying on chosen pepper plant parameters depending on acid concentration (mean ± SD)

Parameters	Concentration of salicylic acid				
	0 SA	1 mmol	2 mmol	5 mmol	10 mmol
Plant height (cm)	28.67 ± 0.47a*	25.00 ± 0.00b	20.67 ± 0.47c	17.67 ± 0.47d	12.00 ± 0.00e
Shoot diameter (mm)	8.00 ± 0.00d	14.67 ± 0.94a	12.00 ± 0.00b	10.00 ± 0.00c	8.00 ± 0.00d
Number of leaves (No.)	25.33 ± 0.47a	23.33 ± 0.47b	19.67 ± 0.47e	16.67 ± 0.47d	10.67 ± 0.47e
Plant weight (g)	60.00 ± 0.00bc	80.00 ± 0.01ab	90.00± 0.01a	60.00 ± 0.01bc	40.00 ± 0.00d
SPAD value	50.59 ± 5.00ab	56.14 ± 5.00a	47.32 ± 4.3b	48.97 ± 3.03b	35.90 ± 2.07c

* Means with different lowercase letters in the same row indicate a statistically significant difference according to the Tukey test ($p \leq 0.05$).

Table S2. Effect of SA root-applied on chosen pepper plant parameters depending on acid concentration (average of two terms ± SD).

Parameters	Concentration of salicylic acid				
	0 SA	100 ppm	150 ppm	500 ppm	1000 ppm
Plant height (cm)	28.67 ± 0.47a*	29.33 ± 0.47a	25.67 ± 0.47b	20.67 ± 0.47c	15.33 ± 0.47d
Shoot diameter (mm)	8.00 ± 0.00a	9.67 ± 0.00a	5.67 ± 0.00b	5.33 ± 0.00b	1.67 ± 0.00c
Number of leaves (No.)	25.33 ± 0.47a	20.33 ± 0.47b	15.00 ± 0.00c	11.00 ± 0.00d	6.00 ± 0.00e
Plant weight (g)	60.00 ± 0.001a	50.00 ± 0.003a	30.00 ± 0.00b	30.00 ± 0.002b	0.00 ± 0.000c
SPAD value	49.86 ± 4.80a	44.46 ± 5.00b	39.89 ± 2.58c	30.59 ± 2.59d	12.29 ± 2.74e

*Means with different lowercase letters in the same row indicate a statistically significant difference according to the Tukey test ($p \leq 0.05$).

Table S3. Effect of solution with different EC and SA treatment in hydroponic cultivation on height and number of leaves (average of two terms ± SD).

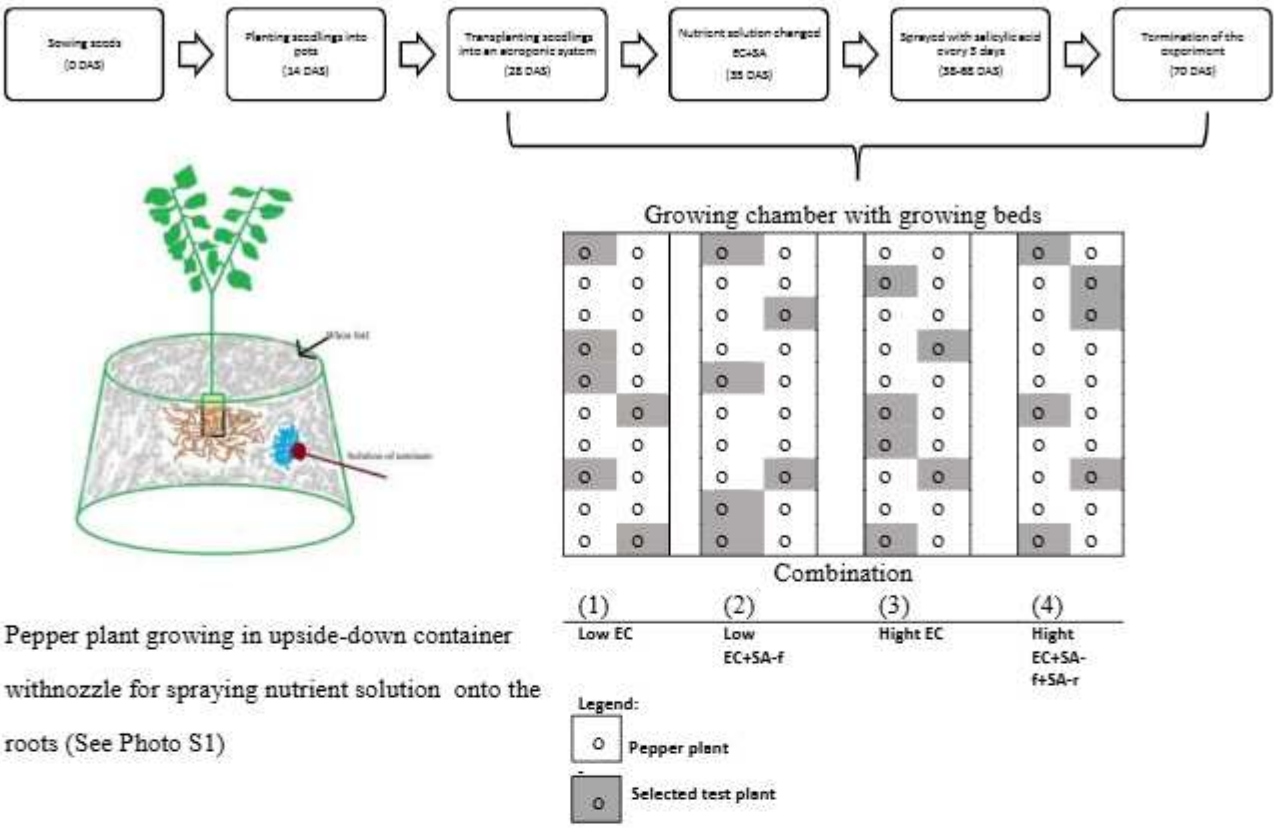
Plant parameters	Measurement dates	Combinations			
		Low EC	Low EC+SA-f	High EC	High EC SA-f +SA-r
Plant height (cm)	0 DAT	35.00 ± 1.22a*	35.25 ± 1.30a	35.75 ± 0.87a	33.50 ± 1.09a
	7 DAT	44.75 ± 1.09a	45.25 ± 1.30a	47.50 ± 2.60a	44.50 ± 1.12a
	14 DAT	62.50 ± 1.80a	63.00 ± 1.41a	60.50 ± 1.12a	61.50 ± 3.20a
	21 DAT	75.00 ± 2.45a	73.00 ± 1.00ab	71.25 ± 1.48ab	68.25 ± 3.35b
	28 DAT	93.25 ± 1.09a	91.25 ± 2.77a	83.75 ± 2.69b	81.50 ± 4.15b
Number of leaves	0 DAT	12.00 ± 0.70a	11.75 ± 0.83a	11.50 ± 0.50a	11.50 ± 1.12a
	7 DAT	13.00 ± 1.22a	13.00 ± 0.71a	13.50 ± 0.50a	13.50 ± 0.87a
	14 DAT	16.50 ± 0.50a	16.50 ± 0.50a	16.75 ± 0.83a	16.75 ± 0.43a
	21 DAT	18.00 ± 1.23a	18.00 ± 1.23a	17.25 ± 0.50a	17.50 ± 0.83a
	28 DAT	19.25 ± 0.83a	18.00 ± 0.71ab	17.50 ± 0.43b	16.75 ± 0.50b

*Means with different lowercase letters in the same row indicate a statistically significant difference according to the Tukey test ($p \leq 0.05$).

A See Graph S1

B

Photo S1. (A) Cultivation of peppers in an aeroponic system where upside-down containers with nozzles for spraying nutrient solution (one for each plant) onto the roots were covered with black and white film and a container for nutrient solution was installed at the beginning of each bed which was automatically pumped into the nozzles and fed to the plants (B) A sweet pepper plant cut into two fruiting shoots.



Pepper plant growing in upside-down container withnozzle for spraying nutrient solution onto the roots (See Photo S1)

Graph S1. Diagram of the conduct of the experiment. Four growing beds, one individual aeroponic system for each combination (20 plants each). Randomly selected test plants for physiological and biochemical measurements are marked (See Photo S1)

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Article

Effect of Salicylic Acid and Calcium on Growth, Yield, and Fruit Quality of Pepper (*Capsicum annuum* L.) Grown Hydroponically

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Abstract: The aim of this study was to investigate the effects of spraying plants with 0.03% salicylic acid (SA), 0.7% calcium nitrate (Ca), and 0.03% salicylic acid together with 0.7% calcium nitrate (SA + Ca) on plant growth, yield, and fruit quality of peppers grown in a mineral wool substrate. The control plants were sprayed with water (C). Two red-fruited sweet pepper cultivars were used in the study: 'Aifos', and 'Palermo', which produce fruits characterized by different shapes. Biometric measurements of the plants showed a higher growth rate of pepper plants when SA and Ca were applied foliarly compared to the control. Plants treated simultaneously with SA and Ca were characterized by the highest steady-state fluorescence yield [Fs]. The relative chlorophyll content of pepper leaves was also higher in plants sprayed with SA, Ca, and SA + Ca than in plants in the control. The analysis of pepper yield showed in both cultivars the effect of foliar treatment of plants with SA and Ca and SA + Ca on increasing pepper resistance to the occurrence of Ca deficiency on pepper fruit (Blossom end rot). Pepper fruits harvested from plants treated with SA, Ca, and SA + Ca had more juicy flesh.

Keywords: CIE Lab; physiological disorder BER; chlorophyll a fluorescence; SPAD index; sensory quality

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1. Introduction

The genus Capsicum includes 40 plant species [1], among which are vegetables and spice plants, including sweet pepper (*Capsicum annuum* L.). After the potato and tomato, peppers are the third most economically important vegetable in the *Solanaceae* family [2]. The cultivated varieties of pepper differ in fruit shape (block, conical, oblong fruit), fruit size and color, and pericarp wall thickness, among others. In commercial production, the most popular sweet pepper varieties are those with fleshy block-type fruit colored red. They are used primarily for fresh consumption but also in processing and for dried or frozen foods [3]. Pepper fruits have a high value in terms of health benefits. They contain bioactive compounds, including phenols, carotenoids, and antioxidants such as β-carotene, or provitamin A, and vitamin C [4–6]. The vitamin C content of pepper fruit depends on a number of factors, including cultivar, cultivation method, weather conditions, and fruit maturity. Its content in ripe fruit of sweet pepper varieties varies between 62 and 150 mg in 100 g of fresh weight. However, there are known varieties whose fruit contains up to 350 mg of ascorbic acid in 100 g of fresh weight [7].

Demand for fresh, good-quality pepper fruits is high throughout the year. Peppers require adequate temperature and plenty of light for proper yield [8]. Such conditions for growing peppers throughout the year can be achieved under covers. Commercial pepper production in temperate climate countries is carried out both in plastic tunnels using conventional, soil-based cultivation and also in year-round greenhouses using soilless cultivation technology, including hydroponics [9]. Soilless culture systems (SCS) are

increasingly being used for vegetable cultivation in the high-tech greenhouse production industry. Soilless cultivation is often referred to as 'hydroponics'. Soilless cultivation using different growing media (substrates), such as rockwool, perlite, and coconut, is the most commonly used SCS in the world for the production of fruit and vegetables, including peppers. This technology of greenhouse pepper production in mineral wool is very popular in the Netherlands [10–13].

The quality of fruit is influenced by a number of cultivation factors. An undesirable phenomenon is the Blossom end rot (BER) physiological disorder, the symptoms of which are located on the fruit, reducing the marketable yield of peppers [14]. The causes of BER are related, among other things, to water stress, which reduces Ca transport in the plant. Too low concentration of Ca in the fruit, particularly at the top of the fruit, results in dry, brown spots, a characteristic of BER. The symptoms of this disorder can cover up to half of the fruit surface. Most often, the onset of the spots is a darkening of the tissues at the top of the fruit resulting from cell death. The appearance of BER symptoms is the result of cell membrane rupture and irregular softening of cell walls due to enzymatic processes of pectin chain breakdown, which is caused by Ca deficiency in the fruit [15]. Calcium is an essential plant nutrient, mainly used for cell wall construction, and cell signaling response, cell membrane stability, and selectivity [16]. Ca^{2+} ions can bind strongly with organic acids (e.g., in vacuoles), limiting Ca mobility [17]. Calcium is relatively immobile in the phloem. Therefore, the contribution of phloem transport to Ca distribution may be limited [18]. Calcium uptake by the root system is transported via the xylem to various tissues and organs [19].

Among the exogenous substances that reduce the adverse effects of various abiotic and biotic stresses in plants, calcium has proven to be effective. Calcium is used not only as an essential nutrient for plant growth but also as a component actively involved in various metabolic processes and as an intracellular messenger for many signal transductions such as abscisic acid (ABA) and reactive oxygen species (ROS) et al. [20,21]. Nowadays, foliar fertilization is widely used as a treatment to complement root fertilization [22] and provide plants with nutrients with limited mobility, such as Ca or micronutrients, among others [23,24].

Salicylic acid is a natural growth regulator of vascular plants that influences plant physiological and metabolic processes, including photosynthesis, transpiration, and transport [25–28]. Foliar application of salicylic acid can reduce the negative effects of stresses and increase the yield of susceptible vegetable species [29]. The first observations on the involvement of SA in plant resistance were made by Raymond F. White in 1979 [30]. The use of acetylsalicylic acid in virus-susceptible tobacco (*Nicotiana tabacum* cv. *Xanthinc*) resulted in the development of resistance to TMV—tobacco mosaic virus [31]. In tobacco with a virus-resistance gene, an increase in endogenous SA levels was found following virus infection, and, at the same time, an accumulation of pathogenesis-related PR (Pathogenesis-Related) proteins was found [32]. SA also has functions in plant development, ranging from seed germination to fruiting, DNA repair, and a variety of abiotic stress tolerance mechanisms [33,34]. However, different vegetable species and cultivars respond very differently to exogenous salicylic acid [35].

Due to the occurrence of high temperatures under covers, especially in summer, peppers are exposed to abiotic stress. The main effect of this stress is a high proportion of non-marketable pepper fruits with BER symptoms. For many years, numerous studies have been conducted on effective ways to reduce the occurrence of calcium deficiency symptoms in peppers and other vegetable species. However, there are few reports on the effect of salicylic acid in reducing BER in peppers grown hydroponically. Hydroponic cultivation of peppers in the greenhouse in an inert substrate is increasingly used due to the high efficiency of irrigation and plant nutrition. On the other hand, problems with physiological disorders occurring in the cultivation result in reduced yield quality. The aim of this study was to evaluate the effects of both calcium nitrate and salicylic acid on the growth, yield, and quality of pepper fruit grown hydroponically.

2. Materials and Methods

2.1. Location of Research

The research was conducted at the Greenhouse Experimental Centre of the Warsaw University of Life Sciences [longitude 21° E, latitude 51°15′ N] in the cultivation chambers of the Department of Vegetable and Medicinal Plants.

2.2. Plant Material and Experimental Conditions

Two red-fruited sweet pepper cultivars were selected for the study: 'Aifos'—with block fruit Seminis brand by Bayer, and 'Palermo'—with elongated pointed fruit by Rijk Zwaan. The 'Aifos' cultivar is characterized by rapid and strong growth, with no tendency to spread. The fruit is 3–4 chambered, red, block type, resistant to cracking, with a long and strong stalk. The flesh thickness of 'Aifos' pepper fruit reaches 10 mm, and the average fruit weight is 220 g. Plants of the 'Palermo' cultivar have a strong root system and a loose habit. The 'Palermo' fruit is elongated, of the Dulce Italiano type, and has a high sugar content. The skin of the fruit of this cultivar is very fine, smooth, and shiny. The average weight of a 'Palermo' fruit is 125 g.

The studies were conducted in two years—2019 (term 1) and 2020 (term 2). In term 1 and equally in term 2, pepper seedlings were planted on 13 May, and cultivation was completed on 15 October. On both dates, the peppers were grown hydroponically in a mineral wool substrate. To prepare the pepper seedlings, seeds of both cultivars were sown into mineral wool plugs on 1 March and 7 March 2019, and 2 March and 6 March 2020. The mineral wool plugs used for sowing seeds were soaked in a nutrient solution before sowing. The plugs were pre-soaked in a nutrient solution with an EC (electrical conductivity) of approximately 1.4 $dS \cdot m^{-1}$ and pH 5.5. The seedling nutrient solution contained the following components in $mg \cdot dm^{-3}$: $N\text{-}NO_3$-195, P-57, K-273, Mg-47, Ca-187, Fe-2, Mn-0.6, B-0.3, Cu-0.15, Zn-0.3, Mo-0.05. After sowing, the seeds were covered with vermiculite and placed in an air-conditioning chamber (Sharma Scientific Co., Delhi, India) at 28 °C day/night (D/N) until the seeds germinated 7 days after sowing (DAS). The pepper seedling plugs (14 DAS) were then placed in Grodan Delta mineral wool cubes by Grodan (measuring 10 cm × 10 cm × 6.5 cm), soaked in nutrient solution with EC 2.8 $dS \cdot m^{-1}$ and pH 5.5. The ready pepper seedlings were planted into mineral wool growing mats on 28 DAS. Grotop Master cultivation mats by Grodan were used in the experiment (measuring 100 cm × 20 cm × 10 cm). There were 8 beds in the cultivation chamber, each bed about 9 m long and about 1 m wide. There were 9 cultivation mats of mineral wool and 3 pepper plants per mat (Figure S4). Each plant was cut into two shoots. The plant density in the chamber was 2.5 plants per 1 m^2 of growing area. The nutrient solution was dosed to each plant with a single capillary. The nutrient solution was dosed by computer in amounts based on the light conditions and the age of the plants. The nutrient solution concentrated 100 times in tanks A and B was prepared from single fertilizers. The composition of the basic nutrient solution for pepper cultivation was in $mg \cdot dm^{-3}$: $N\text{-}NO_3$-230, P-57, K-330, Mg-55, Ca-180, Fe-2.5, Mn-0.8, B-0.33, Cu-0.15, Zn-0.33, Mo-0.05. The parameters of the capillary nutrient solution averaged over the growing period were EC from 2.9 to 3.2 $dS \cdot m^{-1}$ and pH 5.5–5.8.

Microclimate parameters were controlled with the Hortimax system. In the cultivation chamber, the average day temperature in term 1 was 25.5 °C and 20.9 °C at night, and in term 2, it was 25.8 °C and 20.8 °C, respectively. Very often, during the vegetation period of the plants in each of the cultivation dates studied, the average day temperature was close to 30 °C, and the night temperature was 25 °C. The reason for such high temperatures in the greenhouse was high solar radiation. The radiation sum in term 1 during the growing season of the plants was 192.11 kJ/cm^2, while in term 2 it was 209.41 kJ/cm^2. The daily radiation totals averaged 1231 J/cm^2 in term 1 and 1342 J/cm^2 in term 2 (Figures S1–S3).

The pepper plants were cut into two shoots, removing the side shoots during the treatment. In the main branching of the pepper plants, the first fruit bud was removed. The two strongest shoots were then brought out, and each was wrapped with polypropylene string tied to two wires stretched in parallel at a height of about 3 m above the cultivation bed. Each

pepper shoot was tied with string to a different wire, forming a 'V' plant guidance system. Plants were cut, and excess vegetative parts (e.g., leaves, side shoots) and generative parts (flowers, fruit set) were removed in such a way that one node contained 1 leaf, 1 set, and a side shoot with 1 leaf (1 fruit and 2 leaves). Pruning of the peppers started on 18 DAP (the day after planting) and was carried out every two weeks, depending on the growth of the plants.

Yellow sticky traps from Horiver and Swirski-Mite Plus sachets from Koppert containing the predatory mite species *Amblyseius swirskii* were used for plant protection and pest monitoring.

2.3. Experiential Factors

The research investigated the effect of foliar treatments on plants of two pepper cultivars with individual treatment of salicylic acid (SA), individual treatment of calcium nitrate (Ca), and simultaneous treatment of salicylic acid in combination with calcium nitrate (SA + Ca). The control consisted of plants sprayed with water (C). The experiment was designed using the randomized block method. There were four replicates for each combination, with six plants in each combination.

Plants were sprayed once a week between 7 DAP and 151 DAP. In the (SA) combination, plants were sprayed with individual treatment of salicylic acid at a concentration of 0.03% [34–36]; in the (Ca) combination, plants were sprayed with individual treatment of calcium nitrate at a concentration of 0.7% [37], and in the (SA + Ca) combination plants were sprayed with salicylic acid together with calcium nitrate at a concentration of 0.03% and 0.7%, respectively. Control plants were sprayed with water (C).

2.4. Evaluated Parameters

2.4.1. Biometric Measurements of Plants

In each combination, six representative test plants were selected and measured once a week between 7 DAP and 158 DAP to determine the plant height and the number of fully developed leaves per pepper plant. Plant height was measured with a tape measure from the root neck to the top of the plant. The number of leaves per plant was reported as the sum of the fully developed leaves located on the two shoots of the plant.

2.4.2. Photosynthetic Activity of Pepper Plants

Twice during the cultivation period, on 31 DAP and 102 DAP, modulated chlorophyll a fluorescence of pepper leaves was measured on pepper test plants using an FMS-2 fluorimeter (Hansatech Instruments Ltd., King's Lynn, Norfolk, England). Active, fully mature leaves that were at two developmental stages were selected for measurement: a younger, fully developed 5th leaf, counting from the top of the plant, and an older 10th leaf, counting from the top of the plant. Steady-state fluorescence yield [Fs], light-adapted fluorescence maximum [Fm'] and photosystem II quantum yield [ΦPSII] were measured on these leaves. At the same locations on the leaf, after the leaf had been adapted to darkness for 30 min using special clips, the maximum quantum yield of PSII [Fv/Fm] and the PSII lifetime index [PI] were measured using a Handy PEA fluorometer (Hansatech Instruments Ltd., King's Lynn, Norfolk, England). The relative chlorophyll content of the leaves was then measured at these locations. The measurement was made with a Minolta SPAD-502 Plus chlorophyll meter, and the result was given as an SPAD index. The result was the average of 5 unit measurements taken on one leaf, each at several millimeters apart, avoiding the locations of the conductive bundles in the leaf.

2.4.3. Pepper Fruit Yield

Pepper fruits were harvested at harvest maturity as discolored fruits and fully colored fruits. Harvesting started at 56 DAP, and fruits were harvested as they matured every 10 days or so, up to 158 DAP, both in term 1 and term 2. Harvested fruits were weighed and counted. The weight and number of fruits of total yield (TY), marketable yield (MY), and fruit with BER symptoms were determined.

2.4.4. Dry Matter Content and Color Measurement of the Fruit

Five fruits from each combination were randomly selected for analysis at two time points (84 DAP and 140 DAP). The fruits, without seeds and seed sepals, were cut into small cubes of approximately 4 mm × 4 mm, and representative samples for analysis were taken in triplicate from the fruit samples cut and mixed. The dry matter content of the pepper fruits was determined using the dry-weight method at 105 °C (SUP-65W laboratory dryer, Wamed, Warsaw, Poland). Fruit skin color at each date was measured on three randomly selected fruits from each combination using a MiniScan XE PLUS D/8-S portable color spectrophotometer on the CIE L*a*b* system scale, where L*—lightness [from 0 to 100 units], a*—intensity of red [a* > 0] or green [a* < 0], b*—intensity of yellow [b* > 0] or blue [b* < 0].

2.4.5. Sensory Evaluation of Pepper Fruit Quality

Sensory quality testing of pepper fruits was performed in the Sensory Analysis Laboratory of the Department of Vegetable and Medicinal Plants, which complies with the standards PN-EN ISO 8589:2010/A1:2014-07 [38]. The quantitative descriptive analysis method QDA (Quantitative Description Analysis) was used for the evaluation according to the procedure included in the PN-ISO standard [39–41]. The evaluation was carried out immediately after harvesting the fully colored fruits on two dates: 84 DAP and 140 DAP, both in term 1 and term 2. On each measurement date, 5 fruits from each combination were randomly selected for analysis. Each sample consisted of 3 elongated sticks of pepper fruit pericarp (approximately 80 mm × 40 mm in size). The evaluation team consisted of 18 trained individuals.

The qualitative characteristics of odor, texture, and flavor of pepper fruits harvested from plants from all tested combinations were evaluated. The overall impression relating to sensory quality was also assessed as a separate differentiator. The consumer evaluation concerned general desirability and taste desirability. It was carried out by the same team of 18 people as the profile sensory evaluation, marking on a linear scale of 0 to 10 contractual units [c.u.], with boundary markings: scale minimum—very undesirable; maximum—very desirable. The sensory quality attributes of the pepper fruits were evaluated, and their definitions are presented in Table 1.

Table 1. Pepper fruits sensory descriptors and definitions.

Quality Descriptor		Definition	Anchoring Points
Odor	Odor of fresh pepper fruit	Odor characteristic of fresh pepper fruit	None—very intensive
Texture	Skin hardness	Degree of force needed to bite the skin	Soft—very hard
	Flesh fibrousness	Mouthfeel of flesh homogeneity	Smooth—very fibrous
	Flesh firmness	Degree of force needed for chewing the flesh	Soft—companies
	Flesh juiciness	Amount of liquid released when the sample is chewed	Not very juicy
Flavor and taste descriptors	Typical pepper flavor	Flavor characteristic of fresh sweet pepper fruit	None—very intensive
	Sour taste	Basic taste	Not very intensive
	Sweet taste	Basic taste	Not very intensive
	Bitter taste	Basic taste	Not very intensive
	Pungent flavour	Flavor which gives an impression of burning on the tongue	None—very intensive
	Off-flavor	Untypical flavor of pepper fruit	None—very intensive
Overall quality	Overall quality	General sensory quality impression	Low-quality—high-quality fruit
	Overall desirability and overall taste desirability	Overall consumer quality	Highly undesirable—highly desirable

2.5. Statistical Analysis

Statistical analysis was performed using one-factor, two-factor, and three-factor analysis of variance, ANOVA (Statistica, version 13, Warsaw, Poland). A detailed comparison of means was performed using the Tukey test at a significance level of $\alpha = 0.05$.

When developing the results of the sensory quality evaluation of the peppers, the ANALSENS ver. 6 program was used to prepare the tests, record individual evaluations, and statistically process the results.

3. Results

3.1. Biometric Measurements of Plants

The results of the biometric measurements showed the effect of the treatment of peppers with individual treatments of SA and Ca on plant growth and the number of leaves in peppers. Weekly pepper shoot length growth depended on plant treatment and cultivar. Spraying peppers with individual treatment of calcium nitrate influenced higher weekly shoot growth of peppers compared to control plants sprayed with water (Table 2).

Table 2. Effect of salicylic acid and calcium treatment of pepper plants on weekly growth of the stem, height of the plant, and number of leaves depending on cultivar [±SE].

Parameter	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Weekly growth of stem [cm]	'Aifos'	term 1	19.7 ± 1.99 ns	20.3 ± 1.77 ns	19.2 ± 1.77 ns	16.8 ± 1.69 ns *
		term 2	19.7 ± 1.99 ns	20.5 ± 1.76 ns	18.2 ± 1.77 ns	16.8 ± 1.69 ns
		Average	19.8 ± 1.42 NS	20.4 ± 1.25 NS	18.2 ± 1.25 NS	16.8 ± 1.20 NS
	'Palermo'	term 1	22.5 ± 2.05 ns	25.3 ± 2.17 ns	23.1 ± 1.89 ns	20.7 ± 1.55 ns
		term 2	24.6 ± 2.37 ns	25.3 ± 2.17 ns	23.1 ± 1.89 ns	20.7 ± 1.55 ns
		Average	23.5 ± 1.57 NS	25.3 ± 1.53 NS	23.1 ± 1.34 NS	20.8 ± 1.10 NS
	Average		21.7 ± 2.12 AB	22.8 ± 1.99 A	20.6 ± 1.85 AB	18.8 ± 1.64 B
Height of plant [cm]	'Aifos'	term 1	142.9 ± 6.21 ns	139.9 ± 6.00 ns	135.6 ± 5.24 ns	133.5 ± 5.15 ns
		term 2	142.4 ± 6.39 ns	139.1 ± 6.13 ns	134.0 ± 5.27 ns	131.7 ± 5.15 ns
		Average	142.7 ± 4.46 NS	139.5 ± 4.29 NS	134.8 ± 3.72 NS	132.6 ± 3.65 NS
	'Palermo'	term 1	172.8 ± 6.24 ns	170.5 ± 6.37 ns	170.8 ± 5.87 ns	159.2 ± 6.12 ns
		term 2	171.5 ± 6.28 ns	167.5 ± 6.37 ns	169.7 ± 5.95 ns	158.1 ± 6.18 ns
		Average	172.1 ± 4.43 NS	169.0 ± 4.51 NS	170.2 ± 4.19 NS	158.6 ± 4.36 NS
	Average		157.4 ± 0.25 A	154.3 ± 3.19 AB	152.5 ± 2.97 AB	145.6 ± 2.93 B
No. of leaves [No./plant]	'Aifos'	term 1	30.8 ± 1.02 a	30.7 ± 0.97 a	27.3 ± 0.82 ab	27.4 ± 0.79 ab
		term 2	28.3 ± 1.07 ab	27.9 ± 0.97 ab	24.4 ± 0.82 b	24.5 ± 0.78 b
		Average	29.5 ± 0.75 A	29.25 ± 0.69 A	25.8 ± 0.59 B	25.9 ± 0.57 B
	'Palermo'	term 1	39.0 ± 1.25 a	37.9 ± 1.02 a	35.3 ± 1.25 ab	32.7 ± 1.03 bc
		term 2	36.0 ± 1.23 ab	34.9 ± 1.03 ab	32.4 ± 0.92 bc	29.8 ± 1.02 c
		Average	37.5 ± 0.89 A	36.4 ± 0.74 AB	33.9 ± 0.66 BC	31.3 ± 0.74 C
	Average		33.5 ± 0.62 A	32.8 ± 0.54 A	29.9 ± 0.49 B	28.6 ± 0.49 B

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to the combination term × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

The 'Palermo' plants had longer weekly shoot growth than the 'Aifos' plants. Plants sprayed with individual treatment of SA were more than 11 cm higher on 158 DAP than plants in the control. Spraying peppers with salicylic acid and SA + Ca influenced higher weekly shoot growth of peppers compared to control plants. Plants treated with foliar individual treatment of SA, individual treatment of Ca, and SA + Ca were higher than control plants. Peppers treated with both individual treatments of SA and Ca had more leaves than plants in the control (Table 2). Plants of the 'Palermo' cultivar were higher

than those of the 'Aifos' cultivar, reaching an average height of about 172 cm by 158 DAP, while plants of the 'Aifos' cultivar reached about 143 cm (Table 2). Plants treated with individual treatment of SA and individual treatment of Ca had a higher number of leaves per plant than the control and plants treated simultaneously with SA and Ca (SA + Ca). The parameters of plant height and number of leaves reached higher values for the cultivar 'Palermo' than for 'Aifos' (Table 2; Figure S5).

3.2. Photosynthetic Activity of Peppers

The highest steady-state fluorescence yield was found in plants treated simultaneously with SA and Ca—SA + Ca combination (Table 3). The highest value of the Fs parameter of chlorophyll a fluorescence was found in younger 5th leaves, counting from the top of the plant in the cultivar 'Palermo', and the lowest in older 10th leaves, counting from the top of the pepper shoot in the cultivar 'Aifos'. It was found that plants sprayed simultaneously with SA and Ca had a lower quantum yield of photosystem II than plants from the other combinations. The highest maximum PSII quantum yield was found in plants treated with individual treatment of Ca compared to the control and plants treated with individual treatment of SA. The PSII viability index was also higher in plants treated with individual treatment of Ca than in control plants. Young 5th leaves had the highest PI in the 'Aifos' cultivar in the combination sprayed with individual treatment of SA. Older 10th leaves, counting from the top of the pepper shoot, had the lowest PI in 'Palermo' plants in the combination where Ca was applied together with SA (SA + Ca) (Table 3). The relative chlorophyll content of pepper leaves was significantly higher in plants sprayed with individual treatment of SA, individual treatment of Ca, and SA + Ca than in the control. The results indicate that the SPAD index values were higher in the 10th leaves than in the 5th leaves (Table 3). In the 'Aifos' plants treated with individual treatment of SA in the 10th leaves, counting from the shoot apex, the relative chlorophyll content was the highest. However, in the cultivar 'Palermo', in plants sprayed together with SA and Ca, the 5th leaves, counting from the shoot apex, obtained a higher SPAD index than the 5th leaves in the control (Table 3). No differences were found between cultivars for the parameters Fm, ΦPSII, Fv/Fm, and SPAD (Figure S6).

Table 3. Effect of salicylic acid and calcium treatment of pepper plants on selected chlorophyll a fluorescence parameters and chlorophyll index of leaves depending on cultivar [mean of two terms ± SE].

Parameter	Cultivar	Leaf Stage	Treatment			
			SA	Ca	SA + Ca	Control
Fs	'Aifos'	5th	512.8 ± 18.4 bc	582.2 ± 24.8 abc	627.9 ± 35.4 ab	523.8 ± 25.7 bc *
		10th	478.6 ± 24.6 c	495.7 ± 33.3 bc	664.9 ± 52.6 a	549.9 ± 27.8 abc
		Average	495.7 ± 13.9 B	538.9 ± 21.5 B	646.4 ± 31.8 A	536.9 ± 19.0 B
	'Palermo'	5th	606.6 ± 24.1 ns	568.8 ± 27.7 ns	755.6 ± 32.2 ns	534.9 ± 28.6 ns
		10th	582.5 ± 35.1 ns	571.2 ± 36.9 ns	574.6 ± 32.0 ns	553.3 ± 34.3 ns
		Average	594.5 ± 21.3 NS	569.9 ± 23.1 NS	665.1 ± 20.0 NS	544.1 ± 20.9 NS
	Average		545.2 ± 13.4 B	554.5 ± 15.8 B	655.7 ± 16.7 A	540.5 ± 14.1 B
Fm	'Aifos'	5th	2026.0 ± 63.3 ns	2902.0 ± 110.1 ns	2147.0 ± 76.0 ns	2031.4 ± 86.0 ns
		10th	2044.5 ± 100.0 ns	2166.4 ± 121.6 ns	2303.6 ± 81.1 ns	2131.4 ± 90.9 ns
		Average	2035.3 ± 50.9 NS	2534.2 ± 60.1 NS	2225.3 ± 56.4 NS	2081.4 ± 62.9 NS
	'Palermo'	5th	2318.8 ± 80.5 ns	2188.0 ± 94.0 ns	2438.1 ± 140.0 ns	2090.9 ± 104.3 ns
		10th	2251.7 ± 86.6 ns	2287.9 ± 112.1 ns	2162.2 ± 99.5 ns	2122.2 ± 103.0 ns
		Average	2285.2 ± 59.3 NS	2237.9 ± 73.4 NS	2300.1 ± 55.9 NS	2106.6 ± 66.3 NS
	Average		2160.2 ± 40.6 NS	2386.1 ± 44.2 NS	2262.7 ± 43.0 NS	2094.0 ± 45.7 NS

Table 3. *Cont.*

Parameter	Cultivar	Leaf Stage	Treatment			
			SA	Ca	SA + Ca	Control
ΦPSII	'Aifos'	5th	0.74 ± 0.00 abc	0.73 ± 0.02 abc	0.69 ± 0.02 c	0.74 ± 0.01 abc
		10th	0.76 ± 0.02 ab	0.76 ± 0.01 a	0.70 ± 0.02 bc	0.74 ± 0.01 abc
		Average	0.75 ± 0.00 A	0.75 ± 0.01 A	0.70 ± 0.02 B	0.74 ± 0.01 A
	'Palermo'	5th	0.73 ± 0.01 ns	0.73 ± 0.01 ns	0.71 ± 0.01 ns	0.75 ± 0.00 ns
		10th	0.74 ± 0.01 ns	0.74 ± 0.01 ns	0.73 ± 0.02 ns	0.75 ± 0.02 ns
		Average	0.73 ± 0.01 NS	0.74 ± 0.01 NS	0.72 ± 0.01 NS	0.75 ± 0.00 NS
	Average		0.74 ± 0.001 A	0.75 ± 0.003 A	0.71 ± 0.01 B	0.75 ± 0.001 A
Fv/Fm	'Aifos'	5th	0.81 ± 0.008 abc	0.82 ± 0.007 ab	0.80 ± 0.006 c	0.81 ± 0.002 bc
		10th	0.81 ± 0.003 abc	0.82 ± 0.003 a	0.81 ± 0.008 abc	0.81 ± 0.008 bc
		Average	0.81 ± 0.001 B	0.82 ± 0.008 A	0.81 ± 0.003 B	0.81 ± 0.005 B
	'Palermo'	5th	0.80 ± 0.009 ns	0.81 ± 0.002 ns	0.80 ± 0.001 ns	0.80 ± 0.006 ns
		10th	0.80 ± 0.001 ns	0.81 ± 0.007 ns	0.80 ± 0.005 ns	0.80 ± 0.04 ns
		Average	0.80 ± 0.002 AB	0.81 ± 0.002 A	0.80 ± 0.005 B	0.80 ± 0.002 B
	Average		0.81 ± 0.006 B	0.82 ± 0.001 A	0.80 ± 0.003 B	0.80 ± 0.004 B
PI	'Aifos'	5th	7.7 ± 0.33 a	7.6 ± 0.36 ab	7.3 ± 0.40 ab	7.0 ± 0.30 ab
		10th	6.9 ± 0.41 ab	7.3 ± 0.35 ab	6.8 ± 0.26 ab	6.2 ± 0.33 b
		Average	7.3 ± 0.25 AB	7.4 ± 0.25 A	7.1 ± 0.24 AB	6.6 ± 0.23 B
	'Palermo'	5th	6.7 ± 0.24 ns	6.7 ± 0.28 ns	6.2 ± 0.28 ns	6.4 ± 0.29 ns
		10th	6.2 ± 0.25 ns	6.5 ± 0.33 ns	5.8 ± 0.21 ns	6.2 ± 0.37 ns
		Average	6.4 ± 0.17 A	6.6 ± 0.22 A	6.0 ± 0.18 A	6.3 ± 0.22 A
	Average		6.9 ± 0.15 AB	7.0 ± 0.17 A	6.5 ± 0.15 AB	6.4 ± 0.16 B
SPAD	'Aifos'	5th	65.4 ± 1.10 c	64.3 ± 0.91 c	65.7 ± 1.01 c	64.0 ± 1.39 c
		10th	72.2 ± 2.29 a	71.4 ± 0.75 a	70.8 ± 2.30 ab	66.7 ± 0.93 bc
		Average	68.8 ± 0.78 NS	67.8 ± 0.74 NS	66.8 ± 0.90 NS	68.2 ± 0.72 NS
	'Palermo'	5th	63.2 ± 0.98 cd	64.0 ± 1.01 cd	66.1 ± 1.21 bc	60.2 ± 1.13 d
		10th	70.9 ± 0.93 a	70.7 ± 0.98 a	69.8 ± 0.80 ab	66.0 ± 2.25 bc
		Average	67.0 ± 0.84 NS	67.3 ± 0.82 NS	65.6 ± 0.73 NS	67.9 ± 0.81 NS
	Average		67.9 ± 0.57 A	67.6 ± 0.55 A	68.1 ± 0.75 A	64.2 ± 0.58 B

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to combination leaf stage × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

3.3. Pepper Yields

Total pepper fruit yield and marketable yield did not differ significantly between plants treated with individual treatment of SA and individual treatment of Ca or SA + Ca treatment compared to the control, although in term 1, the marketable yield in the 'Aifos' cultivar treated with individual treatment of SA was significantly higher than in the control. In term 2, there was also such a trend, but the difference was not statistically significant (Table 4). Plants in the control showed a higher fruit weight affected by BER than plants in which both individual treatment of SA and individual treatment of Ca were applied weekly and in combination where plants were sprayed simultaneously with SA + Ca. The average weight of marketable pepper fruit was higher in plants sprayed with individual treatment of SA and individual treatment of Ca than in the control (Table 4). The marketable yield of the cultivar 'Palermo' was lower than that of the cultivar 'Aifos', especially in term 1. A higher fruit weight with BER was found in this cultivar compared to the cultivar 'Aifos' (Table 4). The number of fruits in total yield was higher in control plants than in plants treated with individual treatment of SA or individual treatment of Ca. In marketable yield, there were no significant differences in fruit number between combinations. The number of fruits in total yield in the cultivar 'Aifos' was lower than in the cultivar 'Palermo'

(Table 5). In term 1, the cultivar 'Aifos' in total yield, on average of the combinations tested, produced about 18.5 fruits per plant during the growing season, and in term 2, it produced, on average, 16.9 fruits per plant. The cultivar 'Palermo', on the other hand, produced 43.7 and 46.4 fruits per plant, respectively (Table 5). For marketable yield in term 1, the cultivar 'Palermo' had more marketable fruit in combination with individual treatment of SA and individual treatment of Ca than in the control (Table 5). For fruit with BER occurrence, plants sprayed with individual treatment of SA and individual treatment of Ca, and in the SA + Ca combination, had less fruit with BER than the control. The cultivar 'Palermo' had more fruit with BER symptoms than the cultivar 'Aifos' (Table 5). Total yield did not differ significantly between cultivars, while for the average weight of fruit and marketable yield parameter, lower values were found for the 'Palermo' cultivar compared to 'Aifos'. The cultivar 'Palermo' had higher values for the following parameters: number of fruits TY, number of fruits MY, number of fruits with BER, and weight of fruits with BER (Figure S7).

Table 4. Effect of salicylic acid and calcium treatment of pepper plants on total and marketable yield, fruit with BER, and average weight of fruit depending on cultivar [±SE].

Parameter	Cultivar	Term of Growing	Treatment			
			SA	Ca	Ca + SA	Control
Total yield [kg/plant]	'Aifos'	Term 1	3.0 ± 1.15 ns	2.5 ± 1.49 ns	2.5 ± 1.56 ns	2.5 ± 0.83 ns *
		Term 2	3.0 ± 0.34 ns	2.9 ± 2.03 ns	3.2 ± 0.36 ns	3.1 ± 0.81 ns
		Average	3.0 ± 1.13 NS	2.7 ± 1.77 NS	2.8 ± 1.90 NS	2.8 ± 1.46 NS
	'Palermo'	Term 1	2.8 ± 1.28 ab	2.7 ± 0.95 ab	2.3 ± 0.30 b	2.1 ± 1.01 b
		Term 2	3.1 ± 2.14 ab	2.6 ± 5.41 ab	3.8 ± 2.21 ab	4.2 ± 1.39 a
		Average	2.9 ± 2.07 NS	2.7 ± 3.36 NS	3.0 ± 3.01 NS	3.2 ± 3.92 NS
	Average		3.0 ± 1.11 NS	2.7 ± 1.79 NS	2.9 ± 1.69 NS	3.0 ± 2.02 NS
Marketable yield [kg/plant]	'Aifos'	Term 1	2.3 ± 1.10 ab	2.0 ± 1.71 ab	1.7 ± 1.49 ab	1.4 ± 1.06 b
		Term 2	2.5 ± 0.72 a	2.4 ± 1.75 ab	2.4 ± 1.65 ab	2.3 ± 0.59 ab
		Average	2.4 ± 1.10 NS	2.2 ± 1.96 NS	2.0 ± 2.11 NS	1.8 ± 1.72 NS
	'Palermo'	Term 1	1.0 ± 0.76 abc	1.0 ± 0.36 abc	0.7 ± 0.72 bc	0.3 ± 0.43 c
		Term 2	1.5 ± 1.72 ab	1.3 ± 2.58 abc	2.1 ± 1.23 a	2.1 ± 1.00 a
		Average	1.3 ± 1.64 NS	1.1 ± 2.00 NS	1.4 ± 2.69 NS	1.2 ± 3.21 NS
	Average		1.8 ± 1.63 NS	1.7 ± 1.79 NS	1.7 ± 1.79 NS	1.5 ± 1.87 NS
Fruit with BER [kg/plant]	'Aifos'	Term 1	0.8 ± 0.52 ab	0.5 ± 0.77 b	0.8 ± 0.23 ab	1.1 ± 0.56 a
		Term 2	0.5 ± 0.71 b	0.6 ± 0.36 b	0.8 ± 0.75 ab	0.9 ± 0.38 ab
		Average	0.6 ± 0.86 B	0.6 ± 0.64 B	0.8 ± 1.06 AB	1.0 ± 0.61 A
	'Palermo'	Term 1	1.8 ± 0.57 ns	1.7 ± 0.88 ns	1.6 ± 0.54 ns	1.8 ± 0.78 ns
		Term 2	1.6 ± 0.71 ns	1.4 ± 1.81 ns	1.7 ± 0.82 ns	2.2 ± 0.63 ns
		Average	1.7 ± 0.78 NS	1.5 ± 1.60 NS	1.6 ± 0.76 NS	2.0 ± 0.94 NS
	Average		1.2 ± 1.39 NS	1.1 ± 1.43 NS	1.2 ± 1.08 NS	1.5 ± 1.28 NS
Weight of marketable fruit [g]	'Aifos'	Term 1	233.0 ± 2.44 ns	237.4 ± 6.06 ns	223.1 ± 6.59 ns	178.7 ± 11.47 ns
		Term 2	226.7 ± 10.49 ns	234.8 ± 10.30 ns	218.4 ± 5.67 ns	178.1 ± 3.94 ns
		Average	229.9 ± 10.00 NS	236.1 ± 9.96 NS	220.7 ± 14.72 NS	178.5 ± 15.20 NS
	'Palermo'	Term 1	144.6 ± 7.18 ns	144.9 ± 7.08 ns	131.5 ± 2.98 ns	92.6 ± 12.04 ns
		Term 2	148.8 ± 3.58 ns	140.3 ± 10.44 ns	132.4 ± 9.23 ns	93.1 ± 2.62 ns
		Average	146.7 ± 4.82 A	142.6 ± 4.52 A	131.9 ± 12.94 AB	92.8 ± 7.56 B
	Average		188.3 ± 13.75 NS	189.4 ± 14.53 NS	176.3 ± 12.66 NS	135.7 ± 13.45 NS

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to the combination term × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

Table 5. Effect of salicylic acid and calcium treatment of pepper plants on number of fruit in total and marketable yield and fruit with BER depending on cultivar [±SE].

Parameter	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Total yield [No./plant]	'Aifos'	Term 1	19.5 ± 0.62 ab	16.4 ± 0.86 ab	17.0 ± 1.07 ab	21.2 ± 0.28 a *
		Term 2	15.9 ± 0.34 ab	12.5 ± 2.03 b	19.6 ± 0.36 ab	19.5 ± 0.81 ab
		Average	17.7 ± 0.82 AB	14.4 ± 1.79 B	18.3 ± 0.97 AB	20.4 ± 1.94 A
	'Palermo'	Term 1	41.9 ± 3.78 ab	39.6 ± 1.76 ab	42.0 ± 0.41 ab	51.3 ± 2.00 ab
		Term 2	40.1 ± 2.14 ab	35.0 ± 5.41 b	49.2 ± 2.21 ab	61.2 ± 1.39 a
		Average	41.0 ± 2.10 B	37.3 ± 4.33 B	45.6 ± 2.10 AB	56.2 ± 3.27 A
	Average		29.3 ± 3.17 NS	25.9 ± 3.48 NS	32.00 ± 3.39 NS	38.3 ± 4.40 NS
Marketable yield [No./plant]	'Aifos'	Term 1	12.1 ± 0.50 ns	11.2 ± 0.81 ns	10.2 ± 0.91 ns	9.8 ± 0.47 ns
		Term 2	12.5 ± 0.21 ns	9.8 ± 1.52 ns	13.1 ± 0.84 ns	12.3 ± 0.46 ns
		Average	12.3 ± 0.42 NS	9.7 ± 1.33 NS	11.6 ± 1.07 NS	11.0 ± 0.66 NS
	'Palermo'	Term 1	12.3 ± 1.14 ab	12.1 ± 0.47 ab	11.0 ± 0.82 ab	4.7 ± 0.27 b
		Term 2	16.6 ± 1.61 ab	14.7 ± 3.13 ab	20.9 ± 1.85 a	22.5 ± 2.59 a
		Average	14.4 + 1.79 NS	13.4 + 2.41 NS	15.9 + 2.32 NS	13.6 + 3.71 NS
	Average		13.4 ± 0.90 NS	11.6 ± 1.34 NS	13.8 ± 1.29 NS	12.3 ± 1.80 NS
Fruit with BER [No./plant].	'Aifos'	Term 1	7.3 ± 0.73 ab	5.2 ± 0.87 b	6.8 ± 0.27 b	11.5 ± 0.61 a
		Term 2	3.3 ± 0.53 b	4.2 ± 0.27 b	6.5 ± 0.57 b	7.2 ± 0.39 ab
		Average	5.3 ± 0.98 B	4.7 ± 0.71 B	6.7 ± 0.47 AB	9.3 ± 0.93 A
	'Palermo'	Term 1	29.6 ± 2.49 bc	27.5 ± 1.35 bc	31.1 ± 1.09 bc	46.6 ± 2.07 a
		Term 2	23.5 ± 0.61 c	20.4 + 2.53 c	28.3 ± 0.77 bc	38.7 ± 2.03 ab
		Average	26.6 ± 2.20 B	23.9 ± 2.48 B	29.7 ± 1.11 B	42.6 ± 2.58 A
	Average		16.0 ± 2.75 NS	14.3 ± 2.57 NS	18.2 ± 2.77 NS	26.0 ± 4.13 NS

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to the combination term × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

3.4. Dry Matter Content and Color Evaluation of the Fruit

There was no effect of spraying plants with individual treatment of SA and individual treatment of Ca on the dry matter content of pepper fruits (Table 6). 'Aifos' fruit, on average from the combinations and cultivation dates tested, contained 8.4% dry matter, and 'Palermo' fruit contained 10.2% dry matter, respectively. CIE Lab color parameters such as L*—lightness and a* intensity of red for pepper fruits did not depend on the applied plant sprays of individual treatment of SA and individual treatment of Ca. However, the parameter b*, characterizing the intensity of yellow [b* > 0], showed lower values in fruit from the individual treatment of Ca-sprayed plants compared to the control and individual treatment of SA and Ca + SA combinations (Table 6). The parameters of fruit length, diameter of fruit, and thickness of pericarp of pepper fruits did not depend on the treatment applied. Significant differences occurred between cultivars (Table S1). No differences were found between cultivars for the parameter L*, while the values of the parameters a* and b* for 'Palermo' were lower than for 'Aifos' (Figure S6). The dry matter content of the pepper fruits differed between cultivars. Fruits of the 'Palermo' cultivar had a higher dry matter content than those of the 'Aifos' cultivar (Figure S7).

Table 6. Effect of salicylic acid and calcium treatment of pepper plants on dry weight content and CIE Lab color of fruit depending on cultivar [±SE].

Parameter	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Dry weight [%]	'Aifos'	Term 1	7.8 ± 0.17 b	8.7 ± 0.24 ab	9.6 ± 0.08 ab	8.4 ± 0.09 ab *
		Term 2	8.1 ± 0.13 ab	7.9 ± 0.25 b	8.9 ± 0.09 a	8.0 ± 0.03 b
		Average	8.0 ± 0.13 B	8.3 ± 0.23 AB	8.8 ± 0.08 A	8.2 ± 0.01 B
	'Palermo'	Term 1	13.2 ± 1.63 a	10.1 ± 0.05 ab	8.1 ± 1.36 b	9.5 ± 0.03 ab
		Term 2	9.8 ± 0.05 ab	8.1 ± 0.14 b	11.4 ± 0.28 ab	11.2 ± 0.03 ab
		Average	11.5 ± 1.06 NS	9.1 ± 0.40 NS	9.8 ± 0.97 NS	10.3 ± 0.36 NS
	Average		9.8 ± 0.74 NS	8.7 ± 0.27 NS	9.3 ± 0.51 NS	9.3 ± 0.36 NS
L* [lightness]	'Aifos'	Term 1	34.4 ± 1.23 ab	32.0 ± 0.97 ab	32.0 ± 1.10 ab	32.3 ± 0.63 ab
		Term 2	31.8 ± 0.93 a	28.2 ± 1.94 b	34.4 ± 1.13 a	30.9 ± 1.12 ab
		Average	32.95 ± 0.87 AB	29.91 ± 1.32 B	33.88 ± 0.82 A	31.51 ± 0.72 AB
	'Palermo'	Term 1	32.5 ± 1.31 ns	43.3 ± 4.92 ns	43.3 ± 1.21 ns	26.8 ± 1.39 ns
		Term 2	29.3 ± 1.18 ns	24.6 ± 2.88 ns	28.3 ± 2.62 ns	35.4 ± 2.67 ns
		Average	30.71 ± 1.03 NS	32.88 ± 4.11 NS	28.48 ± 1.55 NS	31.57 ± 2.15 NS
	Average		31.8 ± 0.72 NS	31.4 ± 2.18 NS	31.2 ± 1.08 NS	31.5 ± 1.13 NS
a* [intensity of red]	'Aifos'	Term 1	31.5 ± 0.87 cd	30.4 ± 1.64 abc	33.8 ± 0.85 ab	30.4 ± 0.55 bcd
		Term 2	29.4 ± 1.04 abc	28.4 ± 1.28 d	34.2 ± 1.17 a	29.7 ± 0.60 abcd
		Average	30.3 ± 0.78 B	29.1 ± 1.07 B	33.9 ± 0.76 A	30.0 ± 0.43 B
	'Palermo'	Term 1	31.7 ± 2.06 ns	21.7 ± 6.81 ns	29.4 ± 3.03 ns	25.8 ± 1.69 ns
		Term 2	26.4 ± 3.62 ns	27.2 ± 1.16 ns	27.2 ± 2.61 ns	30.0 ± 2.75 ns
		Average	28.7 ± 2.38 NS	24.7 ± 3.22 NS	28.2 ± 2.01 NS	28.1 ± 1.83 NS
	Average		29.5 ± 1.26 NS	27.0 ± 1.78 NS	31.1 ± 1.27 NS	29.1 ± 0.96 NS
b* [intensity of yellow]	'Aifos'	Term 1	19.4 ± 1.05 ab	18.6 ± 1.73 ab	18.2 ± 1.02 ab	15.9 ± 0.71 ab
		Term 2	15.8 ± 0.81 ab	16.2 ± 0.84 b	20.9 ± 1.03 a	17.1 ± 1.46 ab
		Average	17.4 ± 0.88 NS	17.3 ± 0.97 NS	19.7 ± 0.85 NS	16.6 ± 0.9 NS
	'Palermo'	Term 1	20.5 ± 1.64 ab	10.7 ± 3.90 b	15.4 ± 0.90 ab	13.6 ± 1.26 ab
		Term 2	13.2 ± 1.97 b	16.3 ± 1.04 ab	16.1 ± 1.74 ab	22.5 ± 1.91 a
		Average	16.4 ± 1.78 NS	13.9 ± 2.05 NS	15.8 ± 1.05 NS	18.5 ± 1.09 NS
	Average		16.9 ± 0.99 NS	15.6 ± 1.20 NS	17.8 ± 0.82 NS	17.6 ± 1.07 NS

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to the combination term × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

3.5. Sensory Analysis of the Fruit

The results of the sensory analysis showed that pepper fruits of both individual treatment of SA and individual treatment of Ca and untreated cultivars did not differ significantly with respect to most of the tested attributes of fruit odor, texture, and taste in term 1 and term 2. The off-flavor parameter was scored 0 by the evaluators (Table 7). Pepper fruits harvested from plants treated with the individual treatment of SA, individual treatment of Ca, and SA + Ca-treated plants had more juicy flesh compared to the control, while the least bitter flavor was found in fruits from the SA + Ca combination. No significant differences were observed in the overall preference of the fruits tested according to treatment and cultivation date (Figure 1). Fruits of the 'Palermo' cultivar were rated significantly higher for sweet taste and overall quality than those of the 'Aifos' cultivar. For the other evaluated parameters, the 'Aifos' fruit achieved higher values compared to the 'Palermo' fruit (Figure 2).

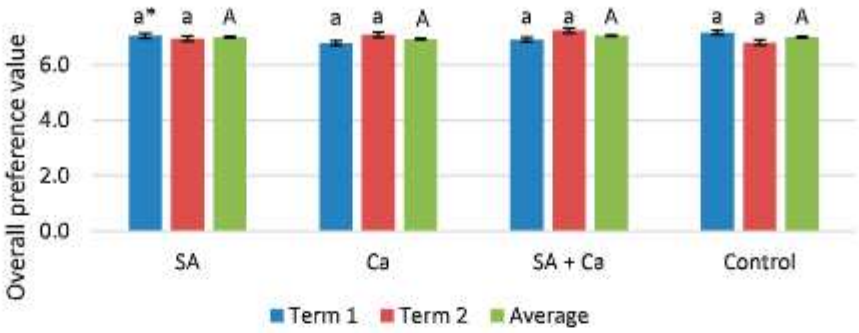

Figure 1. Overall sensory preference of pepper fruits according to plant treatment and cultivation date [± SE]. * Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Small letters refer to combination cultivar × treatment, and capital letters relate to treatment.

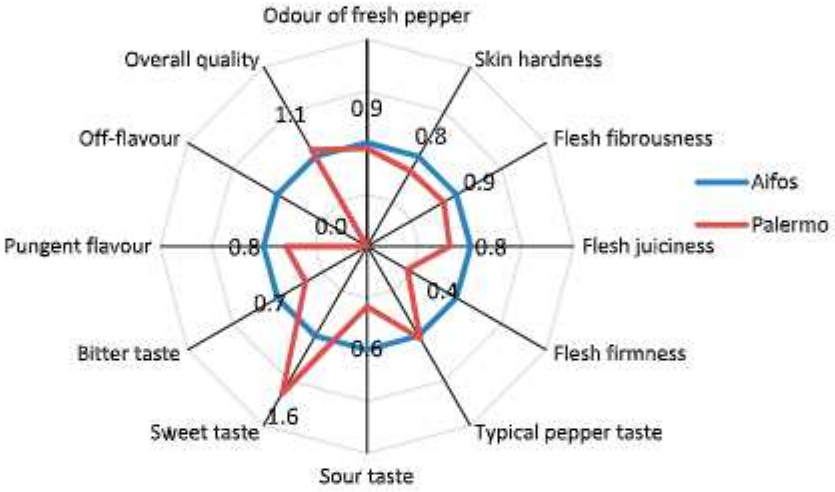

Figure 2. The results of sensory analysis concerning odor, texture, taste, and overall quality for pepper fruits normalized to the values of the 'Aifos' cultivar as radar plots compared to the 'Palermo' cultivar [average of two terms].

Table 7. Effect of salicylic acid and calcium treatment of pepper plants on the result of sensory analysis on the attributes of odor, texture, and taste of fruits depending on the cultivar [±SE].

Attributes of Odor, Texture, and Taste	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Odor of fresh pepper	'Aifos'	Term 1	5.6 ± 0.47 ns	4.4 ± 0.44 ns	4.7 ± 0.47 ns	4.6 ± 0.53 ns *
		Term 2	5.9 ± 0.38 ns	4.7 ± 0.44 ns	5.2 ± 0.49 ns	4.3 ± 0.53 ns
		Average	6.0 ± 0.31 A	4.6 ± 0.31 B	4.9 ± 0.34 AB	4.5 ± 0.38 B
	'Palermo'	Term 1	4.6 ± 0.52 ns	4.2 ± 0.68 ns	4.7 ± 0.68 ns	5.5 ± 0.48 ns
		Term 2	3.9 ± 0.50 ns	4.5 ± 0.68 ns	5.7 ± 0.60 ns	5.2 ± 0.54 ns
		Average	4.0 ± 0.36 NS	4.4 ± 0.48 NS	5.1 ± 0.46 NS	5.4 ± 0.36 NS
	Average		4.9 ± 0.25 NS	4.5 ± 0.29 NS	5.0 ± 0.28 NS	4.9 ± 0.26 NS
Skin hardness	'Aifos'	Term 1	5.8 ± 0.54 ns	6.0 ± 0.45 ns	5.8 ± 0.61 ns	5.6 ± 0.33 ns
		Term 2	6.0 ± 0.55 ns	6.3 ± 0.45 ns	6.2 ± 0.68 ns	5.3 ± 0.32 ns
		Average	6.1 ± 0.38 NS	6.2 ± 0.32 NS	6.0 ± 0.45 NS	5.5 ± 0.23 NS
	'Palermo'	Term 1	5.8 ± 0.57 ns	4.5 ± 0.49 ns	4.5 ± 0.76 ns	4.9 ± 0.68 ns
		Term 2	5.2 ± 0.56 ns	4.8 ± 0.49 ns	5.6 ± 0.72 ns	5.0 ± 0.70 ns
		Average	5.4 ± 0.40 NS	4.7 ± 0.35 NS	5.0 ± 0.53 NS	5.0 ± 0.49 NS
	Average		5.7 ± 0.27 NS	5.4 ± 0.25 NS	5.4 ± 0.36 NS	5.2 ± 0.26 NS

Table 7. *Cont.*

Attributes of Odor, Texture, and Taste	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Flesh fibrousness	'Aifos'	Term 1	5.9 ± 0.44 ns	5.7 ± 0.45 ns	6.8 ± 0.54 ns	6.2 ± 0.39 ns
		Term 2	6.0 ± 0.48 ns	6.0 ± 0.45 ns	6.3 ± 0.49 ns	5.9 ± 0.39 ns
		Average	6.0 ± 0.32 NS	5.9 ± 0.31 NS	6.6 ± 0.37 NS	6.1 ± 0.27 NS
	'Palermo'	Term 1	5.6 ± 0.25 ns	5.5 ± 0.47 ns	4.3 ± 0.45 ns	5.3 ± 0.52 ns
		Term 2	5.4 ± 0.27 ns	5.8 ± 047 ns	5.1 ± 0.43 ns	4.6 ± 0.55 ns
		Average	5.6 ± 0.18 NS	5.7 ± 0.33 NS	4.7 ± 0.32 NS	5.0 ± 0.38 NS
	Average		5.7 ± 0.19 NS	5.7 ± 0.23 NS	5.6 ± 0.28 NS	5.5 ± 0.24 NS
Flesh juiciness	'Aifos'	Term 1	5.6 ± 0.46 ns	6.0 ± 0.45 ns	6.8 ± 0.56 ns	6.0 ± 0.35 ns
		Term 2	6.0 ± 0.45 ns	6.3 ± 0.45 ns	6.6 ± 0.58 ns	5.7 ± 0.35 ns
		Average	5.9 ± 0.34 NS	6.2 ± 0.34 NS	6.7 ± 0.40 NS	5.9 ± 0.25 NS
	'Palermo'	Term 1	5.9 ± 0.45 ns	5.6 ± 0.54 ns	3.6 ± 0.37 ns	3.9 ± 0.44 ns
		Term 2	5.5 ± 0.47 ns	5.9 ± 0.54 ns	4.3 ± 0.38 ns	4.0 ± 0.47 ns
		Average	5.7 ± 0.33 A	5.8 ± 0.39 A	3.9 ± 0.27 B	4.0 ± 0.32 B
	Average		5.7 ± 0.23 AB	5.9 ± 0.25 A	5.3 ± 0.30 AB	5.0 ± 0.23 B
Flesh firmness	'Aifos'	Term 1	6.5 ± 0.52 ns	6.6 ± 0.49 ns	6.9 ± 0.56 ns	7.2 ± 0.44 ns
		Term 2	7.2 ± 0.45 ns	6.9 ± 0.49 ns	6.4 ± 0.50 ns	6.9 ± 0.44 ns
		Average	6.8 ± 0.35 NS	6.8 ± 0.34 NS	6.7 ± 0.38 NS	7.1 ± 0.31 NS
	'Palermo'	Term 1	3.6 ± 0.37 ab	3.5 ± 0.30 ab	2.2 ± 0.23 b	2.5 ± 0.33 b
		Term 2	3.3 ± 0.38 ab	3.8 ± 0.30 a	2.7 ± 0.24 ab	2.4 ± 0.34 ab
		Average	3.5 ± 0.27 A	3.7 ± 0.21 A	2.5 ± 0.17 B	2.5 ± 0.22 B
	Average		5.0 ± 0.30 NS	5.2 ± 0.28 NS	4.5 ± 0.33 NS	4.9 ± 0.35 NS
Typical pepper taste	'Aifos'	Term 1	6.7 ± 0.36 ns	6.3 ± 0.34 ns	6.0 ± 0.18 ns	6.2 ± 0.33 ns
		Term 2	7.0 ± 0.37 ns	6.6 ± 0.34 ns	6.3 ± 0.20 ns	5.9 ± 0.30 ns
		Average	7.0 ± 0.26 A	6.5 ± 0.24 AB	6.2 ± 0.14 AB	6.1 ± 0.21 B
	'Palermo'	Term 1	6.7 ± 0.47 ns	6.0 ± 0.36 ns	6.7 ± 0.37 ns	6.9 ± 0.30 ns
		Term 2	6.2 ± 0.44 ns	6.3 ± 0.36 ns	7.5 ± 0.36 ns	6.7 ± 0.36 ns
		Average	6.4 ± 0.33 NS	6.2 ± 0.26 NS	7.2 ± 0.27 NS	6.9 ± 0.24 NS
	Average		6.6 ± 0.21 NS	6.3 ± 0.18 NS	6.6 ± 0.16 NS	4.4 ± 0.17 NS
Sour taste	'Aifos'	Term 1	3.5 ± 0.45 ns	3.5 ± 0.52 ns	4.2 ± 0.56 ns	3.4 ± 0.49 ns
		Term 2	4.1 ± 0.45 ns	3.8 ± 0.52 ns	4.6 ± 0.61 ns	3.3 ± 0.48 ns
		Average	3.8 ± 0.32 NS	3.7 ± 0.37 NS	4.4 ± 0.41 NS	3.3 ± 0.35 NS
	'Palermo'	Term 1	1.7 ± 0.25 ns	1.6 ± 0.33 ns	2.2 ± 0.44 ns	3.0 ± 0.57 ns
		Term 2	1.6 ± 0.26 ns	1.9 ± 0.33 ns	2.8 ± 0.44 ns	2.6 ± 0.45 ns
		Average	1.7 ± 0.18 NS	1.8 ± 0.24 NS	2.5 ± 0.32 NS	2.8 ± 0.37 NS
	Average		2.6 ± 0.23 NS	2.7 ± 0.25 NS	3.4 ± 0.29 NS	3.0 ± 0.26 NS
Sweet taste	'Aifos'	Term 1	3.9 ± 0.51 ns	3.6 ± 0.53 ns	3.6 ± 0.57 ns	4.3 ± 0.50 ns
		Term 2	3.5 ± 0.46 ns	3.9 ± 0.53 ns	3.8 ± 0.56 ns	4.0 ± 0.50 ns
		Average	3.7 ± 0.35 NS	3.8 ± 0.38 NS	3.8 ± 0.40 NS	4.2 ± 0.36 NS
	'Palermo'	Term 1	6.7 ± 0.50 ns	6.5 ± 0.57 ns	5.9 ± 0.44 ns	5.8 ± 0.54 ns
		Term 2	6.6 ± 0.47 ns	6.8 ± 0.57 ns	6.4 ± 0.49 ns	5.8 ± 0.62 ns
		Average	6.7 ± 0.35 NS	6.7 ± 0.40 NS	6.1 ± 0.33 NS	5.9 ± 0.41 NS
	Average		5.3 ± 0.31 NS	5.2 ± 0.33 NS	4.9 ± 0.30 NS	4.9 ± 0.28 NS

Table 7. *Cont.*

Attributes of Odor, Texture, and Taste	Cultivar	Term of Growing	Treatment			
			SA	Ca	SA + Ca	Control
Bitter taste	'Aifos'	Term 1	0.5 ± 0.28 ns	0.7 ± 0.28 ns	0.1 ± 0.07 ns	0.8 ± 0.28 ns
		Term 2	0.3 ± 0.10 ns	0.7 ± 0.28 ns	0.2 ± 0.08 ns	0.8 ± 0.28 ns
		Average	0.3 ± 0.16 B	0.7 ± 0.20 AB	0.2 ± 0.06 B	0.9 ± 0.20 A
	'Palermo'	Term 1	0.3 ± 0.31 ns	0.5 ± 0.32 ns	0.0 ± 0.05 ns	0.1 ± 0.07 ns
		Term 2	0.6 ± 0.41 ns	0.5 ± 0.32 ns	0.1 ± 0.05 ns	0.1 ± 0.07 ns
		Average	0.7 ± 0.26 NS	0.5 ± 0.22 NS	0.1 ± 0.04 NS	0.2 ± 0.05 NS
	Average		0.4 ± 0.16 AB	0.6 ± 0.15 A	0.1 ± 0.04 B	0.5 ± 0.12 AB
Pungent flavor	'Aifos'	Term 1	1.1 ± 0.39 ns	0.9 ± 0.25 ns	0.9 ± 0.35 ns	0.5 ± 0.17 ns
		Term 2	1.4 ± 0.44 ns	0.9 ± 0.25 ns	1.1 ± 0.39 ns	0.5 ± 0.16 ns
		Average	1.3 ± 0.30 NS	0.9 ± 0.18 NS	1.1 ± 0.26 NS	0.6 ± 0.12 NS
	'Palermo'	Term 1	0.4 ± 0.17 ns	0.5 ± 0.19 ns	0.8 ± 0.27 ns	0.8 ± 0.30 ns
		Term 2	0.5 ± 0.16 ns	1.0 ± 0.19 ns	1.0 ± 0.29 ns	1.0 ± 0.32 ns
		Average	0.5 ± 0.12 NS	0.6 ± 0.13 NS	1.0 ± 0.19 NS	1.0 ± 0.22 NS
	Average		0.8 ± 0.16 NS	0.7 ± 0.11 NS	1.0 ± 0.16 NS	0.7 ± 0.12 NS
Overall quality	'Aifos'	Term 1	6.9 ± 0.19 ns	6.9 ± 0.28 ns	7.3 ± 0.24 ns	7.2 ± 0.23 ns
		Term 2	7.2 ± 0.18 ns	7.2 ± 0.28 ns	7.4 ± 0.26 ns	6.9 ± 0.23 ns
		Average	7.1 ± 0.13 NS	7.1 ± 0.20 NS	7.4 ± 0.18 NS	7.1 ± 0.16 NS
	'Palermo'	Term 1	7.0 ± 0.27 ns	6.6 ± 0.25 ns	6.4 ± 0.43 ns	6.8 ± 0.34 ns
		Term 2	6.5 ± 0.26 ns	6.9 ± 0.24 ns	7.2 ± 0.24 ns	6.4 ± 0.33 ns
		Average	6.7 ± 0.19 NS	6.8 ± 0.18 NS	6.8 ± 0.26 NS	6.7 ± 0.24 NS
	Average		6.9 ± 0.16 NS	6.9 ± 0.14 NS	7.0 ± 0.12 NS	6.9 ± 0.12 NS

* Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Abbreviations: ns, not significant; NS, not significant. Small letters refer to the combination term × treatment, and capital letters relate to treatment (for each cultivar—two-factor analysis of variance, and for the averages of the cultivars—three-factor analysis of variance).

4. Discussion

4.1. Biometric Measurements of Plants and Yielding Peppers

Peppers are an economically important vegetable that is the subject of much research, including efforts to improve cultivation efficiency and fruit quality. Hydroponic cultivation of peppers in inert substrates is not as popular as traditional soil cultivation. This method of cultivation offers the possibility of monitoring and controlling the fertilization and irrigation of plants. Mineral nutrients in the form of foliar fertilization are used to supplement standard fertilization, optimizing the growth and yield of grown plants under stress conditions. Mineral nutrients can affect plant growth and yield, causing changes in plant chemistry, morphology, and anatomy. Consequently, this can trigger or enhance the mechanisms responsible for the plant's resistance to pests and diseases or abiotic stresses. The calcium ion is one of the essential nutrients affecting plant growth and development and higher fruit yield and quality [42]. The study found that spraying peppers with calcium nitrate affected higher weekly shoot growth and number of leaves compared to control, water-sprayed plants. Also, SA-treated plants had greater weekly shoot length increments and gained higher shoots and more leaves during the growing season than the control. Total pepper fruit yield and marketable yield were not significantly different between plants treated with the individual treatment of SA and individual treatment of Ca or SA + Ca treated plants compared to the control. However, there were significantly fewer fruits with BER in plants sprayed with both individual treatment of SA 0.03% and individual treatment of Ca 0.7% and in the combination where plants were sprayed simultaneously with SA 0.03% + Ca 0.7% compared to the control. It was also found that the treatment of plants with individual treatments of SA and Ca influenced higher marketable fruit weight

in both pepper cultivars grown hydroponically. The cultivars tested differed significantly in growth rate, yield, and fruit susceptibility to BER. The cultivar 'Palermo' had more fruit with BER symptoms than the cultivar 'Aifos'. 'Palermo' had a lower average fruit weight than 'Aifos'.

Calcium is mainly involved in the formation of the plant cell wall and is also a signaling molecule that regulates a wide range of physiological and pathological responses [43]. Ca transport to aboveground plant organs depends on several factors, such as Ca^{2+} concentration in xylem sap, balanced mineral nutrition, water uptake and water potential of the plant, transpiration, and growth rate [44]. Excessive Ca accumulation can occur in organs with a high transpiration rate (i.e., leaves) [17], while organs with a low transpiration rate (e.g., fruits) can respond to local Ca deficiencies [16,44]. Studies by El-Tohama et al. [45] and Buczkowska et al. [35] showed positive effects of Ca nutrition on pepper fruit yield.

Salicylic acid, on the other hand, is a natural phenolic acid, an endogenous growth regulator, and has many regulatory functions in plant metabolism [46]. The role of SA in plant growth has been the subject of much less research than has been the case of other plant hormones. Most publications on the subject do not consider SA, or its role is partially described [47–49]. Salicylic acid controls plant performance, including advanced growth, nutrient uptake, protein synthesis, and cell division and differentiation, which is associated with increased yield [50,51]. The effect of exogenous SA on growth depends on the plant species, developmental stage, and SA concentration. Growth-stimulating effects of SA have been reported for soybean [52], wheat [53], maize [54], and chamomile [55]. The results indicate that exogenous SA concentrations >1 mM SA are too high for most plants, but this depends on the plant species. Too high a concentration of SA has a negative effect on plant development and growth [52,54,56]. In contrast, the use of optimal SA concentrations has been shown to have a positive effect on plants. Depending on the experimental conditions, SA clearly stimulated growth under both normal and different abiotic stress conditions in different plant species [57–59].

A study by Souri and Tohidloo [60] showed that salicylic acid applied through the roots has a beneficial effect on tomato seedling growth under saline conditions. Similar results are presented in a study by Arfan et al. [61], where SA application to the roots improved tomato and wheat growth under saline conditions.

The method of foliar spraying of plants plays a key role in improving the growth and yield of vegetable plants by increasing plant's nutrient uptake and efficiency [23,62]. The obtained results are confirmed by studies on the growth of plants treated with foliar SA in other species of the same genus *Capsicum* [63,64], as well as in *Lycopersicum esculentum* [65], *Chrysanthemum morifolium* [66], *Carica papaya* [67], *Oryza sativa* [68], *Triticum aestivum* [69,70], and *Zea mays* [71]. The results of the use of salicylic acid in traditional pepper cultivation are also promising [64,72,73]. The beneficial effects of salicylic acid on plants are also confirmed by studies conducted by Elwan et al. [64], where application at low concentrations [10^{-6} M] resulted in an increase in fresh and dry leaf weight, number of fruits, average fruit weight, and fruit yield of pepper.

4.2. Photosynthetic Activity of Peppers

The leaf is the most important organ of the plant, i.e., the so-called main source of food for the plant in which photosynthesis takes place. The foliar application of Ca closes the stomata and protects the leaves from unfavorable weather conditions [74,75]. In contrast, the application of salicylic acid affects a wide variety of plant processes, including stomatal closure, ion uptake and transport [76], membrane permeability, and the rate of photosynthesis and growth [77].

The study found that the highest steady-state fluorescence yields [Fs] were obtained by pepper plants treated simultaneously with SA [0.03%] and individual treatment of Ca [0.7%]. Plants treated with individual treatment of Ca had the highest maximum PSII quantum yield [Fv/Fm] and the highest PSII viability index [PI] compared to the control and plants treated with individual treatment of SA. The relative chlorophyll content of

pepper leaves was significantly higher in plants treated with individual treatment of SA, individual treatment of Ca, and SA + Ca-treated plants than in the control.

Salicylic acid regulates ionic balance, photosynthetic activity, and ROS detoxification, which ensure normal physiological and biochemical behavior [78–80]. Similar SA properties have been observed in winter wheat [81], green pepper [82], bamboo shoots [83], and cucumber [84], confirming the results obtained in the study. Exogenous application of SA increased the photosynthetic rate in various crops such as thyme [85], radish [86], and maize [87]. Graham and McDonald [88] observed a decrease in Fv/Fm under high temperatures. A decrease in this parameter may indicate active protection of the plant from the sun [89]. Baker and Rosenqvist [90] concluded in their study that a decrease in Fv/Fm may inhibit the rate of photosynthesis and also affect plant growth and development. In contrast, the PI vitality index PSII shows the ability of plants to adapt to stress conditions [91]. SA is involved in improving the rate of photosynthesis through K+ uptake [92] and the ability to increase rubisco activity [93], increasing ATP content and maintaining an optimal K^+/Na^+ ratio in plants [94]. Thus, the application of exogenous SA can enhance photosynthesis, which is a major factor controlling plant growth and yield [95]. The application of SA affects the decomposition and removal of ROS, while antioxidant enzymes reduce the destructive effects of ROS on cell membranes, photosynthetic pigments, proteins, and other macromolecules, affecting the metabolic activity of plants and improving the growth and yield of *A. hirtifolium* by maintaining membrane stability and photosynthetic pigments, improving photosynthetic and respiratory activity of the plant [96].

4.3. Dry Matter Content, Fruit Color Evaluation, and Sensory Analysis of Fruit

There was no effect of spraying plants with individual treatment of SA at a concentration of 0.03% and individual treatment of Ca at a concentration of 0.7% on the dry matter content of pepper fruit. The color parameters L* and a* in pepper fruits did not depend on the application of individual treatment of SA and individual treatment of Ca. In contrast, parameter b* showed lower values in fruits from Ca-sprayed plants compared to the control and plants sprayed with individual treatment of SA and SA + Ca combination. The change in the green color of peppers is linked to the exchange of chloroplast for chromoplast, during which the conversion of pigment content in sweet peppers increases with aging [97]. Confirming the results obtained, a study by Dobón-Suárez et al. [98] showed that preharvest SA treatments did not affect the ripening process of pepper fruits on the plant. Pepper fruits from plants sprayed with individual treatment of SA, individual treatment of Ca, and SA + Ca treatments had more juicy flesh compared to the control, while the least bitter taste was found in fruits from the SA + Ca combination. A study conducted by Javaheri et al. [99] showed that foliar application of salicylic acid significantly improved tomato fruit quality.

5. Conclusions

Foliar application of individual treatment of salicylic acid at a concentration of 0.3% and individual treatment of Ca in the form of a solution of calcium nitrate at a concentration of 0.7% has a beneficial effect on the growth and yield of peppers in hydroponic cultivation and on the quality of pepper fruit. Pepper plants treated with both SA and Ca alone and with both individual treatment of SA and individual treatment of Ca showed less BER on fruit than plants in the control. Research on the foliar application of individual treatment of SA and Ca together with SA in greenhouse peppers grown in mineral wool substrate requires further investigation with other combinations of solution concentrations and frequency of application per plant.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14020329/s1, Figure S1: Average daily air temperature at the cultivation chamber on consecutive growing days according to the date [Term 1.—2019, Term 2.—2020]; Figure S2: Average night-time air temperature at the cultivation chamber on consecutive growing days according to the date [Term 1.—2019, Term 2.—2020]; Figure S3: Dynamics of

daily radiation totals on successive growing days according to term [Term 1.—2019, Term 2.—2020]; Figure S4: The pepper plants grown on mineral wool growing mats fed by dropping fertigation system; Figure S5: Fruit of the 'Palermo' and 'Aifos' cultivars, whole and in cross-section; Table S1: Effect of calcium and salicylic acid treatment of pepper plants on diameter and length of fruit and thickness of pericarp depending on cultivar [mean of two terms ± SE]; Figure S6: Results of plant biometric measurements, photosynthetic activity of peppers, and evaluation of fruit color normalized to 'Aifos' as radar plots compared to 'Palermo' [average of two years]; Figure S7: Results of plant yield measurements normalized to 'Aifos' as radar plots compared to 'Palermo' [T.yield—total yield, M. yield—marketable yield, DW—Dry Weight of fruit].

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References

1. The Plant List 2019 Capsicum. 2019. Available online: http://www.theplantlist.org/browse/A/Solanaceae/Capsicum/ (accessed on 5 January 2024).
2. Mahmood, N.; Abbasi, N.A.; Hafiz, I.; Ali, L; Zakia, S. Effect of biostimulants on growth, yield and quality of bell pepper cv. *Yolo Wonder*. *Pak. J. Agric. Sci.* **2017**, *54*, 311–317. [CrossRef]
3. Baenas, N.; Belović, M.; Ilic, N.; Moreno, D.A.; García-Viguera, C. Industrial use of pepper [*Capsicum annum* L.] derived products: Technological benefits and biological advantages. *Food Chem.* **2019**, *274*, 872–885. [CrossRef]
4. Arimboor, R.; Nataraja, R.B.; Menon, K.R.; Chandrasekhar, L.P.; Moorkoth, V. Red pepper [*Capsicum annuum* L.] carotenoids as a source of natural food colors: Analysis and stability: A review. *J. Food Sci. Technol.* **2015**, *52*, 1258–1271. [CrossRef]
5. Chávez-Mendoza, C.; Sanchez, E.; Muñoz-Marquez, E.; Sida-Arreola, J.P.; Flores-Cordova, M.A. Bioactive compounds and antioxidant activity in different grafted varieties of bell pepper. *Antioxidants* **2015**, *4*, 427–446. [CrossRef] [PubMed]
6. Jamiołkowska, A.; Buczkowska, H.; Thanoon, A.H. Effect of biological preparations on content of saccharides in sweet pepper fruits. *Acta Sci. Pol. Hortorum Cultus* **2016**, *15*, 65–75.
7. Davey, M.W.; Montagu, M.V.; Inze, D.; Sanmartin, M.; Kanellis, A.; Smirnoff, N.; Benzie, I.J.J.; Strain, J.J.; Favell, D.; Fletcher, J. Review: Plant L-ascorbic acid: Chemistry, function, metabolism, bioavailability and effects of processing. *J. Sci. Food Agric.* **2000**, *80*, 825–860. [CrossRef]
8. Bhutia, K.; Khanna, V.; Meetei, T.; Bhutia, N. Effects of climate change on growth and development of chilli. *Agrotechnology* **2018**, *7*, 2. [CrossRef]
9. Sambo, P.; Nicoletto, C.; Giro, A.; Pii, Y.; Valentinuzzi, F.; Mimmo, T.; Lugli, P.; Orzes, G.; Mazzetto, F.; Astolfi, S. Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. *Front. Plant Sci.* **2019**, *10*, 923. [CrossRef] [PubMed]
10. Kołton, A.; Wojciechowska, R.; Leja, M. The effect of various light conditions and different nitrogen forms on nitrogen metabolism in pepper fruits. *Folia Hort.* **2012**, *24*, 153–160. [CrossRef]
11. Qaryouti, M.; Osman, M.; Alharbi, A.; Voogt, W.; Abdelaziz, M.E. Using Date Palm Waste as an Alternative for Rockwool: Sweet Pepper Performance under Both Soilless Culture Substrates. *Plants* **2024**, *13*, 44. [CrossRef]
12. Savvas, D.; Gruda, N. Application of soilless culture technologies in the modern greenhouse industry—A review. *Eur. J. Hortic. Sci.* **2018**, *83*, 280–293. [CrossRef]
13. Sobczak, A.; Kowalczyk, K.; Gajc-Wolska, J.; Kowalczyk, W.; Niedzińska, M. Growth, Yield and Quality of Sweet Pepper Fruits Fertilized with Polyphosphates in Hydroponic Cultivation with LED Lighting. *Agronomy* **2020**, *10*, 1560. [CrossRef]
14. Gilliham, M.; Dayod, M.; Hocking, B.J.; Xu, B.; Conn, S.J.; Kaiser, B.N.; Leigh, R.A.; Tyerman, S.D. Calcium delivery and storage in plant leaves: Exploring the link with water flow. *J. Exp. Bot.* **2011**, *62*, 2233–2250. [CrossRef] [PubMed]
15. Hagassou, D.; Francia, E.; Ronga, D.; Buti, M. Blossom End-Rot in Tomato [*Solanum Lycopersicum* L.]: A Multi-Disciplinary Overview of Inducing Factors and Control Strategies. *Sci. Hortic.* **2019**, *249*, 49–58. [CrossRef]
16. Marschner, P. *Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK, 2012.
17. Freitas, S.T.; Amarante, C.V.T.; Mitcham, E.J. Mechanisms regulating apple cultivar susceptibility to bitter pit. *Sci. Hortic.* **2015**, *186*, 54–60. [CrossRef]

18. Song, W.; Yim, J.; Kurniadinata, O.F.; Wang, H.; Huang, X. Linking fruit Ca uptake capacity to fruit growth and pedicel anatomy, a cross-species study. *Front. Plant Sci.* **2018**, *9*, 575. [CrossRef]
19. Khalaj, K.; Ahmadi, N.; Souri, M.K. Improvement of postharvest quality of asian pear fruits by foliar application of boron and calcium. *Horticulturae* **2016**, *3*, 15. [CrossRef]
20. Marcec, M.J.; Gilroy, S.; Poovaiah, B.W.; Tanaka, K. Mutual interplay of Ca^{2+} and ROS signaling in plant immune response. *Plant Sci.* **2019**, *283*, 343–354. [CrossRef]
21. Shabbir, R.; Javed, T.; Hussain, S.; Ahmar, S.; Naz, M.; Zafar, H. Calcium homeostasis and potential roles to combat environmental stresses in plants. *S. Afr. J. Bot.* **2022**, *148*, 683–693. [CrossRef]
22. Feng, D.; Gao, Q.; Liu, J.; Tang, J.; Hua, Z.; Sun, X. Categories of exogenous substances and their effect on alleviation of plant salt stress. *Eur. J. Agron.* **2023**, *142*, 126656. [CrossRef]
23. Souri, M.K.; Sooraki, F.Y.; Moghadamyar, M. Growth and quality of cucumber, tomato, and green bean under foliar and soil applications of an aminochelate fertilizer. *Hort. Environ. Biotechnol.* **2017**, *58*, 530–536. [CrossRef]
24. Gomes, M.H.F.; Migliavacca, R.A.; Otto, R.; Carvalho, H.W.P.D. Physicochemical characterization of fertilizers containing concentrated suspensions of CuO, $MnCO_3$ and ZnO. *Sci. Agric.* **2020**, *77*, e20180384. [CrossRef]
25. Torres, E.; Recasens, I.; Lordan, J.; Alegre, S. Combination of strategies to supply calcium and reduce bitter pit in 'Golden Delicious' apples. *Sci. Hortic.* **2017**, *217*, 179–188. [CrossRef]
26. Rivas-San, V.M.; Plasencia, J. Salicylic acid beyond defence: Its role in plant growth and development. *J. Exp. Bot.* **2011**, *62*, 3321–3338. [CrossRef] [PubMed]
27. Sahu, G.K. Salicylic acid: Role in plant physiology and stress tolerance. In *Molecular Stress Physiology of Plants*; Rout, G.R., Das, A.B., Eds.; Springer: Bhubaneswar, India, 2013; pp. 217–239. [CrossRef]
28. Jayakannan, M.; Bose, J.; Babourina, O.; Rengel, Z.; Shabala, S. Salicylic acid in plant salinity stress signaling and tolerance. *Plant Growth Regulat.* **2015**, *76*, 25–40. [CrossRef]
29. Khan, M.I.; Fatma, M.; Per, T.S.; Anjum, N.A.; Khan, N.A. Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. *Front. Plant Sci.* **2015**, *6*, 462. [CrossRef]
30. White, R.F. Acetylsalicylic acid [aspirin] induces resistance to tobacco mosaic virus in tobacco. *Virology* **1979**, *99*, 410–412. [CrossRef]
31. Ding, P.; Ding, Y. Stories of Salicylic Acid: A Plant Defense Hormone. *Trends Plant Sci.* **2020**, *25*, 549–565. [CrossRef]
32. Koo, Y.M.; Heo, A.Y.; Choi, H.W. Salicylic acid as a safe plant protector and growth regulator. *Plant Pathol. J.* **2020**, *36*, 1–10. [CrossRef] [PubMed]
33. Serna-Escolano, V.; Martínez-Romero, D.; Giménez, M.J.; Serrano, M.; García-Martínez, S.; Valero, D.; Valverde, J.M.; Zapata, P.J. Enhancing antioxidant systems by preharvest treatments with methyl jasmonate and salicylic acid leads to maintain lemon quality during cold storage. *Food Chem.* **2020**, *338*, 128044. [CrossRef] [PubMed]
34. Aghaeifard, F.M.; Babalar, M.E.; Fallahi, E.; Ahmadi, A. Influence of humic acid and salicylic acid on yield. fruit quality. and leaf mineral elements of strawberry [*Fragaria* x *Ananassa* Duch.] cv. Camarosa. *J. Plant Nutr.* **2016**, *39*, 1821–1829. [CrossRef]
35. Buczkowska, H.; Michalojc, Z.; Wierdak, R.N. Yield and fruit quality of sweet pepper depending on foliar application of calcium. *Turk. J. Agric. For.* **2016**, *40*, 222–228. [CrossRef]
36. Ibrahim, A.; Abdel-Razzak, H.; Wahb-Allah, M.; Alenazi, M.; Alsadon, A.; Dewir, Y.H. Improvement in Growth, Yield, and Fruit Quality of Three Red Sweet Pepper Cultivars by Foliar Application of Humic and Salicylic Acids. Hort. *Technology* **2019**, *29*, 170–178. [CrossRef]
37. Sobczak, A.; Kućko, A.; Pióro-Jabrucka, E.; Gajc-Wolska, J.; Kowalczyk, K. Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation. *Agronomy* **2023**, *13*, 779. [CrossRef]
38. *PN-ISO 8589*; Wersja Polska. Analiza Sensoryczna—Ogólne Wytyczne Dotyczące Projektowania Pracowni Analizy Sensorycznej. PKN: Warsaw, Poland, 1998.
39. *PNISO 11035:1999*; Analiza Sensoryczna. Identyfikacja i Wybór Deskryptorów Do Ustalenia Profilu Sensorycznego z Użyciem Metod Wielowymiarowych. PKN: Warsaw, Poland, 1999.
40. *PN-ISO 11036:1999*; Wersja Polska. Analiza Sensoryczna. Metodologia. Profilowanie Tekstury. PKN: Warsaw, Poland, 1999.
41. *PN-ISO 6564:1999*; Wersja Polska. Analiza Sensoryczna. Metodologia. Metody Profilowania Smakowitości. PKN: Warsaw, Poland, 1999.
42. Malinovsky, F.G.; Batoux, M.; Schwessinger, B.; Hyun Youn, J.; Stransfeld, L.; Win, J.; Kim, S.K.; Zipfel, C. Antagonistic regulation of growth and immunity by the Arabidopsis basic helix-loop-helix transcription factor homolog of brassinosteroid enhanced expression2 interacting with increased leaf inclination binding bHLH1. *Plant Physiol.* **2014**, *164*, 1443–1455. [CrossRef] [PubMed]
43. Souri, M.K.; Hatamian, M. Aminochelates in plant nutrition; a review. *J. Plant Nutr.* **2019**, *42*, 67–78. [CrossRef]
44. Val, J.; Monge, E.; Risco, D.; Blanco, A. Effect of pre-harvest calcium sprays on calcium concentrations in the skin and flesh of apples. *J. Plant Nutr.* **2008**, *31*, 1889–1905. [CrossRef]
45. El-Tohamy, W.A.; Ghoname, A.A.; Abou-Hussein, S.D. Improvement of pepper growth and productivity in sandy soil by different fertilization treatments under protected cultivation. *J. Appl. Sci. Res.* **2006**, *2*, 8–12.
46. Karlidag, H.; Yildirim, E.; Turan, M. Salicylic acid ameliorates the adverse effect of salt stress on strawberry. *Sci. Agric.* **2009**, *66*, 180–187. [CrossRef]

47. Santner, A.; Estelle, M. Recent advances and emerging trends in plant hormone signaling. *Nature* **2009**, *459*, 1071–1078. [CrossRef] [PubMed]
48. Santner, A.; Calderon-Villalobos, L.I.A.; Estelle, M. Plant hormones are versatile chemical regulators of plant growth. *Nat. Chem. Biol.* **2009**, *5*, 301–307. [CrossRef]
49. Wolters, H.; Jurgens, G. Survival of the flexible: Hormonal growth control and adaptation in plant development. *Nat. Rev. Genet.* **2009**, *10*, 305–317. [CrossRef] [PubMed]
50. El Tayeb, M.A.; Ahmed, N.L. Response of wheat cultivars to drought and salicylic acid. *Am. Eurasian J. Agron.* **2010**, *3*, 1–7.
51. Askari, E.; Ehsanzadeh, P. Effectiveness of exogenous salicylic acid on root and shoot growth attributes, productivity, and water use efficiency of water deprived fennel genotypes. *Hortic. Environ. Biotechnol.* **2015**, *56*, 687. [CrossRef]
52. Gutierrez-Coronado, M.A.; Trejo-Lopez, C.; Larque-Saavedra, A. Effects of salicylic acid on the growth of roots and shoots in soybean. *Plant Physiol. Biochem.* **1998**, *36*, 563–565. [CrossRef]
53. Shakirova, F.M.; Sakhabutdinova, A.R.; Bezrukova, V.; Fatkhutdinova, R.A.; Fatkhutdinova, D.R. Changes in the hormonal status of wheat seedlings induced by salicylic acid and salinity. *Plant Sci.* **2003**, *164*, 317–322. [CrossRef]
54. Gunes, A.; Inal, A.; Alpaslan, M.; Eraslan, F.; Bagci, E.G.; Cicek, N. Salicylic acid induced changes on some physiological parameters symptomatic for oxidative stress and mineral nutrition in maize (*Zea mays* L.) grown under salinity. *J. Plant Physiol.* **2007**, *164*, 728–736. [CrossRef]
55. Kováčik, J.; Gruz, J.; Backor, M.; Strnad, M.; Repcak, M. Salicylic acid-induced changes to growth and phenolic metabolism in Matricaria chamomilla plants. *Plant Cell Rep.* **2009**, *28*, 135–143. [CrossRef]
56. Kováčik, J.; Klejdus, B.; Hedbavny, J.; Bačkor, M. Salicylic acid alleviates NaCl-induced changes in the metabolism of Matricaria chamomilla plants. *Ecotoxicology* **2009**, *18*, 544–554. [CrossRef]
57. Manzoor, K.; Ilyas, N.; Batool, N.; Ahmad, B.; Arshad, M. Effect of salicylic acid on the growth and physiological characteristics of maize under stress conditions. *J. Chem. Soc. Pak.* **2015**, *37*, 588–593.
58. Sakhabutdinova, A.R.; Fatkhutdinova, D.R.; Bezrukova, M.V.; Shakirova, F.M. Salicylic acid prevents the damaging action of stress factors on wheat plants. *Bulg. J. Plant Physiol.* **2003**, *29*, 314–319.
59. Yildirim, E.; Ekinci, M.; Turan, M.; Dursun, A.; Kul, R.; Parlakova, F. Roles of glycine betaine in mitigating deleterious effect of salt stress on lettuce (*Lactuca sativa* L.). *Arch. Agron. Soil Sci.* **2015**, *61*, 1673–1689. [CrossRef]
60. Souri, M.K.; Tohidloo, G. Effectiveness of different methods of salicylic acid application on growth characteristics of tomato seedlings under salinity. *Chem. Biol. Technol. Agric.* **2019**, *6*, 26. [CrossRef]
61. Arfan, M.; Athar, H.R.; Ashraf, M. Does exogenous application of salicylic acid through the rooting medium modulate growth and photosynthetic capacity in two differently adapted spring wheat cultivars under salt stress? *J. Plant Physiol.* **2007**, *164*, 685–694. [CrossRef]
62. Stevens, J.; Senaratna, T.; Sivasithamparam, K. Salicylic acid induces salinity tolerance in tomato (*Lycopersicon esculentum* cv. Roma): Associated changes in gas exchange, water relations and membrane stabilisation. *Plant Growth Reg.* **2006**, *49*, 77–83. [CrossRef]
63. Haytova, D. A review of foliar fertilization of some vegetables crops. *Annu. Rev. Res. Biol.* **2013**, *3*, 455–465.
64. Elwan, M.W.M.; El-Hamahmy, M.A.M. Improved productivity and quality associated with salicylic acid application in greenhouse pepper. *Sci. Hortic.* **2009**, *122*, 521–526. [CrossRef]
65. Sánchez-Chávez, E.; Barrera-Tovar, R.; Muñoz-Márquez, E.; Ojeda-Barrios, D.L.; Anchondo-Nájera, A. Efecto del ácido salicílico sobre biomasa, actividad fotosintética, contenido nutricional del chile jalapeño. *Rev. Chapingo Ser. Hortic.* **2011**, *17*, 63–66. [CrossRef]
66. Larqué-Saavedra, A.; Martín-Mex, R.; Nexticapan-Garcéz, A.; Vergara-Yoisura, S.; Gutiérrez-Rendón, M. Efecto del ácido salicílico en el crecimiento de plántulas de tomate (*Lycopersicon esculentum* Mill.). *Rev. Chapingo Ser. Hortic.* **2010**, *16*, 183–187. [CrossRef]
67. Villanueva-Couoh, E.; Alcántar-González, G.; Sánchez-García, P.; Soria-Fregoso, M.; Larqué-Saavedra, A. Efecto del ácido salicílico y dimetilsulfóxido en la floración de *Chrysanthemun morifolium* (Ramat) Kitamura en Yucatán. *Rev. Chapingo Ser. Hortic.* **2009**, *15*, 25–31. [CrossRef]
68. Martín-Mex, R.; Nexticapan-Garcéz, A.; Herrera-Tuz, R.; Vergara-Yoisura, S.; Larqué-Saavedra, A. Efecto positivo de aplicaciones de ácido salicílico en la productividad de papaya (*Carica papaya*). *Rev. Mex. Cienc. Agric.* **2012**, *3*, 1637–1643. [CrossRef]
69. Anwar, S.; Iqbal, M.; Raza, S.H.; Iqbal, N. Eficacy of seed preconditionning with salicylic and ascorbic acid in increasing vigor of rice (*Oryza sativa* L.) Seedling. *Pak. J. Bot.* **2013**, *45*, 157–162.
70. Hayat, S.; Fariduddin, Q.; Ali, B.; Ahmad, A. Effect of salicylic acid on growth and enzyme activities of wheat seedlings. *Acta Agron. Hung.* **2005**, *53*, 433–437. [CrossRef]
71. Tucuch-Hass, C.J.; Alcántar-González, G.; Larqué, S.A. Efecto del ácido salicílico en el crecimiento de la raíz y biomasa total de plántulas de trigo. *Terra Latinoam.* **2015**, *33*, 63–68.
72. Tucuch-Haas, C.J.; Alcántar-González, G.; Volke-Haller, V.H.; Salinas-Moreno, Y.; Trejo-Téllez, L.I.; Larqué-Saavedra, A. Efecto del ácido salicílico sobre el crecimiento de raíz de plántulas de maíz. *Rev. Mex. Cienc. Agric.* **2016**, *7*, 709–716.
73. Abou El-Yazied, A. Effect of foliar application of salicylic acid and chelated zinc on growth and productivity of sweet pepper (*Capsicum annuum* L.) under autumn planting. *Res. J. Agric. Biol. Sci.* **2011**, *7*, 423–433.
74. Hanieh, A.; Mojtaba, D.; Zabihollah, Z.; Vahid, A. Effect of pre-sowing salicylic acid seed treatment on seed germination and growth of greenhouse sweet pepper plants. *Indian J. Sci. Technol.* **2013**, *6*, 3868–3871. [CrossRef]

75. Waraich, E.A.; Ahmad, R.; Halim, A.; Aziz, T. Alleviation of temperature stress by nutrient management in crop plants: A review. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 221–244. [CrossRef]
76. Gunes, A.; Inal, A.; Alpaslan, M.; Cicek, N.; Guneri, E.; Eraslan, F.; Guzelordu, T. Effects of exogenously applied salicylic acid on the induction of multiple stress tolerance and mineral nutrition in maize (*Zea mays* L.). *Arch. Agron. Soil Sci.* **2015**, *51*, 687–695. [CrossRef]
77. Barkosky, R.R.; Einhellig, F.A. Effects of salicylic acid on plant water relationship. *J. Chem. Ecol.* **1993**, *19*, 237–247. [CrossRef] [PubMed]
78. Ahmad, F.; Singh, A.; Kamal, A. Ameliorative effect of salicylic acid in salinity stressed Pisum sativum by improving growth parameters, activating photosynthesis and enhancing antioxidant defense system. *Biosci. Biotechnol. Res. Commun.* **2017**, *10*, 481–489. [CrossRef]
79. Nooren, S.; Fatima, K.; Athar, H.U.R.; Ahmad, S.; Hussain, K. Enhancement of physio-biochemical parameters of wheat through exogenous application of salicylic acid under drought stress. *J. Anim. Plant Sci.* **2017**, *27*, 153–163.
80. Nie, W.; Gong, B.; Chen, Y.; Wang, J.; Wei, M.; Shi, Q. Photosynthetic capacity, ion homeostasis and reactive oxygen metabolism were involved in exogenous salicylic acid increasing cucumber seedlings tolerance to alkaline stress. *Sci. Hortic.* **2018**, *235*, 413–423. [CrossRef]
81. Tasgín, E.; Atící, Ö.; Nalbantoglu, B. Effects of salicylic acid and cold on freezing tolerance in winter wheat leaves. *Plant Growth Regul.* **2003**, *41*, 231–236. [CrossRef]
82. Fung, R.W.M.; Wang, C.Y.; Smith, D.L.; Gross, K.C.; Tian, M. MeSA and MeJA increase steady-state transcript levels of alternative oxidase and resistance against chilling injury in sweet peppers (*Capsicum annuum* L.). *Plant Sci.* **2004**, *166*, 711–719. [CrossRef]
83. Luo, Z.; Wu, X.; Xie, Y.; Chen, C. Alleviation of chilling injury and browning of postharvest bamboo shoot by salicylic acid treatment. *Food Chem.* **2012**, *131*, 456–461. [CrossRef]
84. Zhang, W.P.; Jiang, B.; Lou, L.N.; Lu, M.H.; Yang, M.; Chen, J.F. Impact of salicylic acid on the antioxidant enzyme system and hydrogen peroxide production in *Cucumis sativus* under chilling stress. *Zeitschrift für Naturforschung C* **2011**, *66*, 413–422. [CrossRef] [PubMed]
85. Najafian, S.; Khoshkhui, M.; Tavallali, V.; Saharkhiz, M.J. Effect of salicylic acid and salinity in thyme (*Thymus vulgaris* L.): Investigation onchanges in Gas exchange, water relations, and membrane stabilization andbiomass accumulation. *Aust. J. Basic Appl. Sci.* **2009**, *3*, 2620–2626.
86. Nazir, N.; Ashraf, M.; Ejaz, R. Genomic relationships in oilseed Brassica with respect to salt tolerance photosynthetic capacity and ion relations. *Pak. J. Bot.* **2001**, *33*, 483–501.
87. Khodary, S. Effect of salicylic acid on the growth, photosynthesis and carbohydrate metabolism in salt stressed maize plants. *Int. J. Agric.* **2003**, *8530*, 179–187.
88. Graham, A.W.; McDonald, G.K. Effect of zinc on photosynthesis and yield of wheat under heat stress. In Proceedings of the 10th Australian Agronomy Conference, Hobart, Tasmania, 29 January–1 February 2001.
89. Horton, P.; Ruban, A.V.; Walters, R.G. Regulation of light harvesting in green plants. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1996**, *47*, 655–684. [CrossRef] [PubMed]
90. Baker, N.R.; Rosenqvist, E. Applications of chlorophyll fluorescence can improve crop production strategies: An examination of future possibilities. *J. Exp. Bot.* **2004**, *55*, 1607–1621. [CrossRef] [PubMed]
91. Prost, L.; Jeuffroy, M.H. Replacing the nitrogen nutrition index by the chlorophyll meter to assess wheat N status. *Agron. Sustain. Dev.* **2007**, *27*, 321–330. [CrossRef]
92. Fayez, K.A.; Bazaid, S.A. Improving drought and salinity tolerance in barley by application of salicylic acid and potassium nitrate. *J. Saud. Soc. Agric. Sci.* **2014**, *13*, 45–55. [CrossRef]
93. Lee, S.Y.; Damodaran, P.N.; Roh, K.S. Influence of salicylic acid on rubisco and rubisco activase in tobacco plant grown under sodium chloride in vitro. *Saud. J. Biol. Sci.* **2014**, *21*, 417–426. [CrossRef] [PubMed]
94. Hayat, Q.; Hayat, S.; Irfan, M.; Ahmad, A. Effect of exogenous salicylic acid under changing environment: A review. *Environ. Exp. Bot.* **2010**, *68*, 14–25. [CrossRef]
95. Natr, L.; Lawlor, D.W. *Handbook of Photosynthesis*; CRC Press: Boca Raton, FL, USA, 2015.
96. Yousefvand, P.; Sohrabi, Y.; Heidari, G.; Weisany, W.; Mastinu, A. Salicylic Acid Stimulates Defense Systems in Allium hirtifolium Grown under Water Deficit Stress. *Molecules* **2022**, *27*, 3083. [CrossRef]
97. Gong, Y.; Mattheis, J.P. Effect of ethylene and 1-methylcyclopropene on chlorophyll catabolism of broccoli florets. *Plant Growth Regul.* **2003**, *40*, 33–38. [CrossRef]
98. Dobón-Suárez, A.; Giménez, M.J.; Castillo, S.; García-Pastor, M.E.; Zapata, P.J. Influence of the Phenological Stage and Harvest Date on the Bioactive Compounds Content of Green Pepper Fruit. *Molecules* **2021**, *26*, 3099. [CrossRef]
99. Javaheri, M.; Mashayekhi, K.; Dadkhah, A.; Tavallaee, F.Z. Effects of salicylic acid on yield and quality characters of tomato fruit (*Lycopersicum esculentum* Mill.). *Int. J. Agric. Crop Sci.* **2012**, *4*, 1184–1187.

SUPPLEMENTARY

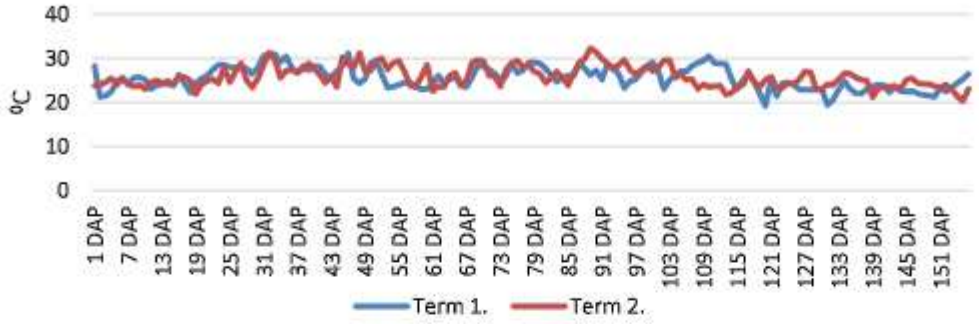

Figure S1. Average daily air temperature at the cultivation chamber on consecutive growing days according to the date [Term 1.—2019, Term 2.—2020]

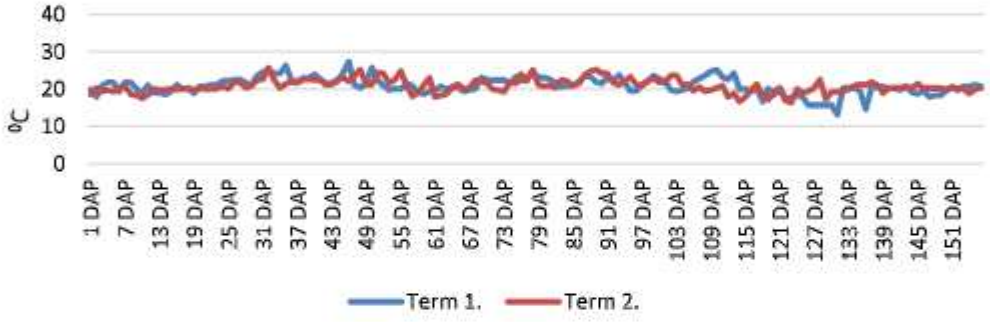

Figure S2. Average night-time air temperature at the cultivation chamber on consecutive growing days according to the date [Term 1.—2019, Term 2.—2020]

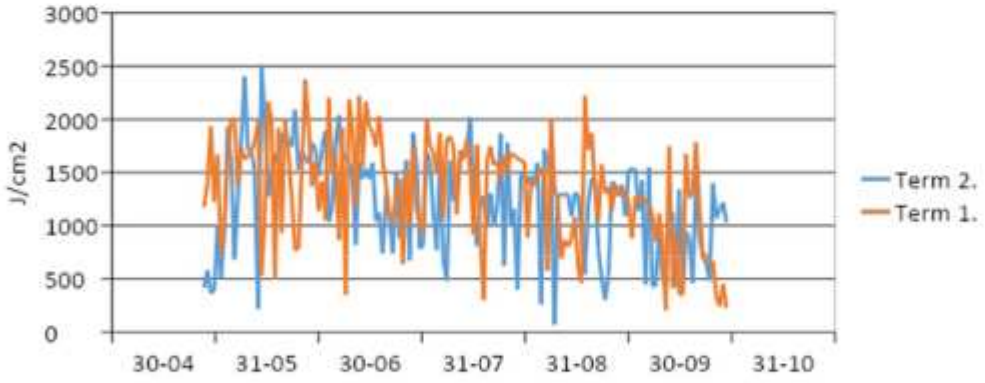

Figure S3. Dynamics of daily radiation totals on successive growing days according to term [Term 1.—2019, Term 2.—2020]

Figure S4. The pepper plants grown on mineral wool growing mats fed by dropping fertigation system.

Figure S5. Fruit of the 'Palermo' and 'Aifos' cultivars, whole and in cross-section.

Table S1. Effect of salicylic acid and calcium treatment of pepper plants on diameter and length of fruit and thickness of pericarp depending on cultivar [mean of two terms ± SE]

Parameter	Cultivar	Treatment			
		SA	Ca	SA + Ca	Control
Length of fruit [mm]	Aifos	85.3 ± 1.64 c*	90.2 ± 2.74 c	84.3 ± 1.97 c	88.9 ± 3.48 c
	Palermo	234.2 ± 11.39 a	222.6 ± 6.37 ab	209.0 ± 7.97 ab	196.4 ± 10.21 b
	Average	159.8 ± 22.25 A	156.4 ± 19.42 A	146.6 ± 18.45 A	142.7 ± 16.43 A
Diameter of fruit [mm]	Aifos	91.4 ± 1.80 a	90.1 ± 1.28 a	88.9 ± 1.80 a	88.3 ± 2.28 a
	Palermo	51.1 ± 0.31 b	49.8 ± 1.12 b	47.5 ± 0.85 b	47.4 ± 2.48 b
	Average	71.3 ± 5.87 A	69.9 ± 5.87 A	68.2 ± 6.05 A	67.8 ± 6.13 A
Thickness of pericarp [mm].	Aifos	6.3 ± 0.45 ab	7.3 ± 0.32 a	6.7 ± 0.21 ab	6.2 ± 0.49 abc
	Palermo	5.3 ± 0.39 bc	5.1 ± 0.34 bc	5.0 ± 0.44 bc	4.2 ± 0.47 c
	Average	5.8 ± 0.33 A	6.2 ± 0.40 A	5.9 ± 0.35 A	5.2 ± 0.44 A

*Means with different letters indicate a statistically significant difference according to the Tukey HSD test at $\alpha = 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant. Small letters refer to combination cultivar × treatment interaction, capital letters relate to treatment

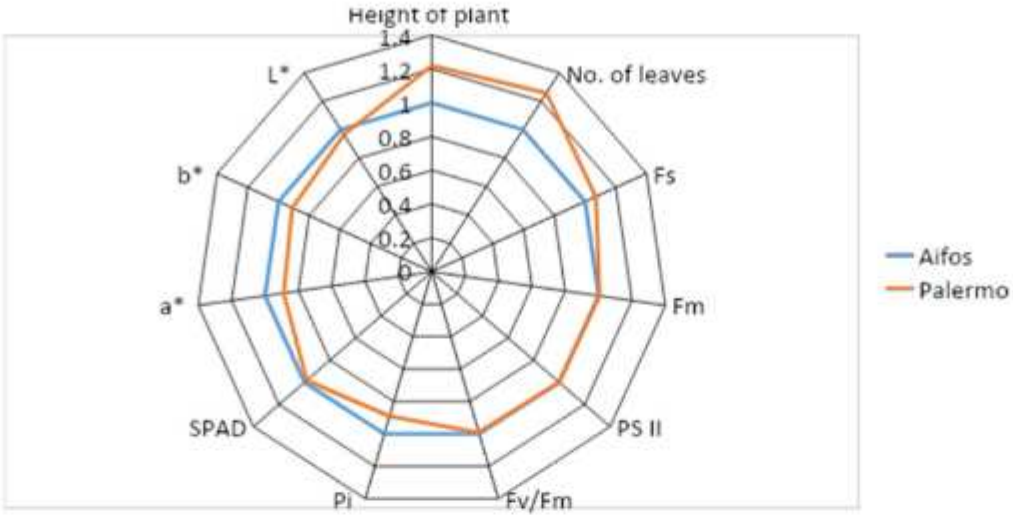

Figure S6. Results of plant biometric measurements, photosynthetic activity of peppers and evaluation of fruit colour normalised to 'Aifos' as radar plots compared to 'Palermo' [average of two years]

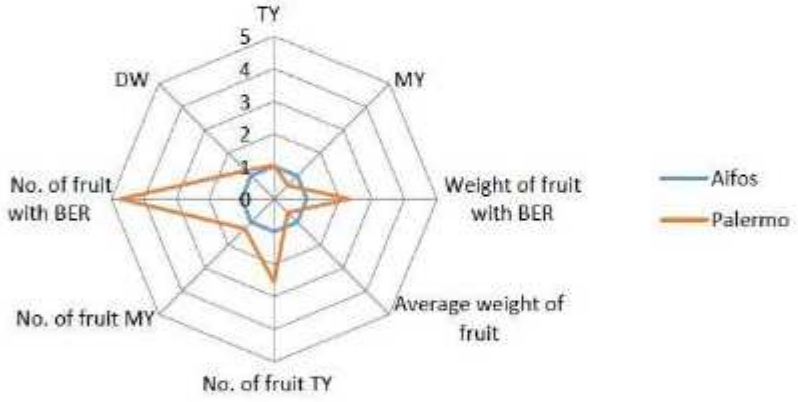

Figure S7. Results of plant yield measurements normalised to 'Aifos' as radar plots compared to 'Palermo': TY—Total Yield; MY—Marketable Yield, DW—Dry Weight of fruit [average of two years]

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Article

Effect of Foliar Application of Calcium and Salicylic Acid on Fruit Quality and Antioxidant Capacity of Sweet Pepper (*Capsicum annuum* L.) in Hydroponic Cultivation

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Abstract: The aim of this study was to investigate the effect of foliar application of calcium and salicylic acid on improving the physicochemical quality, sensory quality and antioxidant potential of pepper fruits grown hydroponically in mineral wool substrate. Two sweet pepper varieties with red fruit type were used: block Aifos and elongated Palermo. Fruit quality was tested from four plant treatment combinations: (1) water (control), (2) calcium nitrate 0.7% (Ca), (3) salicylic acid 0.03% (SA), (4) calcium nitrate and salicylic acid combined (Ca+SA). Fruits of both varieties showed high concentrations of health-promoting constituents, including potassium, phosphorus, vitamin C (over 47 mg 100 g^{-1} of FW (fresh weight)), and carotenoids, with capsanthin being the most abundant (more than 1226 µg 100 g^{-1} of FW). The results of the sensory evaluation demonstrated that the attributes tested scores above 7 out of 10, indicating a high sensory quality. The antioxidant activity of pepper fruits was determined by three different methods: DPPH (method for measuring the antioxidant activity of DPPH), ABTS (method for measuring the antioxidant activity of ABTS) and TPC (total polyphenol content) and averaged more than 86%, 78% RSC (radical scavenging capacity) and almost 54 mg CE (catechin) 100 g^{-1} of FW for both cultivars, respectively. Fruit quality results were analysed using PCA (principal component analysis). The first two principal components (PC1 and PC2) explained almost 54% of the variation, highlighting the strong correlations of PC1 with dry matter content, soluble sugars, potassium, acidity and sensory characteristics of pepper fruit such as skin hardness and flesh firmness. The application of SA to peppers resulted in an increase in the carotenoid content of the fruit. Furthermore, a notable positive correlation was detected between total sugars and the sugar/acid ratio when Ca+SA was combined in both cultivars. Palermo fruit showed better quality parameters and higher antioxidant activity, making this sweet pepper variety particularly valuable in a health-promoting context.

Keywords: mineral substrate; commercial yield; abiotic stress; BER; carotenoids; sugars

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1. Introduction

Peppers are a very popular ingredient, both as a vegetable and as a spice. Pepper fruits are characterised by their high degree of flavour and health-promoting properties [1,2].

The incorporation of pepper fruits in the diet is strongly recommended due to the presence of bioactive compounds in these fruits that act as antioxidants [3]. Pepper fruits are an excellent source of antioxidants such as polyphenolic compounds, carotenoids, vitamins C, A, E, flavonoids and are rich in minerals, making them an important source of nutrients in the human diet [4–6]. Their solvent extracts exhibit potent antifungal, antibacterial and chemotherapeutic activities [7]. A diversity of morphological characteristics, fruit size, and quality are observed among the numerous varieties of pepper. The quality and chemical composition of pepper fruits are also influenced by agronomic and environmental factors [6]. Red and orange pepper fruits are valued for the presence of carotene and capsanthin, while β-cryptoxanthin, zeaxanthin, lutein and β-carotene are responsible for the yellowish–orange colour of peppers [8]. In contrast, green peppers represent a significant source of chlorophylls [9]. The researchers have observed that the levels of ascorbic acid, along with the colouring and ripening of the fruit, have either decreased or remained unchanged in some pepper varieties, while in other varieties there has been an increase. In contrast, provitamin A content increased with progressive fruit colouration in most pepper cultivars, with the exception of yellow cultivars. Brown peppers showed the highest provitamin A activity of 10–15% RDA (retinol activity equivalents) per 100 g^{-1} of FW, compared to other varieties with different fruit colours [10]. The properties of hot and semi-spicy peppers are mainly due to the presence of capsaicinoids in their fruits, a complex of alkaloids that give them their characteristic spicy taste and biological activity. Capsaicinoids are mainly accumulated in the cells of the placental epidermis and in the seed sepals of the fruit [11]. Sweet peppers are distinguished by their high vitamin C content and the absence of large amounts of capsaicinoids, including capsaicin. The concentration of these substances in sweet pepper fruit is below 0.02% of dry weight [12,13]. The interest in natural antioxidants in food and other biological materials is due to their safety, as well as their potential nutritional and therapeutic value. Bioactive compounds, including polyphenols, carotenoids (α-carotene, β-carotene, lycopene and lutein) and vitamins A, B, C and E, which are present in fruits and vegetables, have been found to exhibit protective effects against cellular oxidation [14,15]. The regular consumption of these bioactive compounds with food in adequate quantities represents an important factor in the prevention of noncommunicable diseases, including cancer and cardiovascular disease [16–19]. The growing interest in natural antioxidants has prompted a surge in research activity aimed at assessing the antioxidant properties of plant-based products [20–22]. The antioxidant capacity of foods depends on the synergistic action of various antioxidant compounds. In addition to other reasons, the determination of the antioxidant capacity of foods in vitro demands a combination of more than one analytical method [23]. The determination of antioxidant activity frequently employs methods that involve the scavenging of free, stable radicals, such as the use of ABTS+ and DPPH [24,25]. It is frequently the case that antioxidant potential is also expressed in terms of total polyphenol content [26].

In addition to varietal traits, environmental factors also affect the nutritional profile of pepper fruit. Growing vegetables under cover allows for a high yield with stable quality. Nowadays, the majority of greenhouse cultivation is based on soilless technology, which is characterised by high efficiency and the use of a variety of substrates [27,28]. The soilless cultivation system (SCS) is regarded as a particularly promising solution, combining increased crop yield with minimal impact on the supporting ecosystem [29,30]. Soilless cultivation techniques are an effective solution in cases of water scarcity and low soil fertility [31]. Furthermore, they support plant growth under abiotic stress conditions, primarily salinity and drought [32]. However, soilless cultivation requires control of the root system in a reduced root zone volume, in comparison to the techniques employed in soil-based cultivation [33]. In hydroponic cultivation of key vegetable species such as tomatoes,

peppers and cucumbers, mineral wool is the substrate most often used [34,35]. This inert substrate allows for control of root system parameters and high predictable yields [36,37]. On the other hand, physiological disorders are a common problem in greenhouse pepper production, which often employs the hydroponic method. These are usually caused by various types of abiotic stresses. A disorder known as dry rot, abbreviated blossom-end rot (BER), is a common cause of reduced quality in pepper fruit. The occurrence of BER is attributable to various factors. One such factor is water stress, which has the effect of inhibiting calcium transport in the plant [38–40].

Calcium is a crucial nutrient for plants, promoting optimal growth and development. It is essential for maintaining cell wall stability and integrity and improving fruit quality [41–43]. It is involved in intercellular signalling, affecting plant metabolism and cell growth [44]. Calcium is considered a secondary messenger molecule that balances the presence of stored intracellular Ca. In response to a variety of stimuli, calcium levels are elevated. When plants are subjected to stress, intracellular signalling events are triggered in the cell. Calcium signalling begins with sensors that recognise elevated calcium ion levels and activate protein kinases. The activated kinases regulate a number of genes, which in turn lead to phenotypic responses associated with stress tolerance [39,45].

The majority of the research concentrates on the utilisation of formulations in agricultural crops with the objective of reducing the incidence of adverse stress effects in plants. This includes the use of salicylic acid in the cultivation of certain vegetable species. Salicylic acid (SA) is one of the phenolic compounds produced by plants from the hydroxyl group or derivatives. Plant phenols are commonly described as specialised metabolites that perform vital functions, including the biosynthesis of lignin and allelopathic compounds that regulate plant responses to external stimuli [46], thermoregulation [47] and defence signalling activity in plants [46]. SA also stimulates morphological, physiological and biochemical pathways of general plant defence [48,49]. By inducing disease tolerance in plants (*Arabidopsis*, *Nicotiana benthamiana* and tomato), SA also controls ion uptake and antioxidant defence [50]. According to Sobczak et al. [51], foliar application of salicylic acid to pepper plants at a concentration of 0.03% positively influences the growth and yield of peppers in hydroponic cultivation and on pepper fruit quality. The treatment of pepper plants with SA resulted in a reduced proportion of fruit manifesting symptoms of BER [51]. Additionally, the application of SA in aeroponic cultivation has been observed to promote favourable growth and development in pepper plants. Peppers grown at high nutrient solution concentrations (EC (electrical conductivity) about 7 dS m^{-1}) showed symptoms of oxidative stress. The application of SA was found to reduce both the number and weight of fruits showing symptoms of calcium deficiency. The results obtained by Sobczak et al. [52] confirm the effect of SA in alleviating high substrate EC stress in pepper, increasing the photosynthetic activity of pepper leaves by increasing, among other things, overall PSII-PI viability and leaf SPAD index. According to Sobczak et al. [52], high EC disrupts the oxidative balance, while exogenous SA activates CAT (catalase), which detoxifies large amounts of ROS (reactive oxygen species) and alleviates the stress response. Furthermore, Amin et al. [53] report that spraying pepper plants with salicylic acid has the effect of significantly increasing peroxidase activity while maintaining catalase activity at a level comparable to that of the untreated control. SA applied before harvest induced a significant increase in polyphenol oxidase and peroxidase activity in pepper fruit [53]. As reported by Jiankang et al. [54], pre- and post-harvest application of SA resulted in better control over the pathogens affecting pears and cherries. This was achieved by inducing the defence immune system [54] and stimulating the activity of antioxidant enzymes [55]. At present, there is a considerable volume of research examining the efficacy of employing diverse eustressors in crop cultivation, the way they are applied, the impact of concentration levels

or the amount of doses [56–58]. In order to reduce the negative effects of stresses occurring in pepper cultivation, effective solutions are constantly being sought for commodity subproduction, including those involving soilless cultivation techniques. At the same time, a great deal of attention is paid to factors increasing the quality of vegetables, especially with regard to health-promoting components. Therefore, the aim of this study was to evaluate the effectiveness of foliar application of calcium (Ca) to sweet pepper plants in comparison to treatment with an SA solution and a simultaneous application of Ca and SA, in order to determine the impact on the physicochemical quality, sensory quality and antioxidant capacity of sweet pepper fruits grown hydroponically.

2. Materials and Methods

2.1. Location of Research

The research was carried out at the Greenhouse Experimental Centre of Warsaw University of Life Sciences (21° E, 51°15′ N), within the cultivation chambers of the Department of Vegetable and Medicinal Plants. The greenhouse is covered with glass (ridge height: 6.70 m, sidewall height of 3.50 m).

2.2. Plant Material and Experimental Design

Two sweet pepper varieties with red fruit were selected for the study: Aifos F1 (Seminis, Bayer) block type and Palermo F1 (Rijk Zwaan) Dulce Italiano type. The study was conducted in 2019 (term 1) and 2020 (term 2), using a hydroponic system with mineral wool substrate for the cultivation of peppers. Pepper seedlings were planted on growing mats in the experimental chamber on 13 May in both 2019 and 2020 (0 DAP–day after planting). The seedlings were planted on 28 DAS (days after sowing) into Grotop Master mats (Grodan), with three plants per mat, at a density of 2.5 plants/m^2 (1.2 × 0.55 m). Plants were cultivated on two shoots and a nutrient solution of a specific composition was supplied by capillaries. The average daytime temperature was 25.5–25.8 °C and nighttime temperature was 20.8–20.9 °C. The radiation totals were 192.11 kJ cm^{-2} (term 1) and 209.41 kJ cm^{-2} (term 2). The cultivation details are outlined in Sobczak et al. [51].

Experimental Factors

Aifos and Palermo pepper plants were sprayed once a week between 7 and 151 DAP (day after planting). The following treatments were applied to the plants: (1) control plants were sprayed with water (control), (2) calcium nitrate at a concentration of 0.7% (Ca), (3) salicylic acid at a concentration of 0.03% (SA) and (4) calcium nitrate in a combination with with salicylic acid at a concentration of 0.7% and 0.03% (Ca+SA), respectively. Oleate 85 EC (rapeseed oil) Danmar was used as a surfactant. Tests for each cultivar and combination (Ca; SA; Ca+SA and control) were performed in 4 replicates. A repetition was a randomly selected experimental plot with two mineral wool growing mats, i.e., 6 plants. The experiment was conducted on both dates using the randomised block method.

2.3. Evaluated Parameters

Physicochemical analyses of the fruit, evaluation of the antioxidant activity of the fruit and sensory evaluation of the fruit were carried out immediately after fruit harvest, during term 1 and term 2 on two occasions: 84 DAP (5 August) and 140 DAP (30 September). Fruits that had reached physiological maturity and full colouration were harvested for subsequent analysis. Five fruits from each combination were randomly selected for physicochemical analyses. Fruits without seeds or seed sepals were cut into cubes of approximately 4 mm × 4 mm. Following the preparation of the mixed fruit sample, triplicate samples were then taken for analysis.

2.3.1. Physicochemical Analysis of the Fruit

Dry matter content (DW)

The dry matter content of the fruit was determined using the dryer-weight method at 105 °C, as described in detail by Sobczak et al. [51].

Ascorbic acid (AA)

Total vitamin C content was determined in accordance with the method of Odriozola-Serrano et al. [59] and Grobelna et al. [60]. Ascorbic acid content was determined by high-performance liquid chromatography (HPLC) with the use of the UV–vis SPD-10A VP detector (Shimadzu, Kyoto, Japan), LC-10AT pump (Shimadzu, Kyoto, Japan), CTO-10AS VP oven (Shimadzu, Kyoto, Japan), DEGASSEX model D-4400 (Shimadzu, Kyoto, Japan) degasser by Shimadzu, using the software for collecting LC Solution data (Shimadzu, Kyoto, Japan, version 1.21 SP1). An OnyxMonolithic C18 column, 100 × 4.6 mm (Phenomenex) was used. The mobile phase was the H_3PO_4 solution. The results were recorded at 254 nm. The content of L-ascorbic acid is expressed as milligram content per 100 g sample.

Total Soluble Solids (TSS)

In order to determine the concentration of dissolved components in the cell juice, the juice was extracted from finely chopped pepper fruits. Subsequently, the sugar extract content was measured using an Atago refractometer, with the result expressed in °Brix. The TSS/TA ratio was calculated by dividing the TSS score by the TA (total acidity) score.

Total sugars (TS)

The total sugar content of the tested fruits was determined using the Luff-Schoorl method [60]. The ratio of the total sugar content to the acidity of the pepper fruits was determined as the quotient TS:TA.

Total acidity (TA)

The acidity of the pepper fruits was determined by a titration potentiometric method [61].

Nitrates

Nitrate concentration (NO_3) was determined spectrophotometrically using a FIAstar instrument (Foss Tecator AB, Hoeganaes, Sweden) at 440 nm, and P concentration using a colorimetric assay. K and Ca concentrations were determined using the flame method.

Carotenoids

The content of β-carotene, β-cryptoxanthin, lutein, ascorbic acid, neoxanthin, zeaxanthin, violaxanthin and capsanthin in fruits was quantified by HPLC using a Shimadzu LC-20 system (Kyoto, Japan). To prepare the samples, 2 g of Na_2SO_4 per 100 g^{-1} was added to each pepper fruit sample and then homogenised. Then, 5 g of this homogenised material was taken, a pinch of quartz sand was added and ground in a mortar with acetone at a temperature of 4 °C. The extract was transferred to 50 mL volumetric flasks and made up with the same acetone. The supernatant obtained after centrifugation (1500 rpm) was filtered using a 25 mm filter with a pore size of 0.22 µm (Supelco IsoDisc™ PTFE syringe filter) into vials. The vials were placed on a thermostatted tray (4 °C) and 5 µL was applied to a column (Phenomenex, Kinetex 2.6 µm, C18, 100 mm × 4.6 mm) thermostatted at 40 °C using an autosampler. Methanol in isocratic elution was used as the mobile phase. Data for β-carotene were collected at 450 nm, 430 nm for chlorophyll a and 470 nm for chlorophyll b.

2.3.2. Evaluation of Antioxidant Potential

Preparation of fruit extracts

The extracts were prepared from the pericarp pulp with peel. They were obtained by ultrasonic-assisted extraction with methanol (25 mL 1 g^{-1} of raw material), for a period of 60 min. The extraction process was performed at room temperature. The extracts were

filtered through a tissue paper filter and then centrifuged. The filtrate was collected in a clean tube. The samples were stored at 4 °C until the point of analysis.

DPPH Assay

The assay involved the colorimetric measurement of the extent to which a known amount of DPPH (2,2-diphenyl-1-picrylhydrazyl) was reduced by the extract. DPPH is a stable cation radical that has an unpaired electron on the valence shell. It forms a nitrogen bridge on one of the nitrogen atoms. When reacting with the test substance, it releases a hydrogen atom, transforming into the reduced form of DPPH. This reaction is accompanied by a colour change of the solution from violet to pale yellow, which is quantitatively measured spectrophotometrically at 517 nm. The result is given in % DPPH inhibition [62].

Preparation of DPPH radical solution

First, 0.012 g of DPPH was weighed and quantitatively transferred to a 100 mL volumetric flask. It was then made up to the mark with pure methanol and the reagent was dissolved using an ultrasonic bath for approximately 60 min. The reagent was stored in a dark glass bottle.

Preparation of reagent blank

We added 1 mL of distilled water to 3 mL of methanol and 1 mL of DPPH solution. The whole mixture was mixed well and, 10 min after the last component was added, the absorbance was measured at λ = 517 nm.

Preparation of test solutions

We took 0.5 mL of extract and transferred it to a 10 mL volumetric flask and made it up to 10 mL with methanol. Then, 0.2 mL of test sample, 1 mL, 3 mL of methanol and 1 mL of DPPH radical solution were measured into the tube. Ten minutes after the last reagent was added, the absorbance of the mixture against methanol was measured at λ = 517 nm.

The percentage of DPPH inhibition was calculated according to the formula:

$$\% \text{ DPPH} = [(AB - AA)/AB] \times 100$$

where

AA is bsorbance of test solution (t = 10 min);

AB is absorbance of the blank (t = 0 min) [63];

The antioxidant activity of the tested extracts was given as the percentage of DPPH radical scavenging capacity (RSC, %).

ABTS Assay

Assessment of antioxidant activity by the ABTS (2,2′-azobis(3-ethylbenzothiazoline-6-sulfonate) method involves the reduction of the colourful, intensely blue–green cation radical ABTS+ (the oxidised form) to the colourless ABTS, which is the reduced form. The radical is reduced by antioxidants present in the test sample [64].

Preparation of the ABTS solution

A 4.9 mM potassium persulphate ($K_2S_2O_8$) solution was prepared, with a stability period of only one day. To prepare the solution, 0.132 g of $K_2S_2O_8$ was weighed and thoroughly dissolved in 100 mL of redistilled water. The PSB phosphate buffer, pH 7.4, was then prepared. This solution was prepared from two PBS tablets dissolved in 400 mL of redistilled water.

ABTS solution was prepared by dissolving one ABTS tablet in 1.3 mL potassium persulphate solution and 1.3 mL distilled water. The solution was stored in a dark location at room temperature for a period of 16 h. After this time, a working solution of ABTS was prepared by diluting it with PBS so that its absorbance at 734 nm was A = 070.

Sample Measurement

One by one, 100 µL of the test extract and 1 mL of ABTS were added to the cuvette. Six minutes after the addition of the last component, the measurement was performed in a spectrophotometer at 734 nm. The drift capacity of the stable ABTS radical was calculated according to the formula

$$\% \text{ ABTS} = [(AB - AA)/AB] \times 100$$

where

AA is absorbance of test solution (t = 6 min);

AB is absorbance of the blank (t = 0 min) [65].

The antioxidant activity of the tested extracts was given as the percentage of ABTS radical scavenging capacity (RSC, %).

TPC Assay

The determination was performed by the colorimetric method using the Folin–Ciocalteu reagent [66].

Preparation of extracts

The analysis was conducted on 5% methanolic extracts prepared from pericarp with peel, obtained through ultrasound-assisted extraction for 60 min. The extraction was performed at room temperature.

Preparation of the calibration curve

A calibration curve was prepared from a standard solution of (+)catechin in methanol (catechin concentration 50 mg 100 cm^3). We added 0.5, 1.25, 2.5, 3.75 and 5 cm^3 of the catechin solution to 25 cm^3 flasks successively. The flasks were topped up with methanol 25 cm^3. From each flask, 2.5 cm^3 of the solution was taken into 25 cm^3 flasks and topped up with redistilled water. A volume of 5 cm^3 of these solutions was taken and 0.25 cm^3 of Folin–Ciocalteau reagent (diluted 1:1 with redistilled water and 0.5 cm^3 of 7% Na_2CO_3) was added. After thorough mixing, the solutions were left to stand in the dark. After 30 min, the absorbance of the solutions was measured in a spectrophotometer at 760 nm. A calibration curve was plotted from the results obtained [67].

Specific measurement

Dilutions of the initial extract were prepared, 2-, 5- and 10-fold with methane. For the analysis, 2.5 cm^3 of each sample was popped and topped up with water to 25 cm^3. Then, 5 cm^3 each was taken from the solutions and 0.25 cm^3 of Folin–Ciocalteu reagent and 0.5 cm^3 of 7% Na_2CO_3 were added. The samples were mixed thoroughly and set aside in a dark place. After 30 min, the absorbance was measured in a spectrophotometer at 760 nm. The result was expressed as mg catechin (CE) 100 g^{-1} of FW (mg CE 100 g^{-1} of FW).

2.3.3. Sensory Evaluation of Pepper Fruit Quality

The QDA method (quantitative description analysis) was used for sensory quality testing of pepper fruits evaluation, which is described in Sobczak et al. [51].

2.4. Statistical Methods

The results were statistically processed using multivariate factor analysis. Based on the average values of traits for each experimental setup, divided by pepper variety, a multivariate factor analysis was conducted. The principal component analysis (PCA) method was used to reduce the number of variables and capture the main sources of variance in the data. To maximise the variance of loadings between factors and minimise their variance within the new factor, Varimax rotation was applied. Based on the obtained components, in the form of correlation coefficients of the studied variables with the components and

the correlation of factor objects divided by variety, the interdependencies were illustrated using a biplot. Analyses were performed using IBM SPSS Statistics version 29.

3. Results

3.1. Physicochemical and Sensory Characteristics, Yield and Antioxidant Potential of Pepper Fruits

The detailed yield characteristics of Aifos and Palermo peppers grown hydroponically, as well as the dry matter content of the fruit and the distinguishing characteristics of the sensory evaluation of the pepper fruits, are described in Sobczak et al. [51]. Data for the treatment of pepper plants with Ca, SA and their combination are published in the article Sobczak et al. [51]. High levels of solar radiation and high air temperature were recorded during the pepper yielding period [51]. However, the commercial fruits of peppers of both cultivars obtained at date 1 and date 2 were of high quality. On the other hand, a high proportion of BER fruit was found in the total pepper yield, especially in the cultivar Palermo (Table 1). Pepper plants treated with both Ca and SA alone and with both Ca and SA showed less BER on fruit than plants in the control [51]. Commercial sweet pepper fruits from plants grown hydroponically in a mineral wool substrate were characterised by high health-promoting quality. High concentrations of the mineral salts potassium and phosphorus, vitamin C averaging over 47 mg 100 g^{-1} of FW, carotenoids including lutein averaging more than 209 μg 100 g^{-1} of FW, capsanthin more than 1226 μg 100 g^{-1} of FW, β-cryptoxanthin more than 88 μg 100 g^{-1} of FW and α and β carotene more than 168 and 735 μg 100 g^{-1} of FW, respectively, were found in the fruit of both cultivars (Table 1). In the evaluation of sensory quality, the peppers obtained an overall sensory preference score for the cultivars of more than 7 points out of a maximum of 10, which indicates their high sensory quality [51]. Fruits of both cultivars were characterised by high antioxidant activity measured by DPPH, ABTS and TPC methods obtaining, on average, levels of oxidative activity in each method of more than 86%; more than 78% RSC and almost 54 mg CE 100 g^{-1} of FW, respectively (Table 1). Large differences were found between the heights of individual parameters in pepper fruits depending on the cultivar. The fruits of the Aifos cultivar accumulated more potassium ions, bioactive compounds such as lutein, capsanthin, β-cryptoxanthin and α and β- carotene. At the same time, in the sensory evaluation, they were considered to be fruits with a tougher skin than those of the Palermo variety. They were rated higher than Palermo variety fruit in terms of most distinguishing characteristics such as flesh fibrousness, flesh juiciness, flesh firmness, sour taste, bitter taste, pungent flavour and overall quality of pepper fruit but these differences were not statistically significant. On the other hand, sweetness was significantly higher for Palermo than for Aifos. Palermo fruit was characterised by higher dry matter content, TSS and sugar/acid ratio TSS/TA and TS/TA than Aifos fruit and tended to receive higher overall sensory preference scores than Aifos fruit in the consumer evaluation (Table 1). In addition, the Palermo fruit received higher scores for antioxidant activity, regardless of the method used in this study to measure the activity of the fruit in vitro (Table 1).

Table 1. Average values with standard deviation of the examined physicochemical parameters of fruit quality, sensory quality, yield and antioxidant activity of pepper fruits for cultivars Aifos and Palermo. The table indicates the codes for the parameters used in the processing of the results of principal component analysis, PCA.

Parameter	Unit	Code	Cultivar		Average
			Aifos	Palermo	
Physicochemical composition (average of 48 values)					
Dry weight	%	DW	8.36 ± 0.50	9.91 ± 1.69	9.14 ± 1.47

Table 1. *Cont.*

Parameter	Unit	Code	Cultivar		Average
			Aifos	Palermo	
Total soluble solids	°Brix	TSS	8.40 ± 0.58	9.63 ± 0.99	9.01 ± 1.01
Total sugars	g 100 g^{-1} FW	TS	3.83 ± 1.68	4.35 ± 1.90	4.09 ± 1.80
Titratable acidity		TA	0.21 ± 0.02	0.17 ± 0.04	0.188 ± 0.03
TSS/TS ratio	i.u.	TSS/TA	40.70 ± 3.99	58.82 ± 10.87	49.761 ± 12.22
TS/TA ratio	i.u.	TS/TA	18.59 ± 8.39	26.01 ± 10.91	22.301 ± 10.373
Phosphorus	mg kg^{-1} FW	P	223.92 ± 25.38	214.83 ± 49.60	219.38 ± 39.46
Nitrates		NO_3	108.14 ± 4.32	110.00 ± 3.81	109.07 ± 4.16
Calcium		Ca	23.02 ± 4.08	24.09 ± 4.30	23.56 ± 4.20
Potassium		K	2294.48 ± 122.82	2180.94 ± 216.45	2237.71 ± 184.12
Ascorbic acid	mg 100 g^{-1} FW	AA	48.15 ± 10.07	47.15 ± 5.97	47.65 ± 8.25
Neoxanthin	μg 100 g^{-1} FW	Neox.	39.23 ± 27.05	36.53 ± 12.31	37.88 ± 20.95
Lutein		Lut.	234.36 ± 172.64	184.80 ± 74.89	209.58 ± 134.68
Zeaxanthin		Zeax.	24.68 ± 12.97	19.50 ± 4.10	22.09 ± 9.91
Violaxanthin		Violax.	6.46 ± 5.16	3.55 ± 2.98	5.00 ± 4.44
Capsanthin		Caps.	1478.43 ± 1309.22	974.31 ± 528.73	1226.37 ± 1024.95
β-cryptoxanthin		Crypt.	100.63 ± 56.74	76.11 ± 21.86	88.37 ± 44.51
α-carotene		α-carot.	198.25 ± 121.44	138.09 ± 101.78	168.17 ± 115.48
β-carotene		β-carot.	820.81 ± 458.92	650.26 ± 417.85	735.53 ± 444.89
Sensory quality (average of 48 values)					
Odour of fresh pepper	0–10 point's scale	Odor-fre.p.	5.01 ± 1.93	4.78 ± 2.43	4.89 ± 2.19
Skin hardness		Skin-hard.	5.97 ± 2.08	5.00 ± 2.59	5.49 ± 2.39
Flesh fibrousness		Flesh-fibr.	6.14 ± 1.88	5.24 ± 1.83	5.69 ± 1.91
Flesh juiciness		Flesh-juic.	6.18 ± 1.90	4.86 ± 2.05	5.52 ± 2.081
Flesh firmness		Flesh-firmn.	6.84 ± 1.98	3.02 ± 1.37	4.93 ± 2.555
Typical pepper taste		Taste-p.	6.46 ± 1.27	6.65 ± 1.58	6.55 ± 1.43
Sour taste		Taste-so.	3.74 ± 2.14	2.21 ± 1.66	2.98 ± 2.06
Sweet taste		Taste-swe.	3.79 ± 2.11	6.40 ± 2.12	5.09 ± 2.48
Bitter taste		Taste-bit.	0.51 ± 0.89	0.36 ± 1.08	0.44 ± 0.99
Pungent flavour		Flav.pung.	0.97 ± 1.31	0.80 ± 1.02	0.88 ± 1.17
Off-flavor		Flav.of.	0 ± 0	0 ± 0	0 ± 0
Overall quality		OQ	7.18 ± 0.95	6.766 ± 1.22	6.973 ± 1.11
Overall sensory preference		Over.sense.pref.	6.73 ± 1.40	7.29 ± 1.43	7.009 ± 1.44
Yield (average of 48 values)					
Total yield	g $plant^{-1}$	Tyield	2844.07 ± 469.92	2955.05 ± 925.76	2899.56 ± 730.41
Fruit with BER		BER	738.48 ± 266.25	1714.22 ± 353.67	1226.35 ± 581.57
Marketable yield		MYield	2105.58 ± 553.39	1240.82 ± 714.44	1673.20 ± 769.27
No. of Fruit Total yield	No. $plant^{-1}$	No.fr.Tyield	17.69 ± 3.97	45.04 ± 11.63	31.37 ± 16.26
Fruit with BER		No.fr.BER	6.51 ± 2.92	30.70 ± 9.62	18.60 ± 14.09
Marketable yield		No.fr.Myield	11.18 ± 3.47	14.34 ± 7.70	12.76 ± 6.13
Antioxidant activity of pepper fruits (average of 48 values)					
In vitro antioxidant DPPH assay	% RSC	DPPH	64.12 ± 2.49	73.30 ± 2.92	68.71 ± 5.35
ABTS assay		ABTS	72.86 ± 2.47	83.43 ± 4.17	78.22 ± 6.32
Total phenolic content	mg CE 100 g^{-1} FW	TPC	47.10 ± 3.50	60.80 ± 5.60	53.91 ± 8.31

3.2. PCA Analysis for Physicochemical and Sensory Quality Parameters of Peppers Considering Foliar Treatment of Peppers with Calcium (Ca), Salicylic Acid (SA) and Calcium Combined with Salicylic Acid (Ca+SA)

Table 1 shows the mean values of the physicochemical and sensory quality parameters, as well as the yield characteristics and antioxidant activity of the fruit of the two pepper cultivars Aifos and Palermo. Each parameter studied was identified by a code (Table 1), which was used in the graphs (PCA) principal component analysis.

A PCA factor analysis performed for fruit physicochemical and sensory quality parameters depending on foliar treatment of peppers with calcium (Ca), salicylic acid (SA) and calcium combined with salicylic acid (Ca+SA), showed more than 95% variability in the five principal components (Table 2).

Table 2. Eigenvalues and proportion of the total variance in 8 experimental combinations (cultivar: Aifos and Palermo x treatment: control; Ca; SA; Ca+SA), as explained by the first five principal components for the physicochemical and sensory quality parameters of pepper fruit and the correlation coefficients between these parameters and the first five PCs.

Parameter [a]	Principal Components (PCs)				
	PC1	PC2	PC3	PC4	PC5
DW	**−0.661** [b]	−0.499	−0.521	0.036	−0.097
TSS	**−0.655**	**−0.638**	−0.282	0.076	0.135
TS	−0.031	−0.086	**−0.905**	0.165	−0.283
TS/TA	−0.472	−0.176	**−0.816**	0.138	−0.153
TA	**0.935**	0.203	0.175	0.015	−0.123
TSS/TA	**−0.867**	−0.373	−0.191	−0.047	0.171
P	0.202	0.000	0.225	−0.050	**0.916**
NO_3	−0.306	**−0.557**	−0.114	−0.420	**0.617**
Ca	−0.399	−0.072	0.400	−0.241	**0.782**
K	**0.915**	−0.119	0.099	0.303	−0.028
AA	0.177	0.054	0.676	0.195	**−0.671**
Neox.	0.026	**0.574**	0.275	−0.216	**0.720**
Lut.	0.326	**0.657**	0.436	−0.495	0.030
Zeax.	0.294	**0.596**	**0.723**	0.014	0.183
Violax.	0.337	**0.792**	0.384	0.246	−0.118
Caps.	**0.538**	0.453	**0.613**	−0.149	0.157
Crypt.	0.434	0.713	0.469	−0.008	−0.053
α-carot.	0.368	**0.823**	0.082	0.334	−0.197
β-carot.	0.359	**0.800**	−0.072	0.315	0.190
Odor-fre.p.	0.176	0.256	0.111	**0.912**	−0.233
Skin-hard.	**0.789**	0.386	0.025	0.017	0.089
Flesh-fibr.	**0.518**	**0.685**	0.035	−0.46	0.123
Flesh-juic.	0.413	**0.598**	0.086	**−0.529**	0.341
Flesh-firmn.	**0.710**	0.559	0.335	−0.248	0.068
Taste-p.	−0.115	−0.139	−0.042	**0.900**	−0.105
Taste-so.	**0.892**	0.313	0.092	0.194	−0.110
Taste-swe.	**−0.863**	−0.434	−0.234	−0.083	0.041
Taste-bit.	0.055	−0.068	**0.513**	**−0.768**	0.162
Flav.pung.	0.428	0.173	−0.098	**0.876**	−0.008
OQ	**0.779**	0.609	−0.009	−0.055	−0.061
Over.sense.pref.	**−0.855**	−0.306	−0.307	0.128	−0.183

Table 2. *Cont.*

Parameter [a]	Principal Components (PCs)				
	PC1	PC2	PC3	PC4	PC5
Total variance explained-rotation sums of squared loadings					
Total	9.598	7.138	4.704	4.624	3.410
% of Variance	30.961	23.026	15.174	14.916	11.001
Cumulative %	30.961	53.986	69.161	84.077	95.078

a—Parameters described in Table 1; b—Bold values indicate the maximum correlation coefficient of the variable with the obtained components.

The first and third principal components (PC1, PC3) explain more than 46% of the variation and the first and second (PC1, PC2) almost 54% of the variation (Table 2, Figures 1 and 2). The PC1 component is most strongly correlated with fruit quality parameters (Table 2) such as dry matter content (DW), soluble sugars (TSS), potassium, total acidity per citric acid (TA), sugar/acid ratio (TSS/TA) and variables described in the sensory analysis of pepper fruits such as skin hardness (Skin-hard.), flesh firmness (Flesh-firmn.), sour taste (Taste-so.), sweet taste (Taste-swe.), overall quality (OQ) and also overall sensory preference (Over.sens.pref.). Figures 1 and 2 show clear varietal differences in terms of the above characteristics. In the case of the cultivar Aifos, the values for control are to the right of the intersection of the X axis. The factor used in the experiment, such as the addition of Ca, resulted in a higher correlation with traits positively related to PC1. The total factor applied Ca+SA additionally showed a high correlation with the PC3 component and consequently with inter-variables such as total sugars (TS) and sugar/acid ratio (TS/TA) in pepper fruits (Figure 1). The cultivar Palermo is on the opposite side of the intersection of the X-axis with respect to the characteristics correlated with PC1; i.e., this cultivar was strongly positively correlated with variables such as dry matter content of the fruit (DW), soluble components in cell juice (TSS) and their proportion to acid concentration in the fruit (TSS/TA), as well as with the sensory evaluation discriminator sweet taste (Taste-swe.), whereas it was inversely correlated with variables with which the cultivar Aifos was positively correlated (Figure 1). Both cultivars responded similarly to the Ca+SA factor, showing a high positive correlation with total sugars in fruit (TS) and sugar/acid ratio (TS/TA) (Figure 1).

The PC2 component is most strongly correlated with parameters relating to the concentration of pigments such as lutein, violaxanthin, α-carotene and β-carotene in pepper fruits (Table 2). The use of SA in the experiment shifted these objects up the *y*-axis relative to the control, thus increasing the parameters positively correlated with PC2 (Figure 2). The situation was similar in the case of the Ca+SA experimental system. It can be concluded that the application of SA had a favourable impact on the accumulation of pigments in the pepper fruits. In the context of Ca factor experiments, a significant positive effect was observed for the cultivar Palermo, while the Ca factor for the cultivar Aifos showed an inverse correlation with the PC2 component (Figure 2).

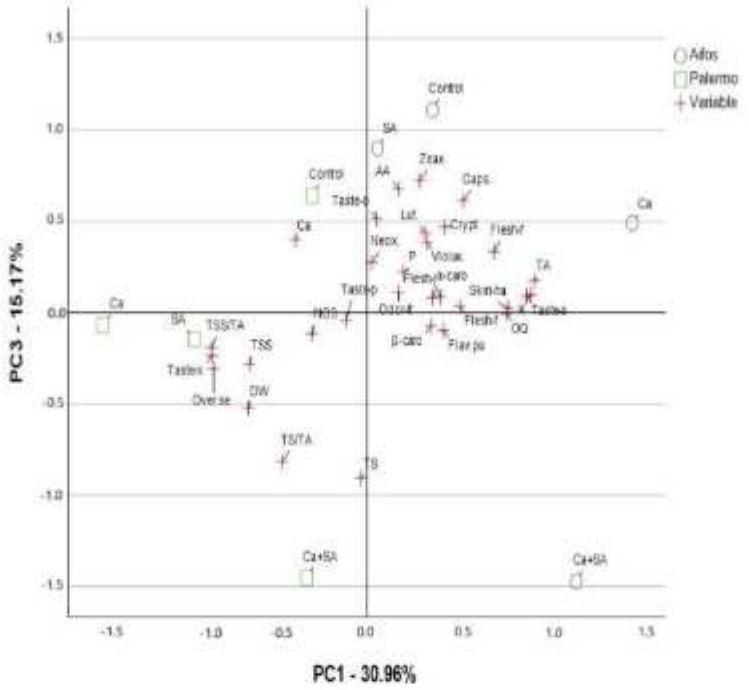

Figure 1. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical and sensory quality parameters in the space of two main components (PC1, PC3) explaining in total more than 46% of the total variability.

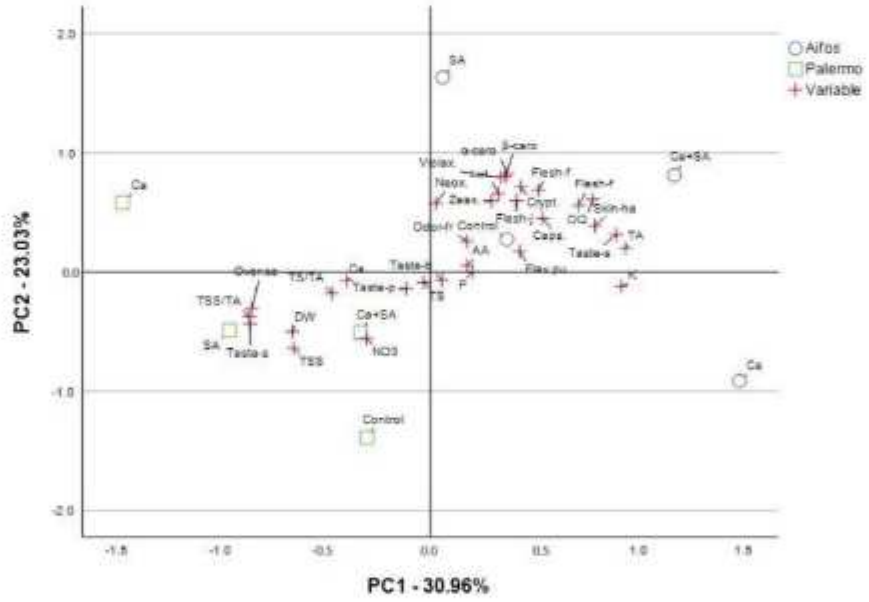

Figure 2. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical and sensory quality parameters in the space of two main components (PC1, PC2) explaining in total close to 54% of the total variability.

3.3. PCA Analysis for Physicochemical Parameters and Antioxidant Activity of Pepper Fruits Considering Foliar Treatment of Plants with Calcium (Ca), Salicylic Acid (SA) and Calcium Combined with Salicylic Acid (Ca+SA)

For PCA analysis of the physicochemical parameters and antioxidant activity of pepper fruits, the four main components explain almost 94% of the variation (Table 3).

Table 3. Eigenvalues and proportion of the total variance in 8 experimental combinations (cultivar: Aifos and Palermo x treatment: control; Ca; SA; Ca+SA), as explained by the first four principal components for the physicochemical parameters and antioxidant properties of pepper fruit and the correlation coefficients between these parameters and the first four PCs.

Parameter [a]	Principal Components (PCs)			
	PC1	PC2	PC3	PC4
DW	**0.640** [b]	−0.537	−0.516	−0.134
TSS	**0.611**	−0.69	−0.282	0.035
TS	0.049	−0.003	**−0.962**	−0.206
TS/TA	0.470	−0.152	**−0.852**	−0.108
TA	**−0.918**	0.314	0.123	−0.066
TSS/TA	**0.842**	−0.479	−0.142	0.108
P	−0.218	−0.018	0.233	**0.909**
NO_3	0.304	**−0.662**	−0.011	0.636
Ca	0.394	−0.183	0.473	**0.753**
K	**−0.949**	−0.003	0.017	−0.097
AA	−0.223	0.122	0.57	**−0.739**
Neox.	0.034	0.487	0.387	**0.762**
Lut.	−0.239	**0.608**	0.547	0.183
Zeax.	−0.265	0.585	**0.741**	0.154
Violax.	−0.279	**0.819**	0.389	−0.168
Caps.	−0.486	0.473	0.632	0.184
Crypt.	−0.406	**0.733**	0.472	0.003
α-carot.	−0.286	**0.886**	0.071	−0.236
β-carot.	−0.266	**0.879**	−0.097	0.180
DPPH	**0.757**	−0.436	−0.461	0.000
ABTS	**0.830**	−0.478	−0.239	0.030
TPC	**0.829**	−0.336	−0.372	0.060
Total variance explained: rotation sums of squared loadings				
Total	6.511	6.073	4.831	3.236
% of Variance	29.597	27.606	21.959	14.708
Cumulative %	29.597	57.203	79.162	93.87

a—Parameters described in Table 1; b—Bold values indicate the maximum correlation coefficient of the variable with the obtained components.

The PC1 component was most strongly correlated with such variables from the chemical analysis as dry matter (DW), potassium (K), cell sap soluble components (TSS), total acidity (TA) and TSS/TA ratio in pepper fruits, and with variables characterising the antioxidant capacity of pepper fruits; i.e., antioxidant DPPH and ABTS assay and total phenolic content (TPC), among others. Figure 3 clearly shows varietal differences in terms of the above characteristics. For the cultivar Aifos, the values for control are to the left of the intersection of the X axis. The factor used in the experiment, for example, spraying the pepper plants with Ca, resulted in a higher correlation with traits negatively associated with PC1. A positive correlation has been identified between the PC2 component and the concentration of carotenoids, including lutein (Lut.), violaxanthin (Violax.), β-cryptoxanthin (Crypt.), α-carotene (α-carot.) and β-carotene (β-carot.), in fruit. The use of the SA factor in the experiment resulted in a shift of these objects relative to the control up the *Y*-axis, thereby leading to an increase in the parameter values that showed a positive correlation with PC2. The situation was similar in the case of the Ca+SA experimental system. The application of the Ca factor demonstrated a significant positive effect on the cultivar Palermo, while the inverse correlation between the Ca factor and the PC2 component was evident in the cultivar Aifos. In conclusion, the addition of SA had a positive effect on the increase of pigments in the pepper fruits tested (Figure 3).

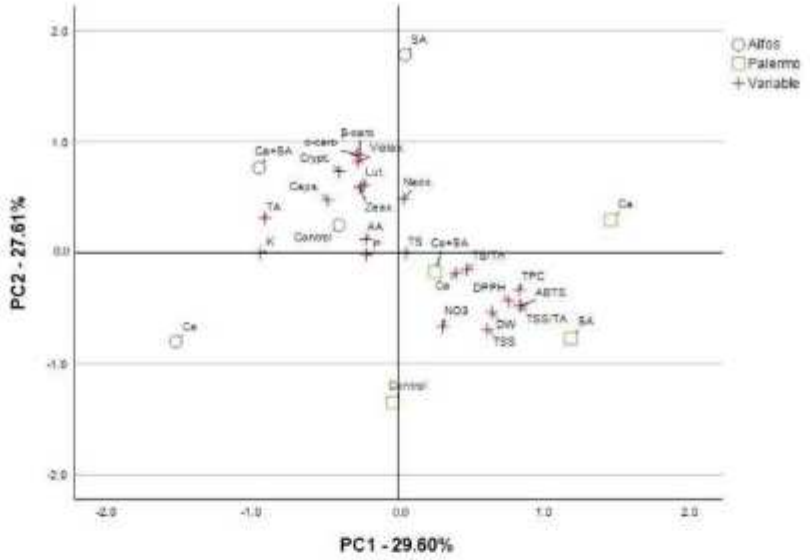

Figure 3. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical parameters and antioxidant properties of pepper fruit in the space of two main components (PC1, PC2) explaining in total more than 57% of the total variability.

Furthermore, the factor Ca+SA demonstrated a strong correlation with the PC3 component, indicating a significant relationship with inter-variables such as the total sugar content of the pepper fruit (TS) and the sugar/acid ratio (TS/TA) (Figure 4). With regard to the traits associated with PC1, the cultivar Palermo lies on the opposite side of the intersection of the X axis. Consequently, this cultivar showed a strong positive correlation with variables such as DW, TSS, TSS/TA, DPPH, ABTS and TPC and an inverse correlation with variables with which the cultivar Aifos was positively correlated. Both varieties responded similarly to the Ca+SA factor showing high positive spiking with the variable TS, TS/TA (Figure 5).

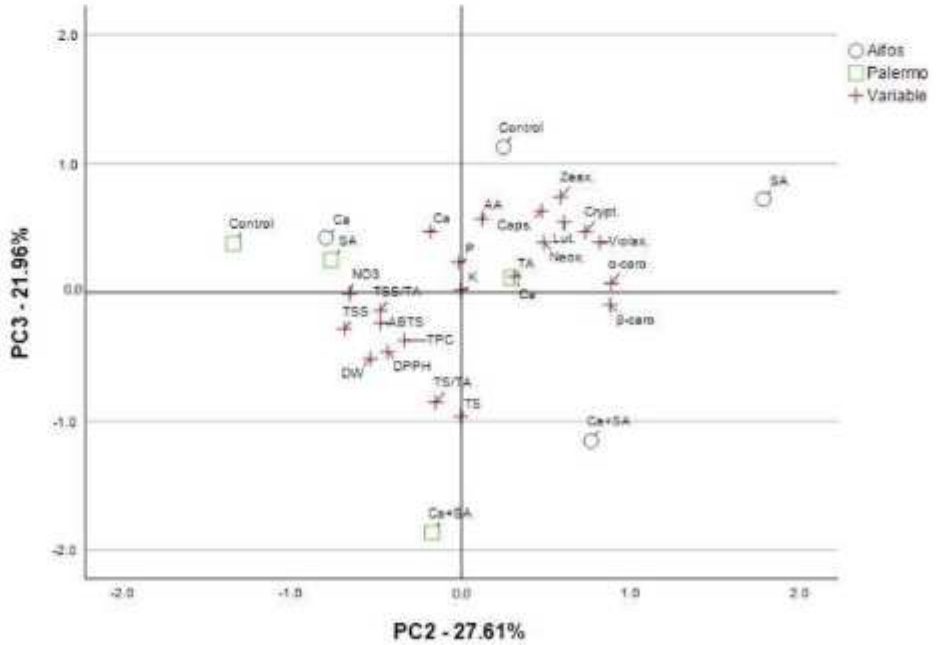

Figure 4. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical parameters and antioxidant properties of pepper fruit in the space of two main components (PC2, PC3) explaining in total more than 49% of the total variability.

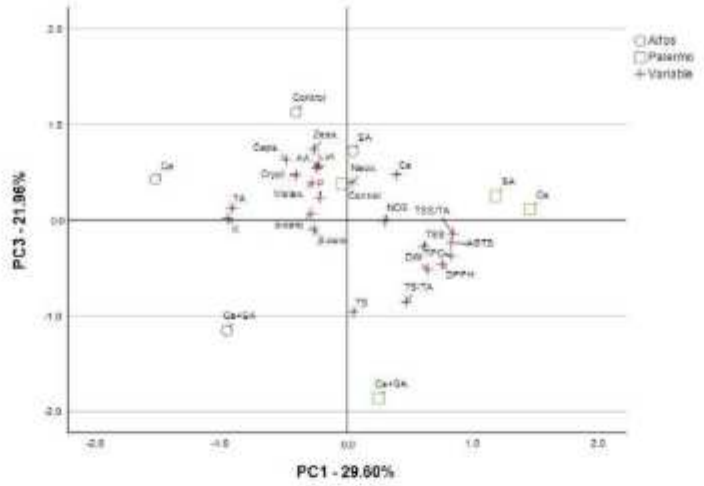

Figure 5. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical parameters and antioxidant properties of pepper fruit in the space of two main components (PC1, PC3) explaining in total more than 51% of the total variability.

3.4. PCA Analysis for Physicochemical Parameters of Pepper Fruit and Yield Parameters Considering Foliar Treatment of Peppers with Calcium (Ca), Salicylic Acid (SA) and Calcium Combined with Salicylic Acid (Ca+SA)

For PCA analysis of physical and chemical parameters and yield of pepper fruit parameters, the four principal components explained almost 93% of the variability (Table 4).

Table 4. Eigenvalues and proportion of the total variance in 8 experimental combinations (cultivar: Aifos and Palermo x treatment: control; Ca; SA; Ca+SA), as explained by the first four principal components for the physicochemical parameters of pepper fruit and yield parameters and the correlation coefficients between these parameters and the first four PCs.

Parameter [a]	Principal Components (PCs)			
	PC1	PC2	PC3	PC4
DW	−0.571	**0.594** [b]	−0.525	0.146
TSS	**−0.719**	0.578	−0.276	0.012
TS	−0.021	0.012	**−0.968**	0.209
TS/TA	−0.199	0.435	**−0.859**	0.119
TA	0.374	**−0.910**	0.127	0.054
TSS/TA	−0.530	**0.820**	−0.147	−0.091
P	−0.041	−0.200	0.254	**−0.839**
NO_3	**−0.685**	0.227	−0.045	−0.649
Ca	−0.216	0.383	0.453	**−0.744**
K	0.049	**−0.896**	0.086	0.190
AA	0.179	−0.197	0.575	**0.711**
Neox.	0.456	0.071	0.376	**−0.767**
Lut.	**0.630**	−0.258	0.480	−0.317
Zeax.	0.609	−0.202	**0.742**	−0.163
Violax.	**0.846**	−0.187	0.405	0.176
Caps.	0.526	−0.476	**0.596**	−0.237
Crypt.	**0.745**	−0.344	0.481	−0.030
α-carot.	**0.916**	−0.205	0.076	0.244
β-carot.	**0.897**	−0.210	−0.110	−0.161
Tyield	−0.186	0.184	−0.057	**0.885**
BER	−0.642	**0.651**	−0.186	0.319

Table 4. *Cont.*

Parameter [a]	Principal Components (PCs)			
	PC1	PC2	PC3	PC4
MYield	0.658	**−0.669**	0.190	−0.072
No.fr.Tyield	**−0.636**	0.594	−0.216	0.395
No.fr.BER	**−0.677**	0.560	−0.165	0.388
No.fr.Myield	−0.207	**0.711**	−0.537	0.355
Total variance explained: rotation sums of squared loadings				
Total	7.806	6.111	4.8	4.522
% of Variance	31.222	24.444	19.198	18.09
Cumulative %	31.222	55.666	74.864	92.954

a—Parameters described in Table 1; b—Bold values indicate the maximum correlation coefficient of the variable with the obtained components.

The components PC1 and PC2 and PC3, in addition to strong correlations with chemical traits of fruit and pigment content, showed correlations with yield and quality traits such as weight of marketable yield of pepper fruit (MYield), number of fruit of total and marketable yield (No. fr. Tyield, and No. fr. Myield) and weight and number of fruit with BER (BER and No. fr. BER). The experimental systems, in which SA was applied, were situated above the control systems and, as a result, demonstrated a positive correlation with PC2-related traits. The introduction of SA may have contributed to the quantity and quality of produce, particularly with regards to the number of healthy fruit, as well as the overall marketable yield. As evidenced in the correlation analysis, this yield was most closely associated with PC1, which is reflected in the graphical representation (Figure 6). The layouts of the SA-added experiments were thus shifted to the right and upwards in the graph relative to the control. At the same time, Figure 7 confirms the clear varietal differentiation in terms of value level and in terms of similar correlations.

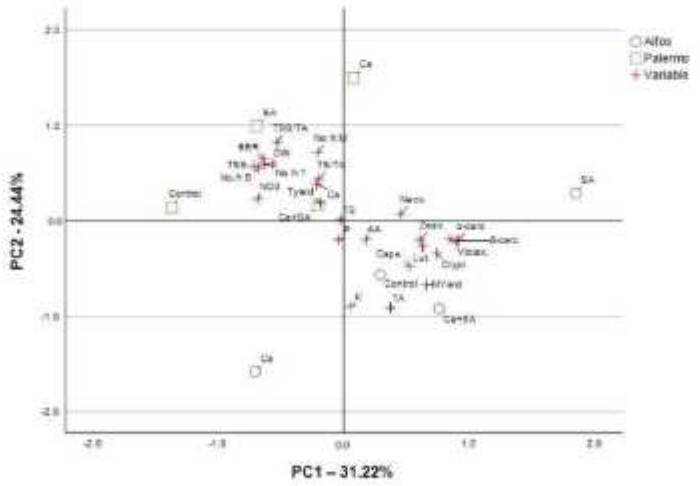

Figure 6. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical parameters of pepper fruit and yield parameters in the space of two main components (PC1, PC2) explaining in total more than 55% of the total variability.

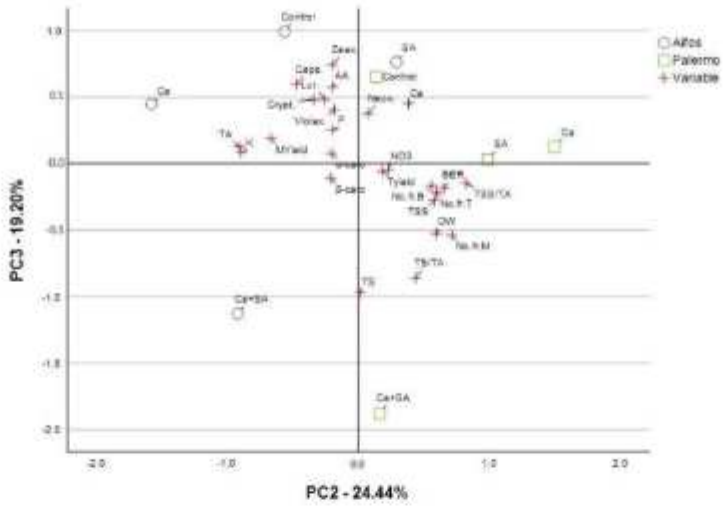

Figure 7. Principal component analysis (PCA) biplot showing the analysed components based on the physicochemical parameters of pepper fruit and yield parameters in the space of two main components (PC2, PC3) explaining in total more than 43% of the total variability.

4. Discussion

4.1. Quality Characteristics of Pepper Fruits Grown Hydroponically

Peppers grown hydroponically in mineral wool substrate produce fruit with high biological value. The fruits of both cultivars tested were characterised by high concentrations of vitamins, carotenoids, mineral salts, sugars and organic acids. Peppers harvested at physiological maturity from plants grown in mineral wool contained on average more than 1226 μg 100 g^{-1} FW of capsanthin. According to Hassan et al. [68], the level of capsanthin is significantly increased during the ripening of red peppers. It is the principal pigment that accounts for almost 80% of the total carotenoids, ranging from 230 to 848 μg 100 g^{-1} of fresh weight in capsicum. The main carotenoids of capsicum include capsanthin, capsorubin, β-carotene, zeaxanthin, violaxanthin, lutein and antheraxanthin, the concentration of which varies according to the ripeness of the fruit [69,70]. Carotenoids are a family of natural pigments covering a spectrum from yellow to red, characterised by strong antioxidant properties. Among these compounds, capsanthin stands out as a valuable carotenoid pigment, not only for its role in determining the degree of colour and fruit maturity of red pepper varieties but also for its high antioxidant properties and potential health-promoting effects [71–73]. Among the labelled carotenoids in ripe Aifos and Palermo fruit, capsanthin had the highest proportion. Among the labelled carotenoids in ripe Aifos and Palermo fruit, capsanthin had the highest contribution. The lutein content of the fruits tested averaged more than 209 μg 100 g^{-1} of FW, β-cryptoxanthin more than 88 μg 100 g^{-1} of FW and α and β carotene more than 168 and 735 μg 100 g^{-1} of FW, respectively. Vitamin C levels averaged more than 47 mg 100 g^{-1} of FW. Vitamin C is thermolabile and its degradation in the product depends on water activity, light access, oxygen content and the presence of heavy metals (e.g., Cu, Fe), the type of raw material, its maturity, and pretreatment [74]. These compounds are responsible for the antioxidant activity observed in peppers [75]. At the same time, the methanolic extracts of Aifos and Palermo fruits tested showed high antioxidant potential. A study by Guil-Guerrero et al. [4] showed that for 10 Spanish pepper varieties, the main carotenoids were lutein and its isomer, accounting for more than 60% of all carotenoids. The content of lycopene as well as the other components in pepper fruits is influenced by various factors. For instance, the analysis of pepper fruits harvested in September revealed higher concentrations of lycopene and β-carotene in comparison to those harvested in July or August [76]. Certainly, the high temperature

occurring during the study period affected the concentration of the different components and the quality of the pepper yield of both varieties. According to Oh and Koh [77], the temperature range of 20–25 °C is conducive to vegetative growth and fruit development in sweet peppers, and the total sugar content of ripe fruit increases significantly at 20–25 °C, while the capsaicinoid content of ripe fruit increases with increasing temperature in the range of 15–30 °C. These results indicate that the temperature range of 20–25 °C is beneficial for vegetative growth, fruit development and fruit quality of peppers [78]. The physicochemical and biological properties of pepper fruits are also determined by their maturity stage at harvest. Pepper fruit ripening is the characteristic change in fruit colour from green to red, yellow, orange or purple depending on the variety. This process involves, among other things, the breakdown of chlorophyll and the synthesis of new carotenoids and anthocyanins, the emission of organic volatiles, the synthesis of new proteins and the cleavage of existing ones and the softening of cell walls [79–81]. Significant differences between the transcriptomes of unripe and ripe pepper fruits, involving thousands of genes, have also been reported [82]. From a redox point of view, fruit ripening has also been found to affect the metabolism of reactive oxygen species (ROS), leading to major changes in the total soluble reducing equivalents and antioxidant capacity of the fruit. The profile of major non-enzymatic antioxidants, including ascorbate, glutathione, carotenoids and polyphenols, has been monitored throughout the ripening process of pepper fruit [83], but less is known about how enzymatic antioxidants evolve during this physiological process. In their study, the in vitro DPPH antioxidant assay and in vitro ABTS tests were at 68.71% RSC and 78.22% RSC, respectively, while the total phenolic content was 53.91 mg CE 100 g^{-1} of FW. A study by Papathanasiou et al. [84] proved that the sweet pepper cultivars Dolma F1, Yahoo F1 and Florinis NS 700 harvested at full maturity (80 days after flowering) are a rich source of antioxidant compounds, including polyphenols and ascorbic acid, and have been found to have the highest antioxidant activity. The tested cultivars Aifos and Palermo differed in terms of the content of individual bioactive components, while on average, fully coloured fruit yielded ascorbic acid of about 48 mg 100 g^{-1} of FW and total phenolic compounds of about 54 mg CE 100 g^{-1} of FW. In contrast, antioxidant activity assessed by the DPPH method averaged about 68% RSC and ABTS method 78% RSC. In a study by Hamed et al. [85], the ranges of total phenolic compounds and flavonoids in peppers were in green fruit 2096 to 7689 $\mu g/g^{-1}$ of FW and red/yellow ripe fruit 204 to 962 $\mu g/g^{-1}$ of FW. Ascorbic acid levels in peppers ranged from 223 to 1025 mg/100 g of dry weight (DW). In contrast, both raw and roasted peppers showed strong antioxidant activity by DPPH, with values ranging from 61% to 87%, and by ABTS, with values ranging from 73 µmol TE/g to 159 µmol TE/g of a freeze-dried sample. As reported by Chilczuk et al. [86], the highest antioxidant activity was observed in sweet pepper fruit extracts prepared with 40% methanol. The highest total content of phenolic compounds was obtained in an analogous extract derived from hot pepper fruits, which also demonstrated the most potent cytotoxic activity against the PC-3 cancer line. Medina-Juáre et al. [87] report that the highest percentage of oxidation inhibition for the DPPH radical is associated with the highest levels of gallic acid, chlorogenic acid, epicatechin, rutin, luteolin, resveratrol ($r \geq 0.85$) and ascorbic acid in pepper fruits. Of the varieties tested, Caribe and Bell had the highest antioxidant capacity, which correlated with the highest levels of phenols and total flavonoids. Positive correlations were shown between individual phenols and antioxidant activity, confirming the results obtained in the experiment. Additionally, the researchers demonstrated a positive correlation between individual phenols and antioxidant activity, with the highest correlation observed for catechin, epicatechin, rutin and resveratrol.

The fruit of both pepper varieties examined in the experiment also scored highly in terms of sensory quality and consumer desirability. The observed differences in the

heights of individual fruit quality parameters were dependent on the variety of pepper. PCA analysis showed significant differences between the yield quality characteristics of the Aifos and Palermo cultivars. Fruits of the Palermo cultivar contain significantly more, inter alia, dry matter (DW), soluble sugars (TSS) and potassium and show a higher total acidity (TA) and a higher sugar/acid ratio (TSS/TA). These characteristics influence the higher evaluation of the fruits of this cultivar in terms of sensory quality, particularly in terms of sweet taste and overall sensory preference. Other studies have also shown a significant correlation between the content of chemical attributes of fruit quality and individual determinants of sensory evaluation [88,89].

4.2. Increase in Yield, Quality, and Antioxidant Potential of Pepper Fruit as a Result of CA and SA Application

The Ca and SA spray treatments applied to the crop, and the combination of these compounds in a single spray of Ca combined with SA (Ca+SA), resulted in a beneficial impact on the quality of the pepper crop. This included an increase in the proportion of marketable yield, while the non-marketable crop had a BER symptom prevalence of 99%. Peppers grown under covers, like other vegetables, are exposed to high temperature stress, which occurs during periods of high solar radiation. Depending on the susceptibility of the pepper cultivar to the physiological disorder caused, among other things, by inhibition of transpiration and Ca transport to the fruit tip cells, the proportion of fruit affected by BER in the pepper yield may vary [40,51].

Spraying the plants with Ca increased the total acidity in the pepper fruit. It also improved fruit sensory quality, firmness and increased the antioxidant potential of pepper fruit. Similar results were observed in tomato, where calcium spraying had a beneficial impact on maintaining high fruit firmness, reducing fruit weight loss and increasing soluble solids and total acidity. These treatments also showed positive correlations with total sugars and overall quality during tomato fruit storage, indicating a consistently beneficial effect of calcium on fruit quality parameters [90]. Both pepper cultivars responded similarly to foliar treatment with simultaneous calcium and salicylic acid, i.e., a Ca+SA combination, showing high positive correlations with total sugars in fruit (TS) and total sugars/acids ratio (TS/TA).

The application of SA in the experiment increased compared to the control the concentration of pigments such as lutein, violaxanthin, β-cryptoxanthin, α-carotene and β-carotene in the pepper fruit. A comparable context can be observed with the simultaneous application of calcium and salicylic acid (Ca+SA) to peppers. It can be concluded that the application of SA, either as a standalone treatment or in combination with Ca, has a favourable impact on the pigmentation of pepper fruits. In the context of treating peppers with Ca alone, the cultivar Palermo showed a significant positive effect on the fruit's bioactive components, while the opposite was observed for these pigments in the fruit of the cultivar Aifos following the application of Ca. The factor used in the experiment, for example spraying the pepper plants with Ca, resulted in a higher correlation with total acidity and K content in Aifos fruit. Among others, Khalid et al. [91] found a positive effect of foliar treatment of SA peppers in mitigating the negative effects of salinity stress in peppers. The Ge et al. [92] study revealed that combined TSP (phosphate) + SA treatment of peppers mitigated chilling injury by increasing water retention in the pepper fruit.

Furthermore, the study confirmed that the antioxidant activity of the fruit differed between the two varieties, with the Palermo variety proving to have a higher antioxidant capacity. This was confirmed by three methods, DPPH, ABTS and total polyphenol content of TPC fruit, expressed in mg CE 100 g^{-1} of fresh weight of pepper fruit. According to Dobón-Suárez et al. [93], foliar application of 0.5 mM SA to pepper plants has a significant effect on increasing fruit quality parameters and antioxidant capacity at harvest and after

21 days of storage at 7 °C. Yang et al. [94] proved that exogenous 3 mmol L-1 SA delayed the decrease in firmness, colour, TA and TSS in winter jujube fruits (*Ziziphus jujuba* Mill cv. Dongzao) during their shelf life. At the same time, SA increased the activity of antioxidant enzymes (superoxide dismutase, peroxidase, catalase, ascorbate peroxidase) and the content of ascorbic acid, total phenols, total flavonoids and glutathione in the fruit, which improved the antioxidant properties of the fruit.

The analysis of the results obtained confirmed that the use of SA in peppers can lead to an increase in the number of healthy fruits and the marketable yield. The arrangements of experiments involving the addition of SA confirm the clear varietal differentiation in terms of the level of values and confirm similar correlations. Foliar calcium feeding of sweet pepper plants significantly increased fruit yield in the field crop and resulted in a reduction in the number of fruits with BER symptoms compared to the control. The application of calcium in the form of $Ca(NO_3)_2$ had a positive effect on vitamin C and carotenoid accumulation compared to other calcium fertilisers [95].

Among others, Khazaei and Estaji [96] report that salicylic acid provides improved drought stress tolerance in peppers through its effects on vegetative, biochemical and physiological traits. The foliar application of SA, inducing an antioxidant system in pepper seedlings, resulted in a reduction of the harmful effects of drought conditions and an improvement in plant growth [96]. In contrast, Khalid et al. [97] found that application of SA reduced Hg toxicity in sweet pepper seedlings. SA reduced Hg accumulation in sweet pepper roots and leaves and impeded Hg translocation from roots to fruit. The researchers report the need for continued studies to identify SA signalling pathways, with the aim of providing further insight into these mechanisms in pepper plants. In a study conducted by Dobón-Suárez et al. [98], the application of salicylic acid at a concentration of 0.5 mM to pepper plants prior to the harvesting of green fruit resulted in increased yields (kg per plant, number of fruits and average fruit weight) and increased quality parameters (firmness, greenness and total acidity). Moreover, the content of phenolic compounds and the total antioxidant content both demonstrated a notable increase. The results obtained by Dobón-Suárez et al. [98] suggest that pre-harvest application of SA on pepper plants can be an effective method for increasing yield and improving fruit quality parameters at harvest, while also maintaining post-harvest quality.

5. Conclusions

The hydroponic cultivation of peppers using mineral wool and Ca and SA as nutrients results in fruit with high biological value and excellent sensory qualities. Fruits of the Aifos and Palermo varieties show high concentrations of nutrients and antioxidants, with Palermo having a higher dry matter content, soluble sugars, potassium and a higher sensory score.

Further research should concentrate on optimising hydroponic growing conditions and establishing the mechanisms by which different factors affect yield quality and fruit antioxidant potential. It is also important to extend the research by clarifying the effects of SA application on the flowering biology of pepper plants, the uptake and transport of individual components to the fruit and as well as their health-promoting effects.

The results indicate that foliar treatment of peppers with Ca and SA is even more beneficial in the Ca+SA combination for increasing fruit quality and antioxidant capacity. Therefore, prophylactic spraying of peppers with the Ca+SA mixture can be recommended in hydroponic production. However, the determination of the most effective concentrations of both components requires further research.

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References

1. Carvalho Lemos, V.; Reimer, J.J.; Wormit, A. Color for life: Biosynthesis and distribution of phenolic compounds in pepper (*Capsicum annuum*). *Agriculture* **2019**, *9*, 81. [CrossRef]
2. Tang, B.; Li, L.; Hu, Z.; Chen, Y.; Tan, T.; Jia, Y.; Xie, Q.; Chen, G. Anthocyanin accumulation and transcriptional regulation of anthocyanin biosynthesis in purple pepper. *J. Agric. Food Chem.* **2020**, *68*, 12152–12163. [CrossRef] [PubMed]
3. Al-Snafi, A.E. The pharmacological importance of Capsicum species (*Capsicum annuum* and *Capscicum frutescens*) grown in Iraq. *Pharm. Biol.* **2015**, *5*, 124–142.
4. Guil-Guerrero, J.L.; Martinez-Guirado, C.; Rebolloso-Fuentes, M.M.; Carrique-Perez, A. Nutrient composition and antioxidant activity of 10 pepper (*Capsicum annuun*) varieties. *Eur. Food Res. Technol.* **2006**, *224*, 1–9. [CrossRef]
5. Paredes-Andrade, N.J.; Monteros-Altamirano, A.; Bastidas, C.G.T.; Sørensen, M. Morphological, sensorial and chemical characterization of chilli peppers (*Capsicum* spp.) from the CATIE Genebank. *Agronomy* **2020**, *10*, 1732. [CrossRef]
6. Biratu, W.; Belew, D.; Ettissa, E. Evaluation of hot pepper (*Capsicum annuum* L.) cultivars for growth and dry pod yields against different blended fertilizer and nitrogen rates in raya Azebo, Southern Tigray. *Int. J. Res. Agron.* **2021**, *4*, 15–22. [CrossRef]
7. Srivastava, N.; Sharma, V.; Saraf, K.; Dobriyal, A.K.; Kamal, B.; Jadon, V.S. In vitro antimicrobial activity of aerial parts extracts of *Aconitum heterophyllum* Wall. ex Royle. *Indian J. Nat. Prod. Resour.* **2011**, *2*, 504–507.
8. Ademoyegun, O.T.; Fariyike, T.A.; Aminu-Taiwo, R.B. Effects of poultry droppings on the biologically active compounds in *Capsicum annum* L. (var. Nsukka yellow). *Agric. Biol. J. N. Am.* **2011**, *2*, 665–672. [CrossRef]
9. Yamaguchi, T.; Mizobuchi, T.; Kajikawa, R.; Kawashima, H.; Miyabe, F.; Terao, J.; Takamura, H.; Matoba, T. Radical-scavenging activity of vegetables and the effect of cooking on their activity. *Food Sci. Technol. Res.* **2001**, *7*, 250–257. [CrossRef]
10. Simonne, A.H.; Simonne, E.H.; Eitenmiller, R.R.; Mills, H.A.; Green, N.R. Ascorbic acid and provitamine A contents in unusally colored bell peppers (*Capsicum annum* L.). *J. Food Compos. Anal.* **1997**, *10*, 299–311. [CrossRef]
11. Nurzyńska-Wierdak, R. *Capsicum annuum* L. (bell pepper). A plant with unique bioactive compounds, nutraceutical and phytotherapeutic potential. A review. *Ann. Hortic.* **2022**, *31*, 4. [CrossRef]
12. Loizzo, M.R.; Bonesi, M.; Serio, A.; Chaves-López, C.; Falco, T.; Paparella, A.P.; Menichini, F.; Tundis, R. Application of nine air-dried Capsicum annum cultivars as food preservative: Micro-nutrient content, antioxidant activity, and foodborne pathogens inhibitory effects. *Int. J. Food Prop.* **2017**, *20*, 899–910. [CrossRef]
13. Florkowska, K.; Duchnik, W.; Nowak, A.; Klimowicz, A. Właściwości antyoksydacyjne papryki ostrej odmiany Hungarian yellow. *Pomeranian J. Life. Sci.* **2018**, *64*, 126–131. [CrossRef]
14. Tzika, D.E.; Papadimitriou, V.; Sotiroudis, G.T.; Xenakis, A. Antioxidant properties of fruits and vegetables shots and juices: An electron paramagnetic study. *Food Biophys.* **2008**, *1*, 48–53. [CrossRef]
15. Żurawik, A.; Jadczak, D.; Panayotov, N.; Żurawik, P. Antioxidant properties of pepper (*Capsicum annuum* L.) depending on its cultivar and fruit colouration. *Plant Soil Environ.* **2021**, *67*, 653–659. [CrossRef]
16. Ghazemnezhad, M.; Sherafati, M.; Payvast, G.A. Variation in phenolic compounds, ascorbic acid and antioxidant activity of five coloured bell pepper (*Capsicum annum*) fruits at two different harvest times. *J. Funct. Foods* **2011**, *1*, 44–49. [CrossRef]
17. Kaewseejan, N.; Sutthikhum, V.; Siriamornpun, S. Potential of *Gynura procumbens* leaves as source of flavonoid-enriched fractions with enhanced antioxidant capacity. *J. Funct. Foods* **2015**, *12*, 120–128. [CrossRef]
18. Taher, M.A.; Tadros, L.K.; Dawood, D.H. Phytochemical constituents, antioxidant activity and safety evaluation of Kei-apple fruit (*Dovyalis caffra*). *Food Chem.* **2018**, *265*, 144–151. [CrossRef]
19. Kulawik-Pióro, A. *Marchew zwyczajna* (*Daucus carota* L.) jako źródło substancji aktywnych i jej potencjał farmakologiczny i kosmetologiczny. *Farm. Pol.* **2022**, *78*, 536–548. [CrossRef]
20. Wolfe, K.L.; Liu, R.H. Apple peels as value-added food ingredient. *J. Agric. Food Chem.* **2003**, *51*, 1676–1683. [CrossRef]

21. Maria do Socorro Rufino, M.; Alves, E.R.; de Brito, S.E.; Perez-Jimenez, J.; Saura-Calixto, F.; Mancini-Filho, J. Bioactive compounds and antioxidant capacities of 18 non-traditional tropical fruits from Brazil. *Food Chem.* **2010**, *121*, 996–1002. [CrossRef]
22. Nurzyńska-Wierdak, R.; Papliński, R. Substancje bioaktywne i właściwości lecznicze fasoli zwykłej (*Phaseolus vulgaris* L.). *Ann. Hortic.* **2023**, *32*, 33–51. [CrossRef]
23. Hayouni, E.A.; Abedrabba, M.; Bouix, M.; Hamdi, M. The effects of solvents and extraction method on the phenolic contents and biological activities in vitro of Tunisian *Quercus coccifera* L. and *Juniperus phoenicea* L. fruit extracts. *Food Chem.* **2007**, *105*, 1126–1134. [CrossRef]
24. Alam, M.A.; Saleh, M.; Mohsin, G.M.; Nadirah, T.A.; Aslani, F.; Rahman, M.M.; Roy, S.K.; Juraimi, A.S.; Alam, M.Z. Evaluation of phenolics, capsaicinoids, antioxidant properties, and major macro-micro minerals of some hot and sweet peppers and ginger landraces of Malaysia. *J. Food Process. Preserv.* **2020**, *44*. [CrossRef]
25. Lee, J.G.; Chae, Y.; Shin, Y.; Kim, Y.J. Chemical composition and antioxidant capacity of black pepper pericarp. *Appl. Biol. Chem.* **2020**, *63*, 35. [CrossRef]
26. Salamatullah, A.M.; Hayat, K.; Husain, F.M.; Ahmed, M.A.; Arzoo, S.; Althbiti, M.M.; Alzahrani, A.; Al-Zaied, B.A.M.; Alyahya, H.K.; Albader, N.; et al. Effects of different solvent extractions on total polyphenol content, HPLC analysis, antioxidant capacity, and antimicrobial properties of peppers (red, yellow, and green (*Capsicum annum* L.). *Evid.-Based Complement. Altern. Med.* **2022**, *2022*, 7372101. [CrossRef]
27. Ma, X.; Yu, H. Global burden of cancer. *Yale J. Biol. Med.* **2006**, *79*, 85–94.
28. Matysiak, B.; Kaniszewski, S.; Mieszczakowska-Frąc, M. Growth and quality of leaf and romaine lettuce grown on a vertical farm in an aquaponics system: Results of farm research. *Agriculture* **2023**, *13*, 897. [CrossRef]
29. Gruda, N.S. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy* **2019**, *9*, 298. [CrossRef]
30. Tzortzakis, N.; Massa, D.; Vandecasteele, B.J.A. The tripartite of soilless systems, growing media, and plants through an intensive crop production scheme. *Agronomy* **2022**, *12*, 1896. [CrossRef]
31. Vandecasteele, B.; Van Loo, K.; Ommeslag, S.; Vierendeels, S.; Rooseleer, M.; Vandaele, E. Sustainable growing media blends with woody green composts: Optimizing the N release with organic fertilizers and interaction with microbial biomass. *Agronomy* **2022**, *12*, 422. [CrossRef]
32. Gruda, N.S. Advances in soilless culture and growing media in today's horticulture—An editorial. *Agronomy* **2022**, *12*, 2773. [CrossRef]
33. Maher, M.; Prasad, M.; Raviv, M. Organic soilless media components. In *Soilless Culture*; Academic Press: Cambridge, MA, USA, 2008; pp. 459–504.
34. Kraska, T.; Kleinschmidt, B.; Weinand, J.; Pude, R. Cascading use of Miscanthus as growing substrate in soilless cultivation of vegetables (*Tomatoes, Cucumbers*) and subsequent direct combustion. *Sci. Hortic.* **2018**, 235, 205–213. [CrossRef]
35. Kennard, N.; Stirling, R.; Prashar, A.; Lopez-Capel, E. Evaluation of Recycled Materials as Hydroponic Growing Media. *Agronomy* **2020**, *10*, 1092. [CrossRef]
36. Saha, S.; Monroe, A.; Day, M.R. Growth, yield, plant quality and nutrition of basil (*Ocimum basilicum* L.) under soilless agricultural systems. *Ann. Agric. Sci.* **2016**, *61*, 181–186. [CrossRef]
37. Ferby, V.; Kopta, T.; Komorowska, M.; Fidurski, M. Evaluation of alternative substrates for hydroponics based on biological parameters of leaf lettuce (*Lactuca sativa* L.) and its stress response. *Folia Hortic.* **2023**, *35*, 77–90. [CrossRef]
38. Hepler, P.K. Calcium: A central regulator of plant growth and development. *Plant Cell* **2005**, *17*, 2142–2155. [CrossRef]
39. Srivastava, A.K.; Shankar, A.; Nalini Chandran, A.K.; Sharma, M.; Jung, K.H.; Suprasanna, P.; Pandey, G.K. Emerging concepts of potassium homeostasis in plants. *J. Exp. Bot.* **2020**, *71*, 608–619. [CrossRef]
40. Ahn, J.; Park, M.; Kim, J.; Huq, E.; Kim, J.; Kim, D.-H. Physiological and transcriptomic analyses of healthy and blossom-end-rot (BER)-defected fruit of chili pepper (*Capsicum annuum* L.). *Hortic. Environ. Biotechnol.* **2024**, *65*, 971–980. [CrossRef]
41. Manganaris, G.A.; Vasilakakis, M.; Diamantidis, G.; Mignani, I. Effect of calcium additives on physicochemical aspects of cell wall pectin and sensory attributes of canned peach (*Prunus persica* (L.) Batsch cv. 'Andross'). *J. Sci. Food Agric.* **2005**, *85*, 1773–1778. [CrossRef]
42. Saito, S.; Uozumi, N. Calcium-regulated phosphorylation systems controlling uptake and balance of plant nutrients. *Front. Plant Sci.* **2020**, *11*, 44. [CrossRef] [PubMed]
43. Imenšek, N.; Sem, V.; Kolar, M.; Ivančič, A.; Kristl, J. The distribution of minerals in crucial plant parts of various elderberry (*Sambucus* spp.) interspecific hybrids. *Plants* **2021**, *10*, 653. [CrossRef] [PubMed]
44. Weng, X.; Li, H.; Ren, C.; Zhou, Y.; Zhu, W.; Zhang, S.; Liu, L. Calcium regulates growth and nutrient absorption in poplar seedlings. *Front. Plant Sci.* **2022**, *13*, 887098. [CrossRef] [PubMed]
45. Xiao, Y.; Ma, C.; Li, M.; Zhangzhong, L.; Song, P.; Li, Y. Interaction and adaptation of phosphorus fertilizer and calcium ion in drip irrigation systems: The perspective of emitter clogging. *Agric. Water Manag.* **2023**, *282*, 108269. [CrossRef]
46. Kulbat, K. The role of phenolic compounds in plant resistance. *Biotechnol. Food Sci.* **2016**, *80*, 97–108. [CrossRef]

47. Liu, J.; Liu, H.; Zhao, Z.; Wang, J.; Guo, D.; Liu, Y. Regulation of Actg1 and Gsta2 is possible mechanism by which capsaicin alleviates apoptosis in cell model of 6-OHDA-induced Parkinson's disease. *Biosci. Rep.* **2020**, *40*, BSR20191796. [CrossRef]
48. Wang, L.; Li, S. Role of salicylic acid in postharvest physiology. *Fresh Prod.* **2008**, *2*, 1–5.
49. Vlot, A.C.; Dempsey, D.M.A.; Klessig, D.F. Salicylic acid, a multifaceted hormone to combat disease. *Annu. Rev. Phytopathol.* **2009**, *47*, 177–206. [CrossRef]
50. Jayakannan, M.; Bose, J.; Babourina, O.; Rengel, Z.; Shabala, S. Salicylic acid in plant salinity stress signalling and tolerance. *Plant Growth Regul.* **2015**, *76*, 25–40. [CrossRef]
51. Sobczak, A.; Pióro-Jabrucka, E.; Gajc-Wolska, J.; Kowalczyk, K. Effect of salicylic acid and calcium on growth, yield, and fruit quality of pepper (*Capsicum annuum* L.) grown hydroponically. *Agronomy* **2024**, *14*, 329. [CrossRef]
52. Sobczak, A.; Kućko, A.; Pióro-Jabrucka, E.; Gajc-Wolska, J.; Kowalczyk, K. Effect of salicylic acid on the growth and development of sweet pepper (*Capsicum annum* L.) under standard and high EC nutrient solution in aeroponic cultivation. *Agronomy* **2023**, *13*, 779. [CrossRef]
53. Amin, G.H.; Abdel-Kader, D.Z.; Baraka, M.; Hassan, H.B. Role of salicylic acid in the machinery of acquired tolerance in two *Capsicum* species infected with powdery mildew disease. *Aust. J. Basic Appl. Sci.* **2009**, *3*, 2078–2096.
54. Jiankang, C.; Kaifang, Z.; Weibo, J. Enhancement of post-harvest disease resistance in *Ya Li* pear (*Pyrus bretschneideri*) fruit by salicylic acid sprays on the trees during fruit growth. *Eur. J. Plant Pathol.* **2006**, *114*, 363–370.
55. Yao, H.J.; Shiping, T. Effects of pre-and post-harvest application of salicylic acid or methyl jasmonate on inducing disease resistance of cherry fruit in storage. *Postharvest Biol. Technol.* **2005**, *35*, 253–262. [CrossRef]
56. Xu, X.; Shiping, T. Salicylic acid alleviated pathogen-induced oxidative stress in harvested sweet cherry fruit. *Postharvest Biol. Technol.* **2008**, *49*, 379–385. [CrossRef]
57. Vázquez-Hernández, M.C.; Parola-Contreras, I.; Montoya-Gómez, L.M.; Torres-Pacheco, I.; Schwarz, D.; Guevara-González, R.G. Eustressors: Chemical and physical stress factors used to enhance vegetables production. *Sci. Hortic.* **2019**, *250*, 223–229. [CrossRef]
58. Yasmeen, T.; Ahmad, A.; Arif, M.S.; Mubin, M.; Rehman, K.; Shahzad, S.M.; Wijaya, L. Biofilm forming rhizobacteria enhance growth and salt tolerance in sunflower plants by stimulating antioxidant enzymes activity. *Plant Physiol. Biochem.* **2020**, *156*, 242–256. [CrossRef]
59. Odriozola-Serrano, I.; Hernández-Jover, T.; Martín-Belloso, O. Comparative evaluation of UV-HPLC methods and reducing agents to determine vitamin C in fruits. *Food Chem.* **2007**, *105*, 1151–1158. [CrossRef]
60. Grobelna, A.; Kalisz, S.; Kieliszek, M. The effect of the addition of blue honeysuckle berry juice to apple juice on the selected quality characteristics, anthocyanin stability, and antioxidant properties. *Biomolecules* **2019**, *9*, 744. [CrossRef]
61. *Polish Standard PN-90/A-75101/0*; Determine the Content of Total Sugars as Well as Sacharose and Monosaccharides Using the Luff-Schoorl Method. Polish Committee for Standardization: Warsaw, Poland, 1990.
62. *Polish Standard PN-90/A-75101/04*; Fruit and Vegetable Preserves. Preparation of Samples and Methods for Physicochemical Analysis. Determination of Total Acidity. Polish Committee for Standardization: Warsaw, Poland, 1990.
63. Yen, G.C.; Chen, H.Y. Antioxidant activity of various tea extracts in relation to their antimutagenicity. *J. Agric. Food Chem.* **1995**, *43*, 27–32. [CrossRef]
64. Grajek, W. *Przeciwutleniacze w Żywności. Aspekty Zdrowotne, Technologiczne, Molekularne i Analityczne*; WNT: Warszawa, Poland, 2007.
65. Re, R.; Pellegrini, N.; Proteggente, A.; Pannala, A.; Yang, M.; Rice-Evans, C. Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free. Radic. Biol. Med.* **1999**, *26*, 1231–1237. [CrossRef] [PubMed]
66. Koss-Mikołajczyk, I.; Baranowska, M.; Namieśnik, J.; Bartoszek, A. Determination of antioxidant activity of phytochemicals in cellular models by fluorescence/luminescence methods. *Adv. Hyg. Exp. Med.* **2017**, *71*, 602–617. [CrossRef]
67. Singleton, V.L.; Rossi, J.A. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *Am. J. Enol. Vitic.* **1965**, *16*, 144–158. [CrossRef]
68. Hassan, N.M.; Yusof, N.A.; Yahaya, A.F.; Mohd Rozali, N.N.; Othman, R. Carotenoids of *Capsicum* fruits: Pigment profile and health-promoting functional attributes. *Antioxidants* **2019**, *8*, 469. [CrossRef]
69. Deli, J.; Molnár, P.; Matus, Z.; Tóth, G. Carotenoid composition in the fruits of red paprika (*Capsicum annuum* var. *Lycopersiciforme rubrum*) during ripening; biosynthesis of carotenoids in red paprika. *J. Agric. Food Chem.* **2001**, *49*, 1517–1523. [CrossRef]
70. Rodriguez-Uribe, L.; Guzman, I.; Rajapakse, W.; Richins, R.D.; O'Connell, M.A. Carotenoid accumulation in orange-pigmented *Capsicum annuum* fruit, regulated at multiple levels. *J. Exp. Bot.* **2012**, *63*, 517–526. [CrossRef]
71. Cervantes-Paz, B.; Yahia, E.M.; Ornelas-Paz, J.J.; Victoria-Campos, C.I.; Ibarra-Junquera, V.; Pérez-Martínez, J.D.; Escalante-Minakata, P. Antioxidant activity and content of chlorophylls and carotenoids in raw and heat-processed Jalapeño peppers at intermediate stages of ripening. *Food Chem.* **2014**, *146*, 188–196. [CrossRef]
72. Arimboor, R.; Natarajan, R.B.; Menon, K.R.; Chandrasekhar, L.P.; Moorkoth, V. Red pepper (*Capsicum annuum*) carotenoids as a source of natural food colors: Analysis and stability—A review. *J. Food Sci. Technol.* **2015**, *52*, 1258–1271. [CrossRef]

73. Kennedy, L.E.; Abraham, A.; Kulkarni, G.; Shettigar, N.; Dave, T.; Kulkarni, M. Capsanthin, a plant-derived xanthophyll: A review of pharmacology and delivery strategies. *AAPS PharmSciTech* **2021**, *22*, 203. [CrossRef]
74. Nowacka, M.; Fijalkowska, A.; Dadan, M.; Rybak, K.; Wiktor, A.; Witrowa-Rajchert, D. Effect of ultrasound treatment during osmotic dehydration on bioactive compounds of cranberries. *Ultrasonics* **2018**, *83*, 18–25. [CrossRef]
75. Haßmann, E.; Marszałek, K.; Lipowski, J.; Jasińska, U.; Kazimierczak, R.; Średnicka-Tober, D.; Rembiałkowska, E. Polyphenols and carotenoids in pickled bell pepper from organic and conventional production. *Food Chem.* **2019**, *278*, 254–260. [CrossRef] [PubMed]
76. Chávez-Mendoza, C.; Sánchez, E.; Muñoz-Márquez, E.; Sida-Arreola, J.P.; Flores-Córdova, M.A. Bioactive compounds and antioxidant activity in different grafted varieties of bell pepper. *Antioxidants* **2015**, *4*, 427–446. [CrossRef] [PubMed]
77. Oh, S.Y.; Koh, S.C. Fruit development and quality of hot pepper (*Capsicum annuum* L.) under various temperature regimes. *Hortic. Sci. Technol.* **2019**, *37*, 310–321. [CrossRef]
78. Rodríguez-Ruiz, M.; Mateos, R.M.; Codesido, V.; Corpas, F.J.; Palma, J.M. Characterization of the galactono-1,4-lactone dehydrogenase from pepper fruits and its modulation in the ascorbate biosynthesis. Role of nitric oxide. *Redox Biol.* **2017**, *12*, 171–181. [CrossRef]
79. Corpas, F.J.; Palma, J.M. Nitric oxide on/off in fruit ripening. *Plant Biol.* **2018**, *20*, 805–807. [CrossRef]
80. Zhang, L.; Zhu, M.; Ren, L.; Li, A.; Chen, G.; Hu, Z. The *SlFSR* gene controls fruit shelf-life in tomato. *J. Exp. Bot.* **2018**, *69*, 2897–2909. [CrossRef]
81. González-Gordo, S.; Bautista, R.; Claros, M.G.; Cañas, A.; Palma, J.M.; Corpas, F.J. Nitric oxide-dependent regulation of sweet pepper fruit ripening. *J. Exp. Bot.* **2019**, *70*, 4557–4570. [CrossRef]
82. Cisternas-Jamet, J.; Salvatierra-Martínez, R.; Vega-Gálvez, A.; Stoll, A.; Uribe, E.; Goñi, M.G. Biochemical composition as a function of fruit maturity stage of bell pepper (*Capsicum annuum*) inoculated with *Bacillus amyloliquefaciens*. *Sci. Hortic.* **2020**, *263*, 109107. [CrossRef]
83. Ribes-Moya, A.M.; Adalid, A.M.; Raigón, M.D.; Hellín, P.; Fita, A.; Rodríguez-Burruezo, A. Variation in flavonoids in a collection of peppers (*Capsicum* sp.) under organic and conventional cultivation: Effect of the genotype, ripening stage, and growing system. *J. Sci. Food Agric.* **2020**, *100*, 2208–2223. [CrossRef]
84. Papathanasiou, T.; Gougoulias, N.; Karayannis, V.G.; Kamvoukou, C.A. Investigation of the total phenolic content and antioxidant capacity of three sweet pepper cultivars (*Capsicum annuum* L.) at different development and maturation stages. *Period. Polytech. Chem. Eng.* **2021**, *65*, 219–228. [CrossRef]
85. Hamed, M.; Kalita, D.; Bartolo, M.E.; Jayanty, S.S. Capsaicinoids, polyphenols, and antioxidant activities of *Capsicum annuum*: Comparative study of the effect of ripening stage and cooking methods. *Antioxidants* **2019**, *8*, 364. [CrossRef] [PubMed]
86. Chilczuk, B.; Marciniak, B.; Kontek, R.; Materska, M. Diversity of the chemical profile and biological activity of *Capsicum annuum* L. extracts in relation to their lipophilicity. *Molecules* **2021**, *26*, 5215. [CrossRef] [PubMed]
87. Medina-Juárez, L.A.; Molina-Quijada, D.M.A.; Del Toro-Sánchez, C.L.; González-Aguilar, G.A.; Gámez-Meza, N. Antioxidant activity of peppers (*Capsicum annuum* L.) extracts and characterization of their phenolic constituents. *Comm. Rep. Comm.* **2012**, *37*, 588–593.
88. Kowalczyk, K.; Gajc-Wolska, J.; Radzanowska, J.; Marcinkowska, M. Assessment of chemical composition and sensory quality of tomato fruit depending on cultivar and growing conditions. *Acta Sci. Pol. Hortorum Cultus* **2011**, *10*, 133–140.
89. Felföldi, Z.; Ranga, F.; Roman, I.A.; Sestras, A.F.; Vodnar, D.C.; Prohens, J.; Sestras, R.E. Analysis of physico-chemical and organoleptic fruit parameters relevant for tomato quality. *Agronomy* **2022**, *12*, 1232. [CrossRef]
90. Shehata, S.A.; Abdelrahman, S.Z.; Megahed, M.M.A.; Abdeldaym, E.A.; El-Mogy, M.M.; Abdelgawad, K.F. Extending shelf life and maintaining quality of tomato fruit by calcium chloride, hydrogen peroxide, chitosan, and ozonated water. *Horticulturae* **2021**, *7*, 309. [CrossRef]
91. Abdelaal, K.A.; EL-Maghraby, L.M.; Elansary, H.; Hafez, Y.M.; Ibrahim, E.I.; El-Banna, M.; El-Esawi, M.; Elkelish, A. Treatment of Sweet Pepper with Stress Tolerance-Inducing Compounds Alleviates Salinity Stress Oxidative Damage by Mediating the Physio-Biochemical Activities and Antioxidant Systems. *Agronomy* **2020**, *10*, 26. [CrossRef]
92. Ge, W.; Zhao, Y.; Kong, X.; Sun, H.; Luo, M.; Yao, M.; Wei, B.; Ji, S. Combining salicylic acid and trisodium phosphate alleviates chilling injury in bell pepper (*Capsicum annuum* L.) through enhancing fatty-acid desaturation efficiency and water retention. *Food Chem.* **2020**, *327*, 127057. [CrossRef]
93. Dobón-Suárez, A.; Giménez, M.J.; García-Pastor, M.E.; Zapata, P.J. Salicylic acid preharvest treatment improves green pepper fruit quality and antioxidant capacity during postharvest storage. *Acta Hortic.* **2024**, *1396*, 471–476. [CrossRef]
94. Yang, W.; Kang, J.; Liu, Y.; Guo, M.; Chen, G. Effect of salicylic acid treatment on antioxidant capacity and endogenous hormones in winter jujube during shelf life. *Food Chem.* **2022**, *397*, 133788. [CrossRef]
95. Buczkowska, H.; Michalojc, Z.; Nurzynska-Wierdak, R. Yield and fruit quality of sweet pepper depending on foliar application of calcium. *Turk. J. Agric. For.* **2016**, *40*, 222–228. [CrossRef]

96. Khazaei, Z.; Estaji, A. Impact of exogenous application of salicylic acid on the drought-stress tolerance in pepper (*Capsicum annuum* L.). *J. Plant Physiol. Breed.* **2021**, *11*, 33–46. [CrossRef]
97. Khalid, M.F.; Elezz, A.A.; Jawaid, M.Z.; Ahmed, T. Salicylic acid restricts mercury translocation by activating strong antioxidant defense mechanisms in sweet pepper (*Capsicum annuum* L.). *Environ. Technol. Innov.* **2023**, *32*, 103283. [CrossRef]
98. Dobón-Suárez, A.; Giménez, M.J.; García-Pastor, M.E.; Zapata, P.J. Salicylic acid foliar application increases crop yield and quality parameters of green pepper fruit during postharvest storage. *Agronomy* **2021**, *11*, 2263. [CrossRef]

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mój indywidualny udział w jej powstaniu polegał na opracowaniu metodologii, walidacji, analizie formalnej, gromadzeniu danych oraz przygotowaniu oryginalnego projektu tekstu.

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mój indywidualny udział w jej powstaniu polegał na konceptualizacji, opracowaniu metodologii, programowaniu, walidacji, analizie formalnej, prowadzeniu badań, zarządzaniu zasobami, gromadzeniu danych, przygotowaniu pierwotnej wersji tekstu, jego recenzji i redakcji, opracowaniu wizualizacji oraz sprawowaniu nadzoru.

Mój udział wynosi: 75%

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   Mój udział wynosi: 15%

2. Sobczak A., Sujkowska-Rybkowska M., Gajc-Wolska J., Kowalczyk W., Borucki W., Kalaji H.M., Kowalczyk K. 2021. Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems. Plants 10(10):1975
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, redakcji i przeglądzie tekstu oraz nadzorze merytorycznym.

   Mój udział wynosi: 10%

3. Sobczak A., Kućko A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2023. Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation. Agronomy 13(3):779
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, opracowaniu metodologii, walidacji, prowadzeniu badań, przygotowaniu pierwotnej wersji tekstu, jego recenzji i edycji, administrowaniu projektem oraz pozyskiwaniu funduszy.

   Mój udział wynosi: 10%

4. Sobczak A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2024. Effect of Salicylic Acid and Calcium on Growth, Yield, and Fruit Quality of Pepper (*Capsicum annuum* L.) Grown Hydroponically. Agronomy 14(2):329

mój indywidualny udział w jej powstaniu polegał na konceptualizacji, opracowaniu metodologii, walidacji, prowadzeniu badań, zarządzaniu zasobami, gromadzeniu danych, przygotowaniu pierwotnej wersji tekstu, jego recenzji i redakcji oraz sprawowaniu nadzoru.

Mój udział wynosi: 10%

5. Sobczak-Samburska A., Pióro-Jabrucka E., Przybył J.L., Sieczko L., Kalisz S., Gajc-Wolska J., Kowalczyk K. 2025. Effect of Foliar Application of Calcium and Salicylic Acid on Fruit Quality and Antioxidant Capacity of Sweet Pepper (*Capsicum annuum* L.) in Hydroponic Cultivation. Agriculture 15(1):26
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, opracowaniu metodologii, walidacji, prowadzeniu badań, zarządzaniu zasobami, gromadzeniu danych, przygotowaniu pierwotnej wersji tekstu, jego recenzji i redakcji oraz sprawowaniu nadzoru.

Mój udział wynosi: 10%

.....
Podpis

Warszawa, 01.08.2025

dr Ewelina Pióro-Jabrucka
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Roślin Warzywnych i Leczniczych
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Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy pt.:

1. Sobczak A., Kućko A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2023. Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation. Agronomy 13(3):779
mój indywidualny udział w jej powstaniu polegał na walidacji.

   Mój udział wynosi: 5%

2. Sobczak A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2024. Effect of Salicylic Acid and Calcium on Growth, Yield, and Fruit Quality of Pepper (*Capsicum annuum* L.) Grown Hydroponically. Agronomy 14(2):329
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   Mój udział wynosi: 5%

3. Sobczak-Samburska A., Pióro-Jabrucka E., Przybył J.L., Sieczko L., Kalisz S., Gajc-Wolska J., Kowalczyk K. 2025. Effect of Foliar Application of Calcium and Salicylic Acid on Fruit Quality and Antioxidant Capacity of Sweet Pepper (*Capsicum annuum* L.) in Hydroponic Cultivation. Agriculture 15(1):26
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, opracowaniu metodologii, recenzji i redakcji tekstu oraz sprawowaniu nadzoru.

   Mój udział wynosi: 5%

E. Pióro-Jabrucka
Podpis

Warszawa, 18.07.2025

dr hab. Wojciech Borucki, prof. ucz.
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Botaniki
e-mail: wojciech_borucki@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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mój indywidualny udział w jej powstaniu polegał na konceptualizacji oraz walidacji.

Mój udział wynosi: 5%

.....
Podpis

Warszawa, 01.08.2025

prof. dr hab. Janina Gajc-Wolska
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Roślin Warzywnych i Leczniczych
e-mail: janina_gajc-wolska@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy pt.:

1. Sobczak A., Kowalczyk K., Gajc-Wolska J., Kowalczyk W., Niedzińska M. Growth, Yield and Quality of Sweet Pepper Fruits Fertilized with Polyphosphates in Hydroponic Cultivation with LED Lighting. Agronomy 2020, 10, 1560
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   Mój udział wynosi: 2%

2. Sobczak A., Sujkowska-Rybkowska M., Gajc-Wolska J., Kowalczyk W., Borucki W., Kalaji H.M., Kowalczyk K. 2021. Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems. Plants 10(10):1975
mój indywidualny udział w jej powstaniu polegał na zarządzaniu zasobami oraz administrowaniu projektem.

   Mój udział wynosi: 2%

3. Sobczak A., Kućko A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2023. Effect of Salicylic Acid on the Growth and Development of Sweet Pepper (*Capsicum annum* L.) under Standard and High EC Nutrient Solution in Aeroponic Cultivation. Agronomy 13(3):779
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, zarządzaniu zasobami, sprawowaniu nadzoru, administrowaniu projektem oraz pozyskiwaniu funduszy.

   Mój udział wynosi: 5%

4. Sobczak A., Pióro-Jabrucka E., Gajc-Wolska J., Kowalczyk K. 2024. Effect of Salicylic Acid and Calcium on Growth, Yield, and Fruit Quality of Pepper (*Capsicum annuum* L.) Grown Hydroponically. Agronomy 14(2):329.
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, recenzji i redakcji tekstu, administrowaniu projektem oraz pozyskiwaniu funduszy.

Mój udział wynosi: 5%

5. Sobczak-Samburska A., Pióro-Jabrucka E., Przybył J.L., Sieczko L., Kalisz S., Gajc-Wolska J., Kowalczyk K. 2025. Effect of Foliar Application of Calcium and Salicylic Acid on Fruit Quality and Antioxidant Capacity of Sweet Pepper (*Capsicum annuum* L.) in Hydroponic Cultivation. Agriculture 15(1):26
mój indywidualny udział w jej powstaniu polegał na konceptualizacji, recenzji i redakcji tekstu, administrowaniu projektem oraz pozyskiwaniu funduszy.

Mój udział wynosi: 1%

Janina Gajc-Wolska
Podpis

Warszawa, 21.08.2025

prof. dr hab. Mohamed Kalaji
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Fizjologii Roślin
e-mail: mohamed_kalaji@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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1. Sobczak A., Sujkowska-Rybkowska M., Gajc-Wolska J., Kowalczyk W., Borucki W., Kalaji H.M., Kowalczyk K. 2021. Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems. Plants 10(10):1975

mój indywidualny udział w jej powstaniu polegał na konceptualizacji oraz opracowaniu oprogramowania.

Mój udział wynosi: 1%

Hazem Kalaji
Podpis

Warszawa, 18.07.2025

dr hab. Stanisław Kalisz, prof. ucz.
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
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e-mail: stanislaw_kalisz@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

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mój indywidualny udział w jej powstaniu polegał na przeprowadzeniu części badań.

Mój udział wynosi: 2%

.....
Podpis

Warszawa, 30.07.2025

dr Waldemar Kowalczyk
Instytut Ogrodnictwa – Państwowy Instytut Badawczy
Laboratorium Analiz Chemicznych
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Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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mój indywidualny udział w jej powstaniu polegał na analizie formalnej oraz gromadzeniu danych.

   Mój udział wynosi: 2%

2. Sobczak A., Sujkowska-Rybkowska M., Gajc-Wolska J., Kowalczyk W., Borucki W., Kalaji H.M., Kowalczyk K. 2021. Photosynthetic Efficiency and Anatomical Structure of Pepper Leaf (*Capsicum annuum* L.) Transplants Grown under High-Pressure Sodium (HPS) and Light-Emitting Diode (LED) Supplementary Lighting Systems. Plants 10(10):1975
mój indywidualny udział w jej powstaniu polegał na pozyskiwaniu funduszy.

   Mój udział wynosi: 2%

Waldemar Kowalczyk
Podpis

Warszawa, 18.07.2025

dr Agata Kućko
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Fizjologii Roślin
e-mail: agata_kucko@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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Mój udział wynosi: 10%

Agata Kućko
.....
Podpis

Warszawa, 4.08.2025 r.

mgr inż. Monika Niedzińska
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Roślin Warzywnych i Leczniczych
e-mail: monika_marcinkowska1@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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mój indywidualny udział w jej powstaniu polegał na opracowaniu metodologii, przeprowadzeniu walidacji oraz analizy formalnej.

Mój udział wynosi: 1%

Niedzińska
.....
Podpis

Warszawa, 18.07.2025

dr Jarosław L. Przybył
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Roślin Warzywnych i Leczniczych
e-mail: jaroslaw_przybyl@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy pt.:

1. Sobczak-Samburska A., Pióro-Jabrucka E., Przybył J.L., Sieczko L., Kalisz S., Gajc-Wolska J., Kowalczyk K. 2025. Effect of Foliar Application of Calcium and Salicylic Acid on Fruit Quality and Antioxidant Capacity of Sweet Pepper (*Capsicum annuum* L.) in Hydroponic Cultivation. Agriculture 15(1):26
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Mój udział wynosi: 5%

J. Przybył

.....
Podpis

Warszawa, 18.07.2025

dr inż. Leszek Sieczko
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Biometrii
e-mail: leszek_sieczko@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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mój indywidualny udział w jej powstaniu polegał na opracowaniu metodologii, analizie formalnej oraz prowadzeniu badań.

Mój udział wynosi: 2%

.....
Podpis

Warszawa, 21.07.2025

dr hab. Marzena Sujkowska-Rybkowska
Szkoła Główna Gospodarstwa Wiejskiego w Warszawie
Katedra Botaniki
e-mail: marzena_sujkowska@sggw.edu.pl

Rada Dyscypliny Rolnictwa i Ogrodnictwa
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy pt.:

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mój indywidualny udział w jej powstaniu polegał na programowaniu, walidacji, prowadzeniu badań oraz opracowaniu wizualizacji.

Mój udział wynosi: 5%

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Podpis