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Wpływ podłoża z węgla brunatnego oraz wybranych czynników agrotechnicznych na wzrost, plon i jakość owoców ogórka szklarniowego w uprawie hydroponicznej

Effect of lignite substrate and chosen agrotechnical factors on growth, yield and fruit quality of greenhouse cucumber in hydroponic cultivation

Praca doktorska

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Oświadczenie promotora rozprawy doktorskiej

Oświadczam, że niniejsza rozprawa została przygotowana pod moim kierunkiem i stwierdzam, że spełnia warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego doktora.

Data 17.04.2024 Podpis promotora pracy ....

Oświadczenie autora rozprawy doktorskiej

Świadom odpowiedzialności prawnej, w tym odpowiedzialności karnej za złożenie fałszywego oświadczenia, oświadczam, że niniejsza rozprawa doktorska została napisana przez mnie samodzielnie i nie zawiera treści uzyskanych w sposób niezgodny z obowiązującymi przepisami prawa, w szczególności z ustawą z dnia 4 lutego 1994 r. o prawie autorskim i prawach pokrewnych (tj. z dnia 28 października 2022 r., Dz.U. z 2022 r. poz. 2509 ze zm.)

Oświadczam, że przedstawiona rozprawa nie była wcześniej podstawą żadnej procedury związanej z uzyskaniem stopnia naukowego doktora.

Oświadczam ponadto, że niniejsza wersja rozprawy jest identyczna z załączoną wersją elektroniczną.

Przyjmuję do wiadomości, że rozprawa doktorska poddana zostanie procedurze antyplagiatowej.

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Spis treści

STRESZCZENIE

Effect of lignite substrate and chosen agrotechnical factors on growth, yield and fruit quality of greenhouse cucumber in hydroponic cultivation

The cucumber (*Cucumis sativus* L.) is a very popular and economically important vegetable in Poland and around the world. In intensive production of vegetables under covers, hydroponic cultivation technology in rockwool substrate is most commonly used, but alternative biodegradable substrates are constantly being investigated. In the present study, an evaluation of the effect of lignite substrate and chosen cultivation factors, such as LED (*Light Emitting Diode*) lighting, substrate reuse and high EC of nutrient solution, on morphological, physiological parameters, yield and fruit quality of greenhouse cucumber in hydroponic cultivation was undertaken. The effect of this production technology on post-harvest quality of greenhouse cucumber fruit and their storability was also evaluated. Four research hypotheses were undertaken: (I) The use of biodegradable lignite substrate in hydroponic cucumber cultivation, as an alternative to mineral wool, affects the yield and quality of cucumber fruit, (II) The re-use of lignite mats does not adversely affect plant growth, yield and fruit quality of greenhouse cucumber, while reducing undesirable environmental effects, (III) LED assimilation lighting positively affects the growth and yield and quality of cucumber fruits in hydroponic cultivation with lignite as a solid substrate, (IV) Hydroponic cultivation technology with lignite-based organic substrate and LED assimilation lighting, affects the post-harvest quality of greenhouse cucumber fruits and prolongs their storability.

The study was carried out in 2019-2023. The cucumber cultivation technology using a lignite substrate together with assimilation supplementary lighting with LED lamps influenced, among other things, an increase in cucumber fruit content of β-carotene, lutein, chlorophyll *a* and *b*, total soluble solids (TSS), a decrease in nitrate content, as well as higher hardness and lower water loss during simulated fruit turnover compared to cultivation in a mineral substrate with HPS (*High Pressure Sodium*) lamp irradiation.

The results obtained confirmed the research hypotheses. This represents an important addition to the development of knowledge in the field of a hydroponic cultivation technology in solid media with assimilation lighting.

Keywords: soilless cultivation, organic substrate, assimilative lighting, EC, gas exchange, chlorophyll fluorescence, secondary metabolites, sensory quality

PUBLIKACJE BĘDĄCE PODSTAWĄ ROZPRAWY DOKTORSKIEJ

1. **Łaźny R**., Mirgos M., Przybył J.L., Nowak J.S., Kunka M., Gajc-Wolska J., Kowalczyk K. 2021. Effect of re-used lignite and mineral wool growing mats on plant growth, yield and fruit quality of cucumber and physical parameters of substrates in hydroponic cultivation. Agronomy 11: 998. https://doi.org/10.3390/agronomy11050998 (IF_{2021} 3.949, 100 pkt MNiSW)
2. **Łaźny R**., Nowak J.S., Mirgos M., Przybył J.L., Niedzińska M., Kunka M., Gajc-Wolska J., Kowalczyk W., Kowalczyk K. 2022. Effect of selected physical parameters of lignite substrate on morphological attributes, yield and quality of cucumber fruits fertigated with high EC nutrient solution in hydroponic cultivation. Appl. Sci. 12: 4480. https://doi.org/10.3390/app12094480 (IF_{2022} 2.7, 100 pkt MNiSW)
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LISTA SKRÓTÓW

LED (*Light Emitting Diode*) – diody LED

HPS (*High Pressure Sodium*) – wysokoprężne lampy sodowe

PAR (*Photosynthetically Active Radiation*) – promieniowanie fotosyntetycznie czynne

PPFD (*Photosynthetic Photon Flux Density*) – gęstość strumienia fotosyntetycznego fotonów

RH (*Relative Humidity*) – wilgotność względna

EC (*Electrical Conductivity*) – przewodność elektryczna

WUE (*Water Use Efficiency*) – współczynnik wykorzystania wody

iWUE – chwilowy fotosyntetyczny współczynnik wykorzystania wody

PN – szybkość fotosyntezy netto

gs – przewodność szparkową

E – szybkość transpiracji

Fs – wydajność fluorescencji w stanie ustalonym

Fm' – maksimum fluorescencji dostosowanej do światła

ΦPSII – maksymalna wydajność kwantowa PS II

Fv/Fm – maksymalna wydajność kwantowa PSII po adaptacji w ciemności

SPAD – indeks zawartości chlorofilu

TSS (*Total Soluble Solids*) – rozpuszczalne substancje stałe w soku komórkowym

ROS (*Reactive Oxygen Species*) – reaktywne formy tlenu

HPLC (*High Performance Liquid Chromatography*) – wysokosprawna chromatografia cieczowa)

HDPE (*High Density Polyethylene*) – polietylen o wysokiej gęstości

PE (*Polyethylene*) – polietylen

WSTĘP

W dziedzinie zrównoważonego rolnictwa, hydroponika stanowi wyzwanie, ale i otwiera wiele nowych możliwości w porównaniu do tradycyjnych praktyk rolniczych. Zastosowanie w badaniach węgla brunatnego, jako niekonwencjonalnego podłoża w uprawach hydroponicznych roślin owocujących, jest poszukiwaniem efektywnego zamiennika dla wełny mineralnej. Wraz z malejącą powierzchnią gruntów rolnych i rosnącym zapotrzebowaniem na żywność, poszukiwanie alternatywnych podłoży staje się istotnym aspektem przyszłych upraw. Mając również na względzie ograniczenie negatywnego wpływu na środowisko naturalne, niezbędne jest również badanie zależności i wpływ zużytego w produkcji ogrodniczej podłoża na środowisko. Węgiel brunatny jest kopaliną, jednak produkcja mat uprawowych emituje o 40% mniej gazów cieplarnianych, w porównaniu do produkcji mat uprawowych z wełny mineralnej. Dodatkowo podłoże to może być wykorzystywane przez kilka sezonów, a następnie zastosowane jako nawóz organiczny w produkcji konwencjonalnej. W uprawach prowadzonych z doświetlaniem asymilacyjnym, które mają coraz większe znaczenie także w naszej rodzimej produkcji roślinnej, zastosowanie lamp LED ogranicza zużycie energii i pozwala dobrać spektrum światła do specyficznych wymagań uprawianego gatunku oraz fazy rozwojowej rośliny. Możliwość regulacji widma oraz oszczędność energii, a także stosowanie lamp LED również między roślinami, pozwala na lepsze wykorzystanie potencjału plonotwórczego roślin oraz zapewnia wysoką efektywność upraw i jakość plonu przez cały rok. Komputerowo prowadzona kontrola i precyzja parametrów uprawy w nowych technologiach produkcji szklarniowej, daje dodatkowo możliwość wprowadzenia warunków kontrolowanego stresu abiotycznego, w celu korzystnego dla producenta i konsumenta ukierunkowania zmian w metabolizmie uprawianych roślin. Przykładem jest zastosowanie wysokiego EC pożywki, co może wpłynąć na zwiększenie zawartości związków bioaktywnych w częściach użytkowych warzyw.

Zastosowanie odpowiednich rozwiązań i technologii uprawy może wpłynąć na poprawę i tempo wzrostu i rozwoju roślin oraz wielkość i jakość plonu, a jednocześnie ograniczyć negatywny wpływ na środowisko

1. PRZEGLĄD LITERATURY

1.1. Pochodzenie, systematyka i charakterystyka morfologiczna ogórka

Ogórek jest drugim po pomidorze gatunkiem warzyw najczęściej uprawianym na całym świecie (Pitrat i in. 1999). Znaczenie ekonomiczne ogórka oraz zainteresowanie hodowców sprawiły, że sekwencjonowano pełny genom chloroplastów *Cucumis sativus* (Kim i in. 2006). Uważa się, że gatunek ten ewoluował z kariotypu chromosomów n = 12 i jest jedynym w rodzaju *Cucumis* o liczbie chromosomów równej n = 7 (Renner i in. 2007). Przyjmuje się, że centra ewolucji *Cucumis* znajdują się w Afryce (Akashi i in. 2002, Renner i in. 2007). Opisanie rodzaju *Cucumis* sięga czasów Linneusza (Linnaeus 1735). Gatunek *Cucumis sativus* L. jest rośliną jednoroczną, o zwisającym lub pnącym pokroju, chociaż niektóre odmiany ogórka mają pokrój krzaczasty. System korzeniowy ogórka jest płytki, silnie rozkrzewiony i o dużym zasięgu. Pędy boczne wyrastają pod kątem ostrym, pokryte są bardzo często włoskami wydzielniczymi i rozgałęziają się sympodialnie. Z każdego węzła na pędzie wyrasta pojedynczy liść, jeden owoc lub kilka oraz wąs czepny. Wąsy czepne to przekształcone liście, rzadko są pokryte włoskami. Ogonki liściowe u ogórka różnią się długością w zależności od odmiany. Liście ogórka są proste, z występującymi na ich powierzchni włoskami wydzielniczymi. Blaszka liściowa może być okrągła, nerkowata, trójkątnie jajowata lub sercowata, z trzema do pięciu skośnymi częściami, od płytkich do głęboko klapowanych. Liść ogórka jest ostro zakończony lub rzadko rozwarty. Kwiaty ogórka są jednopłciowe – słupkowe lub pręcikowe (czasami obupłciowe). Rośliny z rodzaju *Cucumis* zazwyczaj są jednopienne. Kielich kwiatu ogórka złożony jest z 5, rzadko 4 płatków liniowych do podłużnych, lub wąsko do szeroko trójkątnych, w kolorze żółtym. Owocem ogórka jest jagoda o zabarwieniu od jasnozielonego do ciemnozielonego, pokryta brodawkami lub gładka (Křístková i in. 2003, Grumet i in. 2022). Charakterystyczną cechą owocu ogórka jest mięsisty perykarp z wieloma nasionami oraz twardą i jędrną skórką. Jak donosi literatura, blisko 80-krotny wzrost liczby komórek w owocolistkach względem podłużnej osi, ich orientacja oraz liczba, stanowi podstawę zróżnicowanej wielkości i kształtu owoców (Liu i in. 2020, Grumet i in. 2022).

1.2. Partenokarpia u ogórka szklarniowego

Partenokarpia może być obligatoryjna lub fakultatywna, a ta ostatnia występuje w momencie, kiedy zapylenie i zapłodnienie zostało uniemożliwione. Jest to zjawisko naturalnie występujące u wybranych roślin, gdzie rozwój owoców następuje bez zapłodnienia (Lietzow i in. 2016). Jest to cecha pożądana w warunkach niesprzyjających lub niedostępnych dla zapylaczy np. w uprawach szklarniowych (Dhatt i Kaur 2016). Badania prowadzone w połowie XX wieku wykazały, że partenokarpię u roślin ogórka można wywołać egzogennymi fitohormonami stymulującymi wzrost, takimi jak auksyny, cytokininy, brasinosteroidy, lub ich kombinacjami. Zauważono również zwiększoną transkrypcję genów odpowiadających za biosyntezę auksyn, giberelin i cytokinin w genetycznie partenokarpicznych owocach oraz w owocach, gdzie uzyskano partenokarpię poprzez zastosowanie fitohormonów (Mandal i in. 2022). Zgodnie z ustaleniami Cui i in. (2014), auksyny oraz wzmożona ekspresja genów odpowiadających za syntezę auksyn w owocach partenokarpicznych odgrywa kluczową rolę. Podobnie jak transport i synteza cukrów podczas zapylenia owoców, tak i we wzroście owoców partenokarpicznych współdziałanie cukrów i hormonów roślinnych wpływa na prawidłowy wzrost tych owoców, a wyższe tempo podziału komórek w owocach powiązane jest z wyższą syntezą węglowodanów (Li i in. 2017, Wang i in. 2021). W niektórych partenokarpicznych liniach ogórka, w szczególności w europejskich typach szklarniowych, zjawisko partenokarpii zostało powiązane z mniejszą predyspozycją do hamowania rozwoju pierwszych owoców, co może bezpośrednio przekładać się na przewagę w plonowaniu nad innymi liniami ogórka (Gou i in. 2022).

1.3. Podłoże z wełny mineralnej oraz jego wpływ na środowisko

Podłoża uprawowe to materiały inne niż gleba, w których roślina rozwija swój system korzeniowy. Mogą to być podłoża mineralne (wełna mineralna, perlit, keramzyt) oraz organiczne (torf, włókno kokosowe, słoma). Właściwości fizyczne i chemiczne podłoża, parametry mikroklimatu oraz możliwości i technologie uprawy, warunkują wydajność i efektywność uprawy (Grunert i in. 2008). W niektórych rejonach świata to właśnie uprawy bezglebowe są jedyną alternatywą produkcji żywności z powodu nadmiernego zasolenia gleby, złej praktyki rolnej lub zmieniającego się klimatu. Poprzez niewłaściwe użytkowanie w wielu miejscach doprowadzono do degradacji gleby, co w konsekwencji wyklucza możliwość uprawy roślin (Kamran i in. 2019, Abdel-Farid i in. 2020). Kontrolowane warunki uprawy systemów hydroponicznych i odizolowanie roślin od podłoża macierzystego znacznie zwiększa wydajność produkcji, w porównaniu z uprawą tradycyjną (Barrett i in. 2016). Efektywność upraw jest w stanie zapewnić podłoże o odpowiednich, stabilnych właściwościach fizycznych (Saha i in. 2016). Najczęściej używanym podłożem w produkcji hydroponicznej pomidora, ogórka lub papryki jest wełna mineralna. Podłoże to powstaje ze skał bazaltowych w temperaturze 1500-1600°C z różnymi dodatkami, co ma na celu uzyskanie pożądanych właściwości. Zapotrzebowanie energetyczne na wyprodukowanie 1 m^3 wełny mineralnej sięga 275 kWh energii pierwotnej, emitując przy tym 167 kg CO_2 do środowiska (Dannehl i in. 2015, Kraska i in. 2018). Dodatkowym problemem jest brak przepisów ściśle regulujących obowiązek utylizacji zużytego podłoża po uprawie. Przykładem może być Holandia, gdzie wełna mineralna po uprawie podlega utylizacji, a następnie wraca do ponownego wykorzystania, natomiast w Kanadzie jest składowana na wysypiskach (Van Den Bosch 2004, Dannehl i in. 2015). W Polsce również istnieje problem utylizacji i składowania wełny mineralnej, co nie jest obojętne dla środowiska, a w konsekwencji dla zdrowia człowieka (Nerlich i Dannehl 2021). Wełna mineralna jest podłożem obojętnym chemicznie, wolnym od chorób i szkodników, posiada stabilne właściwości fizyczne podczas uprawy (tylko w pierwszym roku użytkowania) i nadal ma największe zastosowanie w towarowej produkcji warzyw w systemach hydroponicznych (Dannehl i in. 2015, Kraska i in. 2018, Kennard i in. 2020). Pomimo tego stale poszukiwane są alternatywne organiczne podłoża, w pełni biodegradowalne, które nie będą stanowiły nadmiernego obciążenia dla środowiska naturalnego.

1.4. Alternatywne podłoża organiczne w uprawach szklarniowych

Wielu badaczy podejmowało już próby wskazania podłoża stanowiącego substytut wełny mineralnej, o zbliżonych, odpowiednich dla roślin właściwościach fizycznych. Te alternatywne składniki podłoży organicznych zostały szeroko przebadane, pod kątem przydatności do uprawy, możliwości wykorzystania, właściwości fizycznych oraz łatwości utylizacji (Barrett i in. 2016, Gruda 2019, Xing i in. 2019). Barrett i in. (2016), analizując czynniki leżące u podstaw wyboru właściwego podłoża do uprawy stwierdzili, że musi ono spełniać założenia wydajności, ekonomii i ekologii. Pojawiło się też stwierdzenie, że podłoże organiczne powinno spełniać co najmniej takie same wymagania i działać przy takich samych ograniczeniach jak dostępne powszechnie standardowe podłoża w uprawach hydroponicznych (Barrett i in. 2016, Kraska i in. 2018). Standardowymi podłożami są torf lub włókno kokosowe. Pierwsze z nich to podłoże, które obejmuje wiele różnych materiałów roślinnych, stanowiących szczątki roślin i zwierząt, które podlegały procesom torfienia (Holden 2005). Problemem jest pozyskiwanie torfu, ponieważ wydobycie torfu emituje gazy cieplarniane oraz obniża poziom wód gruntowych (Holden 2005, Gruda 2019). Włókno i pył koksowy to odpad organiczny produkowany w krajach tropikalnych, który powstaje z mezokarpu orzecha kokosowego. W zależności od pochodzenia, może różnić się zawartością potasu, sodu oraz chlorków (Xiong i in. 2017). Obecne liczne badania koncentrują się również na wykorzystaniu jako uniwersalnych podłoży ogrodniczych odpadów z przemysłu drzewnego, kompostów z odpadów organicznych oraz biowęgla (Gruda 2019, Zulfiqar i in. 2019, Solaiman i in. 2020). Ponadto zainteresowania badaczy dotyczą także możliwości wykorzystania jako podłoży biodegradowalnych łupin migdałów, orzechów lub odpadów z przemysłu winiarskiego (Bustamante i in. 2008, Dede i Ozdemir 2018). Możliwość kaskadowego (wielokrotne wykorzystanie podłoża, aż do zakończenia cyklu życia produktu) wykorzystania roślin *Miscanthus* zaproponowano w badaniach Kraska i in. (2018), gdzie negatywny wpływ dla środowiska naturalnego został ograniczony do minimum. Te produkty lub podłoża organiczne często stosowane są w mieszaninach z perlitem lub wermikulitem w celu stabilizacji lub poprawy ich właściwości fizycznych (Kennard i in. 2020).

Podłoże, które może stanowić substytut wełny mineralnej powinno posiadać zbliżone parametry fizyczne jak wełna mineralna, zapewniać właściwy rozwój roślinie, a jego zakup powinien mieć ekonomiczne uzasadnienie wyboru tego podłoża. Ważnym aspektem jest również jego dostępność oraz ograniczenie negatywnego wpływu na środowisko naturalne, na każdym etapie jego produkcji, wykorzystania oraz utylizacji.

1.5. Doświetlanie asymilacyjne lampami LED oraz ich wpływ na fizjologię roślin

Wysokiej jakości warzywa dostępne przez cały rok, to oczekiwania dzisiejszych konsumentów (Kowalczyk i in. 2018). W miesiącach jesienno-zimowych, gdzie natężenie promieniowania słonecznego jest w wielu rejonach świata niewystarczające dla produkcji roślinnej, koniecznym jest zastosowanie sztucznego doświetlania. Jest to niezbędne, ponieważ światło jest istotnym czynnikiem warunkującym prawidłowy wzrost i rozwój roślin, a plon i jego jakość zależy od fotosyntezy (Moon i in. 2023). Zdolność do przebiegu fotosyntezy związana jest bezpośrednio z pigmentami fotosyntetycznymi i fluorescencją chlorofilu, zależną od sprawności fotosystemu, fotosyntetycznego transportu elektronów itd. Czynniki te można regulować poprzez jakość światła (Kowalczyk i in. 2022, Moon i in. 2023). Do tego celu stosowane są lampy emitujące szerokie widmo w zakresie PAR (Gajc-Wolska i in. 2021). W wielkoobszarowych, komercyjnych systemach uprawy, nadal wykorzystywane są lampy HPS, jednak nie są one optymalne z powodu niskiego udziału światła niebieskiego w emitowanym widmie. Udział fal światła niebieskiego nie przekracza w widmie światła lamp sodowych 5%. Dla porównania światło słoneczne zawiera 18% światła niebieskiego (Gajc-Wolska i in. 2021, Moon i in. 2023). Dodatkowym problemem z używaniem lamp sodowych jest ich niska sprawność, gdzie części energii elektrycznej jest zamieniona w promieniowanie podczerwone, czyli ciepło. Jeśli lampy sodowe zostaną umieszczone zbyt blisko roślin, mogą je uszkodzić (Islam i in. 2012). Technologia dotycząca diod elektroluminescencyjnych (LED) w ciągu ostatnich dziesięciu lat rozwinęła się bardzo intensywnie. Dlatego tak szybko lampy LED stały się alternatywą dla wszystkich innych sztucznych źródeł światła (Massa i in. 2008). Dzięki swej wysokiej sprawności, niskiej energochłonności i produkcji ciepła, lampy LED ograniczają koszty produkcji, jednak nadal stanowią duży udział kosztów początkowych w wyposażeniu obiektu w tę technologię (Gómez i Gennaro Izzo 2018). Lampy LED mogą zostać umieszczone nad wierzchołkami roślin, jak i w środku łanu, pomiędzy roślinami. Uprawy szklarniowe to produkcja bardzo intensywna, prowadzona z dużą liczbą roślin przypadającą na jednostkę powierzchni. Skutkiem tego może być także niewystarczająca ilość światła docierającego do niższych partii roślin w ciągu całego roku, co z kolei wpływa na zmianę morfogenezy roślin i intensywności fotosyntezy (Terfa i in. 2013). W uprawie pomidora stwierdzono, że „przechwytywanie” światła przez każdą warstwę łanu istotnie maleje, w kierunku dolnego profilu rośliny pomidora. Stwierdzono również, że tylko 35% „przechwyconego" światła słonecznego dociera do liści znajdujących się poniżej grona (w niższych partiach rośliny) (Song i in. 2016, Tewolde i in. 2016). Już w latach 70 XX wieku odnotowano, że taki niedobór światła wpływa na niską intensywność fotosyntezy netto oraz przyspiesza starzenie się liści (Acock i in. 1978). Badania potwierdzają, że umieszczenie doświetlania LED międzyrzędowo poprawia pionowy rozsył światła oraz sprawność fotosyntetyczną niżej położonych liści wewnątrz łanu, ograniczając zarazem tempo starzenia się dolnych liści (Kowalczyk i in. 2022, Paradiso i in. 2020). Aspekty takie jak natężenie światła oraz jego spektrum, lub długość okresu świetlnego są istotne w powodzeniu całej uprawy. Lampy LED charakteryzują się możliwością doboru spektrum światła dla danego gatunku, a nawet odmiany (Lu i in. 2012). Stwierdzono, że światło niebieskie hamuje wydłużanie hipokotylu u pomidora (Massa i in. 2008), zwiększa suchą masy liści i zdolność fotosyntetyczną papryki (Brown i in. 1995). Również różne proporcje światła czerwonego wpływają na zawartość związków fitochemicznych liści i fotomorfogenezę roślin. Wyniki prowadzonych badań umożliwiają dobór odpowiedniego składu spektralnego dla konkretnego gatunku, co przekłada się na sprawność fotosyntezy, poprawę morfologii roślin i w konsekwencji wynik ekonomiczny gospodarstwa (Song i in. 2016, Kowalczyk i in. 2022, Moon i in. 2023). Jak potwierdzają badania, maksymalne tempo fotosyntezy mierzone w liściach odnotowano w środkowej i dolnej warstwie liścia, a nie na górnej, gdzie natężenie promieniowania było najwyższe (Evans i Vogelmann 2003). Wspomniane głębsze warstwy liścia charakteryzują się większą aktywnością w transporcie elektronów oraz większą ilością białek fotosyntetycznych (Song i in. 2016). Regulacja roztwarcia aparatów szparkowych jest silnie skorelowana z fotosyntezą liścia i odpowiada za asymilację CO_2 i utratę wody przez rośliny (Araújo i in. 2011, Song i in. 2016). Na regulację aparatów szparkowych może wpływać długość fali poprzez konwersję energii, transport jonów przez błony cytoplazmatyczne oraz aktywność metaboliczną (Araújo i in. 2011, Chen i in. 2012, O'Carrigan i in. 2014, Song i in. 2016). Jednak światło to nie jedyny czynnik warunkujący prawidłowy wzrost i rozwój roślin, plon i jego jakość oraz zdolność przechowalniczą owoców.

1.6. Czynniki wpływające na plonowanie oraz jakość i zdolność przechowalniczą owoców ogórka

Odpowiednie podłoże oraz światło to ważne czynniki warunkujące prawidłowy wzrost roślin, ale temperatura, wilgotność względna, odpowiednie wietrzenie to tak zwany mikroklimat. Mikroklimat szklarniowy to zespół parametrów klimatycznych tworzących się wokół rośliny uprawnej i zapewniający jej właściwy wzrost, a co za tym idzie plonowanie (Singh i in. 2017). Mikroklimat można kontrolować za pomocą regulacji cieniówek, systemu ogrzewania, zamgławiania i wentylacji oraz nawadniania i dozowania CO_2. W przypadku uprawy ogórka ważnym czynnikiem warunkującym prawidłowy wzrost jest woda i nawożenie. Jak wskazują badania, odpowiedni czas nawadniania i dawki oraz właściwie prowadzone nawożenie jest bardzo istotne (Wang i in. 2019). Nadmierna ilość wody zmniejsza plon oraz jego jakość, a niewystarczająca ilość powoduje hamowanie wzrostu (Zhang i in. 2011, Singh i in. 2017). Ogórek szklarniowy rośnie szybko i charakteryzuje się dużym zapotrzebowaniem na wodę, jednak zależy to od fazy wzrostu rośliny (Zotarelli i in. 2009). Wzrost zapotrzebowania na wodę oraz efektywność wykorzystania wody (WUE) wzrasta od fazy początku zbiorów, aż do zakończenia wzrostu rośliny (Mao i in. 2003). Również przewodnictwo szparkowe i transpiracja roślin zależy od deficytu ciśnienia pary wodnej. Przewodnictwo szparkowe odgrywa ważną rolę w podziale energii wewnątrz rośliny. Zależne jest od stężenia CO_2, temperatury powietrza oraz potencjału wody w liściach (Singh i in. 2017). Różnica temperatury pomiędzy dniem a nocą oraz dobowy przebieg temperatury wpływa między innymi na długość międzywęźli, wysokość rośliny, orientację liści i pędów oraz zawartość chlorofilu i wzrost owoców (Myster i Moe, 1995). Temperatura także wpływa na tempo przyrastania owoców, wpływając na liczbę komórek. Zakres optymalnej temperatury dla wzrostu ogórka to 22-26°C w dzień i 21-23°C w nocy (Marcelis i Hofman-Eijer 1993, Singh i in. 2017). Również takie czynniki jak zagęszczenie roślin, obciążenie owocami oraz termin uprawy wpływa na plon i jakość wewnętrzną owoców (Gajc-Wolska i in. 2010, Valverde-Miranda i in. 2021). Czynniki te między innymi według Valverde-Miranda i innych (2021), mogą także modyfikować zawartość suchej masy owoców oraz stężenie składników rozpuszczalnych w soku komórkowym (TSS). Wraz ze wzrostem standardów życia oraz rozwojem gospodarczym, konsument, a przez to i producent, prócz plonu coraz więcej uwagi przywiązuje do jakości warzyw i owoców (Gao i in. 2022). Owoc ogórka zwiera 95% wody, 3,6% węglowodanów, jest bogatym źródłem białka, soli mineralnych, błonnika pokarmowego, witaminy C, E oraz witamin z grupy B, kwasu foliowego i pantotenowego. Owoce ogórka zawierają również związki fenolowe i flawonoidowe (Leszczyńska i in. 2016, Ding i in. 2022). Dlatego w ostatnich latach badano różne czynniki modyfikujące jakość owoców, takie jak zmiana strategii uprawy, podłoża organiczne (Khan 2018, Kraska i in. 2018), zastosowanie arbuskularnych grzybów mikoryzowych (Ali i in. 2019), czy stres solny, powodujący wzrost zawartości składników odżywczych w owocach (Rouphael i in. 2018b). Jakość owoców ogórka to szerokie pojęcie, na które składa się wielkość owocu (średnica i długość), kształt, kolor skórki, twardość/jędrność oraz wady dotyczące wyglądu jak wgniecenia, uszkodzenie skórki, uszkodzenia mechaniczne, procesy gnilne (Owoyemi i in. 2021, Valverde-Miranda i in. 2021). Jakość owoców ogórka zależy również od utraty wody (więdnięcie), co prócz straty wody łączy się ze zmianą zawartości polisacharydów w owocu, a zmiana ich zawartości degraduje ścianę komórkową (Nishizawa i in. 2018). Ponad 40% strat wody dotyczy czasu bezpośrednio po zbiorach i podczas dystrybucji warzyw. W krajach uprzemysłowionych do strat produktów ogrodniczych dochodzi najczęściej w czasie ich sprzedaży, a w krajach rozwijających się podczas zbiorów i w czasie ich przetwarzania (Owoyemi i in. 2021, Valverde-Miranda i in. 2021). Dobór odmiany również jest kluczowy w celu zapewnienia jakości owoców oraz trwałości owoców ogórka po zbiorach (Schouten i in. 2004). Aby zachować dłuższą świeżość owoców wykorzystywane są również inteligentne opakowania, wpływające na skład atmosfery wewnątrz, także stosowane są powłoki jadalne czy traktowanie chemiczne tlenkiem azotu (Dong i in. 2012, Patel i Panigrahi 2019, Valverde-Miranda in. 2021). Prócz wszystkich zabiegów pozbiorczych, które przedłużają *shelf-life* warzyw, dobór odpowiedniego podłoża i strategii uprawowej może podwyższyć jakość produktu już na początkowym etapie uprawy. Aby zaspokoić światowy popyt na żywność, ważne jest ukierunkowanie badań na rozwiązania zwiększające efektywność upraw pod osłonami i ograniczające straty na etapie produkcji oraz po zbiorach.

2. CEL BADAŃ I HIPOTEZY BADAWCZE

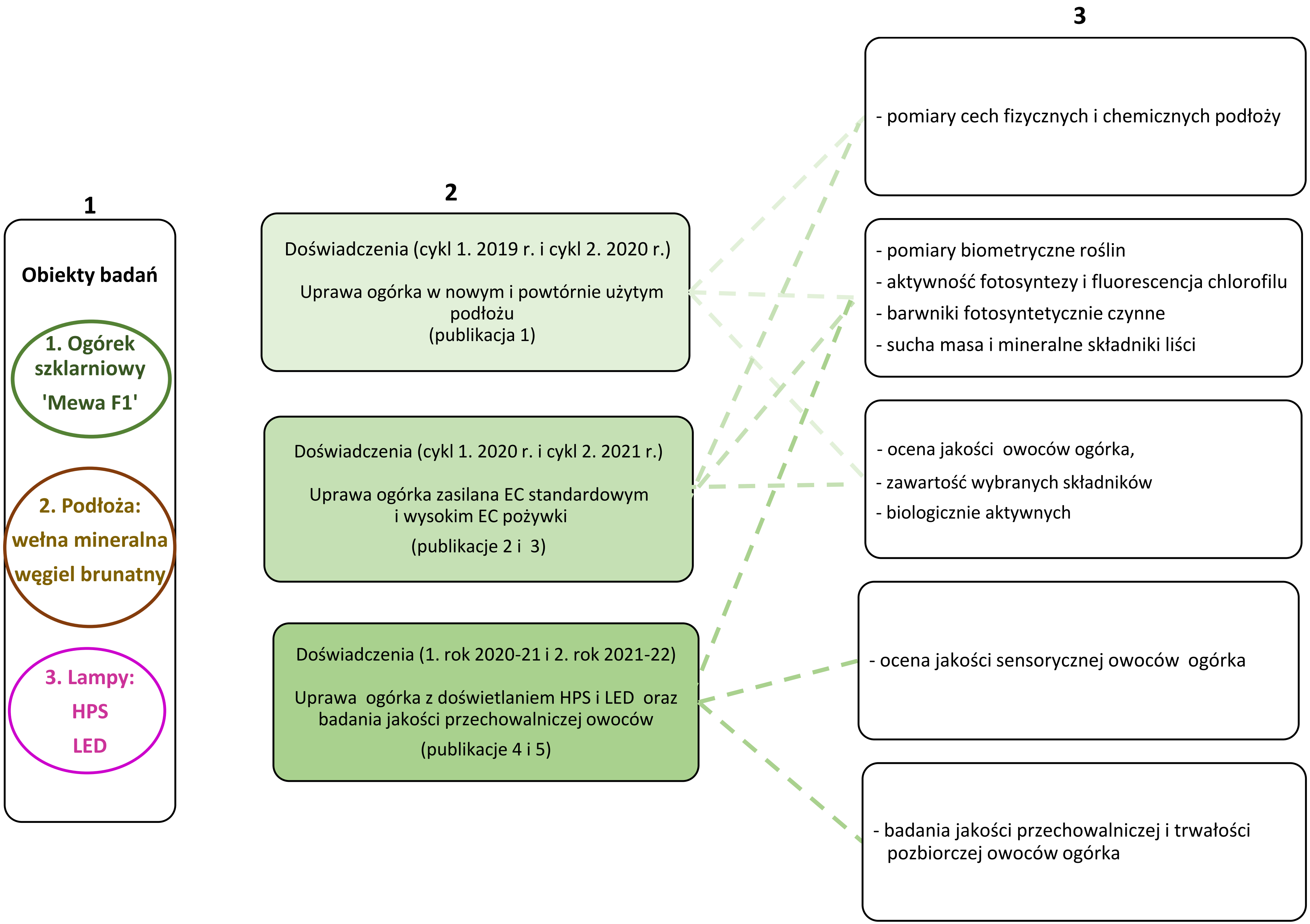
Celem podjętych badań, przedstawionych w załączonych publikacjach, była ocena wpływu podłoża z węgla brunatnego w porównaniu do wełny mineralnej, na wzrost, plon i jakość oraz trwałość pozbiorczą owoców ogórka szklarniowego w uprawie hydroponicznej w różnych warunkach świetlnych. Warunki świetlne różniły się jakością światła poprzez zastosowanie lamp LED, w porównaniu do tradycyjnego doświetlania asymilacyjnego roślin lampami HPS. Badano także cechy jakościowe podłoża i ich wpływ na plonowanie i jakość ogórka, przy stosowaniu mat uprawowych nowych i powtórnie użytych oraz skutki stresu wywołanego wysokim EC pożywki do fertygacji roślin ogórka w zależności od rodzaju podłoża.

Hipotezy badawcze

1. Zastosowanie w uprawie hydroponicznej ogórka biodegradowalnego podłoża z węgla brunatnego, jako alternatywy dla wełny mineralnej, wpływa na plonowanie oraz jakość owoców ogórka.
2. Powtórne użycie mat z węgla brunatnego nie wpływa negatywnie na wzrost roślin, plonowanie i jakość owoców ogórka szklarniowego, jednocześnie ogranicza niepożądane skutki dla środowiska naturalnego.
3. Doświetlanie asymilacyjne w technologii LED wpływa pozytywnie na wzrost i plonowanie oraz jakość owoców ogórka w uprawie hydroponicznej z użyciem węgla brunatnego, jako podłoża stałego.
4. Technologia uprawy hydroponicznej z podłożem organicznym na bazie węgla brunatnego i doświetlaniem asymilacyjnym lampami LED wpływa na jakość pozbiorczą owoców ogórka szklarniowego i wydłuża ich zdolność przechowalniczą.

3. MATERIAŁY I METODY

Badania oceny wpływu podłoża z węgla brunatnego, na wzrost, plon i jakość owoców ogórka szklarniowego prowadzono w technologii uprawy hydroponicznej z doświetlaniem asymilacyjnym. Doświadczenia uprawowe realizowano w latach 2019 – 2023 w Szklarniowym Ośrodku Doświadczalnym SGGW w Warszawie. Porównano efektywność plonowania ogórka w podłożu z węgla brunatnego w stosunku do wełny mineralnej (publikacje 1-4). Badano zmiany fizyko-chemiczne podłoża po zakończeniu uprawy oraz wpływ powtórnego użycia mat z węgla brunatnego na parametry wzrostu roślin, plonowanie i jakość owoców ogórka szklarniowego (publikacja 1). Badano również wpływ wybranych parametrów fizycznych mat z węgla brunatnego na wzrost i rozwój roślin ogórka oraz plon i jego jakość (publikacja 2). Podjęto badania nad wpływem podłoża organicznego (maty uprawowe z węgla brunatnego) w uprawie hydroponicznej na zmniejszanie negatywnych efektów stresu oksydacyjnego u ogórka wywołanego wysokim EC pożywki (publikacja 3). Do doświetlania asymilacyjnego ogórka uprawianego w podłożu z węgla brunatnego w uprawie jesienno-zimowej użyto lamp LED. Porównano efektywność tej technologii uprawy ogórka w warunkach niedoboru światła słonecznego w Polsce z uprawą hydroponiczną ogórka w wełnie mineralnej z doświetlaniem tradycyjnym lampami HPS (publikacja 5). W laboratoriach Katedry Roślin Warzywnych i Leczniczych w INO wykonano badania materiału roślinnego i oceny jakości owoców ogórka bezpośrednio po zbiorze i po przechowywaniu w zależności od warunków uprawy, gdzie oceniono wpływ podłoża z węgla brunatnego na jakość pozbiorczą i zdolność przechowalniczą owoców ogórka szklarniowego (publikacja 4). Na rysunku 1. przedstawiono schemat badań: 1) obiekty badań, 2) terminy wykonanych doświadczeń uprawowych oraz 3) rodzaje prowadzonych pomiarów dotyczących odpowiednio podłoży, roślin i owoców, których wyniki opublikowano w publikacjach nr 1-5, wchodzących w skład rozprawy doktorskiej.



Rys.1. Schemat badań

Szczegółowy opis materiałów i metod użytych do zweryfikowania prawdziwości postawionych hipotez badawczych przedstawiono w publikacjach nr 1-5, wchodzących w skład rozprawy doktorskiej.

3.1. Warunki przeprowadzonych badań

Do badań użyto ogórka szklarniowego odmiany ‘Mewa’ F1 firmy Rijk Zwaan, o owocach długości 20–24 cm i masie 200–240 g. Rośliny uprawiano hydroponicznie w podłożu stałym. Podłoże organiczne użyte w badaniach stanowiły maty z węgla brunatnego Carbomat firmy Carbohort o wymiarach 100 cm × 20 cm × 8 cm. Kontrolę stanowiły maty uprawowe z wełny mineralnej Grotop Matser firmy Grodan o wymiarach 100 cm × 20 cm × 7,5 cm. Do doświetlania asymilacyjnego ogórka zastosowano lampy LED firmy Philips i lampy HPS firmy Gavita. Widmo emitowanego światła przez użyte w badaniach lampy przedstawia wykres S5 i S6.

Badania w szklarni prowadzono w kamerach uprawowych. Parametry mikroklimatu w kamerach kontrolowano za pomocą komputera klimatycznego Ridder HortiMaX-Go (publikacja 1 i 5).

W każdym doświadczeniu rozsadę ogórka przygotowano wysiewając nasiona bezpośrednio do kostek rozsadowych z wełny mineralnej, które zostały nasączone pożywką o pH 5,4 i EC 1,8 $dS \cdot m^{-1}$. Rozsadę doświetlano lampami HPS (Gavita GAN 600 W) przy poziomie światła średnio 170 $\mu mol\ m^{-2} \cdot s^{-1}$ PPFD przez 16 h na dobę. Średnia temperatura powietrza wynosiła D/N 22/21°C, a średnia dobowa wilgotność względna powietrza (RH) około 60–70% i stężenie CO_2 średnio 800 ppm (publikacja 1 i 5). Gotową rozsadę ogórka sadzono na wcześniej przygotowane maty uprawowe. Maty uprawowe na 48 godzin przed sadzeniem rozsady zalewano pożywką (8 dm^3 na matę$^{-1}$) o EC 2,0 $dS \cdot m^{-1}$ i pH 5,5. Po upływie tego czasu, w matach z wełny mineralnej wykonywano otwory drenażowe poprzez nacięcia podłużne jej krótszych boków (przez całą szerokość maty) oraz dwa 4 cm pionowe nacięcia na środku maty (dłuższe boki maty), po jednym z każdej strony maty, zaczynając cięcie od dołu maty. W matach z węgla brunatnego wykonano dwa pionowe nacięcia drenażowe (każdy o długości 5 cm), przecinając folię z tworzywa sztucznego na każdym z dłuższych boków maty, zaczynając nacięcie na wysokości 1 cm od spodu maty. Pożywkę do fertygacji przygotowano z nawozów mineralnych jedno-i dwuskładnikowych, przeznaczonych do upraw hydroponicznych. Skład pożywki podstawowej zastosowany w uprawie ogórka zawierał (mg·dm^{-3}): N-NO_3 230, N-NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15, B 0.33 i Mo 0.05 (publikacja nr 1-5). Pożywkę dozowano przy pomocy automatycznego systemu dozowania nawozów FertiMiX-Go, wyposażonego w sterownik HortiMaX-Go. W badaniach także korzystano z urządzenia dozującego typu Dosatron (D25RE2 0,2–2%) (publikacja 2 i 3).

Owoce ogórka w fazie dojrzałości zbiorczej zbierano z częstotliwością, co drugi dzień. W badaniach nad zdolnością przechowalniczą i trwałością pozbiorczą, owoce ogórka przechowywano w chłodni oraz w pomieszczeniu o temperaturze pokojowej, symulując warunki sprzedaży na półce sklepowej (publikacja 4).

3.2. Terminy i czynniki agrotechniczne przeprowadzonych badań

Publikacja 1: Przygotowując rozsadę ogórka, nasiona wysiewano w dniu 20 listopada 2019 r. w pierwszym cyklu uprawy oraz 26 czerwca 2020 r. w drugim cyklu. Pierwszy cykl uprawy prowadzono przez 12 tygodni, drugi przez 9 tygodni. W pierwszym cyklu dobowa suma promieniowania słonecznego wyniosła średnio 134,0 J/cm^2, a rośliny ogórka doświetlano lampami sodowymi przez 16 h dziennie, uzyskując poziom światła średnio 220 μmol·m^{-2} s^{-1} PPFD (fot. S1 i S2). Lampy wyłączały się automatycznie przy poziomie promieniowania słonecznego 250 W m^{-2}. W drugim cyklu uprawy średnie dzienne promieniowanie słoneczne wynosiło 1474,9 J/cm^2 (wyk. S3 i S4). Temperatura w okresie wegetacyjnym pierwszym i drugim wyniosła odpowiednio, średnio D/N 24/21°C i D/N 25/22°C, a wilgotność powietrza i stężenie CO_2 średnio RH 60–70% i CO_2 800 ppm w obu cyklach uprawy.

Publikacja 2-3: Gotowa rozsada ogórka po 28 dniach od siewu w pierwszym roku badań została posadzona do mat uprawowych w dniu 10 lipca 2020 r., a w drugim – 12 lipca 2021 r.. W obu cyklach posadzono po 3 rośliny ogórka do każdej maty. Uprawy prowadzono do 35. tygodnia roku. W roku 2020 w okresie prowadzenia uprawy, średnia dobowa suma promieniowania słonecznego wyniosła 1474,9 J cm^{-2}, średnia temperatura D/N wynosiła 25/23°C, a wilgotność powietrza i stężenie CO_2 w kamerach doświadczalnych kształtowały się odpowiednio na poziomie około 70% i 800 ppm. W drugim roku eksperymentu średnie dobowe promieniowanie słoneczne wyniosło

1407,0 J cm^{-2}, temperatura D/N 25/22°C, a wilgotność powietrza i stężenie CO_2 w kamerach doświadczalnych wynosiły odpowiednio około 70% i 800 ppm. W każdym roku badań, 7 dni po posadzeniu rozsady do mat uprawowych, zmieniano EC pożywki dla połowy roślin w doświadczeniu poprzez dozowanie pożywki o wysokim EC, wynoszącym około 7 $dS \cdot m^{-1}$ i pH 5,5–5,8. Porównano cztery warunki eksperymentu: 1) MW/kontrola EC – wełna mineralna i pożywka o EC 3,1 $dS \cdot m^{-1}$, 2) L/kontrola EC – węgiel brunatny i pożywka o EC 3,1 $dS \cdot m^{-1}$, 3) MW/wysokie EC – wełna mineralna i pożywka o EC 7 $dS \cdot m^{-1}$, 4) L/wysokie EC – węgiel brunatny i pożywka o EC 7 $dS \cdot m^{-1}$. Doświadczenia założono metodą bloków losowych, w 3 powtórzeniach po 9 roślin w każdym powtórzeniu. Pożywkę dozowano za pomocą systemu nawodnieniowego, w oparciu o rzeczywiste pomiary promieniowania słonecznego i zawartość wody w podłożu. Rośliny prowadzono w systemie wysokiego drutu, na jeden pęd. Dwa razy w tygodniu z pędu owocującego usuwano wszystkie pędy boczne i wąsy czepne, a także 3 najstarsze liście z każdej rośliny. Zarówno w pierwszym, jak i drugim roku badań usuwano pierwsze zawiązki owoców do 4. liścia.

Publikacja 4-5: Rośliny ogórka posadzono w 42 tygodniu roku 2021, po 6 sztuk na matę, uzyskując zagęszczenie 2,7 sztuk na m^2 powierzchni użytkowej w kamerze uprawowej. Rośliny doświetlano lampami HPS 18 szt. (top lighting - Gavita GAN 600 W) (kontrola) oraz lampami LED 24 szt. (top lighting- Philips Green Power LED (DR/W - LB, 195 W) + interlighting - 2 linie diod LED z 18 szt. Philips Green Power LED, moduł 2,5 m HO DR/B 100 W). Rośliny ogórka doświetlano przez 16 godzin na dobę, a warunki świetlne pod względem PAR były w każdej kamerze utrzymywane na poziomie ~320 $\mu mol\ m^{-2}\ s^{-1}$ PPFD. Lampy umieszczone nad wierzchołkami roślin wyłączały się automatycznie przy poziomie promieniowania słonecznego 250 W/m^{-2}. Temperatura oraz inne parametry mikroklimatu zostały ustawione i utrzymywane na poziomie 23/21°C D/N, wilgotność względna powietrza RH 70% i CO_2 800 ppm. Pożywkę dozowano w cyklach interwałowych w ilości od 0.8 do 2.5 dm^3 na roślinę, w zależności od fazy rozwojowej rośliny. Nawadnianie rozpoczynano o godzinie 6:00, a kończono o godzinie 20:00. Po posadzeniu rozsady, z każdej rośliny usunięto pięć pierwszych zawiązków. Rośliny prowadzono przy sznurkach metodą wysokiego drutu, usuwając z pędu owocującego wszystkie pędy boczne oraz wąsy czepne. W okresie owocowania roślin usuwano co drugi zawiązek na pędzie przewodnikowym. W pełni owocowania roślin, co 3 dni usuwano dolne, najstarsze liście (maksymalnie 3 jednorazowo). Do badań szczegółowych wybrano losowo z każdej kombinacji po 6 mat uprawowych (36 roślin), czyli 3 powtórzenia, każde po 2 maty uprawowe (12 roślin w powtórzeniu).

3.3. Zakres wykonanych prac

Publikacja 1: Zbadano wybrane parametry morfologiczne roślin dokonując co 7 dni pomiarów na wybranych losowo 6 roślinach testowych z każdej kombinacji. Mierzono takie parametry jak: tygodniowy przyrost pędu na długość, całkowitą długość pędu, średnicę pędu, długość i szerokość liścia oraz długość ogonka liściowego w pełni rozwiniętego 4. liścia, licząc od wierzchołka rośliny. Wykonano pomiary względnej zawartości chlorofilu w liściach metodą SPAD. Dokonano również pomiarów twardości owocu oraz barwy skórki owocu ogórka. Oceniano w owocach ogórka zawartość związków bioaktywnie czynnych, suchej masy oraz rozpuszczalnych substancji stałych (TSS). Właściwości fizyczne podłoża (mata z węgla brunatnego), oznaczono po odpowiednim przygotowaniu próbek do analiz, gdzie zawartość materii organicznej po spaleniu próbki, oznaczono zgodnie z normą PN-EN 13039 Porowatość, gęstość podłoża oraz zawartość wody i powietrza obliczono zgodnie z normą PN-EN 13041. W podłożu z wełny mineralnej określano kurczliwość podłoży poprzez określenie ubytku objętości. W normie PN-EN 13039 oznaczono także zawartość materii organicznej i popiołu, niezbędną do obliczenia porowatości całkowitej w normie PN-EN 13041.

Publikacja 2: Określono wpływ właściwości fizycznych i fizykochemicznych podłoża na morfologię i zawartość makro- i mikroelementów w liściach roślin ogórka. Zbadano również wpływ podłoża na plon oraz jego jakość. Badano zawartość suchej masy azotanów, TSS i związków bioaktywnych (luteina, β-karoten, chlorofil a i b) w owocach ogórka. Właściwości fizyczne podłoża z wełny mineralnej oraz węgla brunatnego określano zgodnie z normami PN-EN 13039 oraz PN-EN 13041, odpowiednio dla danego podłoża.

Publikacja 3: W badaniach określono wpływ podłoża oraz eustresu wysokiego EC pożywki na parametry morfologiczne roślin, takie jak tygodniowy przyrost pędu na długość, średnicę pędu w dwóch miejscach na pędzie pomiędzy 4. i 5. oraz 9. i 10. w pełni rozwiniętym liściem, licząc od wierzchołka pędu. Mierzono także długość i szerokość liścia oraz długość ogonka liściowego. Ważono także świeżą masę usuniętych liści, pędów bocznych oraz wąsów czepnych, aby określić produktywność roślin. W przeprowadzonych badaniach określono względną zawartość chlorofilu w liściach ogórka metodą SPAD, szybkość fotosyntezy netto (PN), przewodność szparkową (gs) i szybkość transpiracji (E). Dodatkowo na podstawie ilorazu PN/E oraz PN/gs obliczono odpowiednio fotosyntetyczny współczynnik wykorzystania wody (WUE) i chwilowy fotosyntetyczny współczynnik wykorzystania wody (iWUE). Dokonano pomiarów fluorescencji chlorofilu określając takie parametry jak Fs − wydajność fluorescencji w stanie ustalonym, Fm' − maksimum fluorescencji dostosowanej do światła oraz ΦPSII − maksymalna wydajność kwantowa PS II. Maksymalną wydajność kwantową PSII − (Fv/Fm) uzyskano po 30-minutowej adaptacji liści do ciemności. Określono również zawartość suchej masy w liściach i barwników fotosyntetycznych (luteina, β-karoten, chlorofil a i b) oraz wielkość i jakość plonu ogórka.

Publikacja 4: W przeprowadzonych badaniach określono wpływ mat z węgla brunatnego, doświetlania asymilacyjnego lampami LED oraz sposobu przechowywania owoców, na jakość owoców ogórka od zbioru po symulowany obrót. Materiał badawczy stanowiły owoce bezpośrednio zebrane z roślin. Określono procentowy ubytek masy owoców, jędrność owocu, zawartość suchej masy oraz azotanów i TSS w owocach przechowywanych w warunkach symulowanego obrotu. Przeprowadzono również analizę sensoryczną owoców po przechowywaniu w chłodni oraz w temperaturze otoczenia, symulując warunki sprzedaży na niechłodzonej półce sklepowej. W ocenie ogólnej oceniono następujące wyróżniki jakości owoców ogórka: zapach, barwa miąższu, tekstura oraz smak. Ocena ogólna dotyczyła ogólnego wrażenia sensorycznego odbieranego przy ocenie próbki, które obejmowało ocenione wyróżniki tekstury i smaku, skala: zła – bardzo dobra.

Publikacja 5: W badaniach określono wpływ podłoża z węgla brunatnego oraz doświetlania lampami LED i HPS na parametry morfologiczne i fizjologiczne oraz jakość i plonowanie ogórka w uprawie hydroponicznej w porównaniu z podłożem z wełny mineralnej. Podczas prowadzenia uprawy raz w tygodniu mierzono wybrane parametry morfologiczne, takie jak: tygodniowy przyrost pędu na długość, całkowitą długość pędu, średnicę pędu w dwóch miejscach na pędzie pomiędzy 4. i 5. oraz 9. i 10. w pełni rozwiniętym liściem, licząc od wierzchołka pędu. Mierzono także długość i szerokość liścia oraz długość ogonka liściowego. Określono względną zawartość chlorofilu w liściach ogórka metodą SPAD, szybkość fotosyntezy netto (PN), przewodność szparkową (gs) i szybkość transpiracji (E). Dokonano pomiarów fluorescencji chlorofilu a liści ogórka, określając takie parametry, jak maksymalna wydajność kwantowa PS II (ΦPSII), i maksymalna wydajność kwantowa PSII po adaptacji do ciemności − (Fv/Fm). Badano także stopień odżywienia roślin analizując zawartość makro i mikroelementów w liściach ogórka. Określono wielkość i jakość plonu ogórka. Zbadano zawartość suchej masy, rozpuszczalnych substancji stałych (TSS), związków bioaktywnych (*β*-karoten, luteina, chlorofil *a* i *b*) i azotanów w owocach ogórka oraz twardość/jędrność owoców.

3.4. Metody badawcze

3.4.1. Właściwości fizyczne i fizykochemiczne podłoża

Właściwości fizyczne podłoża z węgla brunatnego określono zgodnie z normą PN-EN 13041. Właściwości wodno-powietrzne badano na aparacie piaskowym „Eijkelkamp”, w zakresie podciśnienia 0–100 cm H_2O, stosując 24-godzinny czas ustalenia równowagi wodnej na każdym z 5 poziomów podciśnienia (-3,2, -10, -32, -50 i -100 cm H_2O). Po zakończeniu oznaczeń aparatem piaskowym próbki suszono w temperaturze 105°C i określano kurczliwość podłoży poprzez określenie ubytku objętości. Zawartość materii organicznej oznaczono po spaleniu próbki zgodnie z normą PN-EN 13039. Porowatość, gęstość podłoża oraz zawartość wody i powietrza obliczono zgodnie z normą PN-EN 13041.

Właściwości fizyczne mat z wełny mineralnej określono metodą opracowaną w Naaldwijk w Niderlandii (Wever 2000, Strojny i Nowak 2005, Nowak 2010). Próbki moczono przez 24 h ± 2 h, następnie odsączono wodę i pozostawiono w tym stanie na 3 h. Po tym czasie próbki ponownie zalewano wodą destylowaną w tym samym pojemniku przez 30 min, a następnie bezpośrednio po odsączeniu wody przenoszono je do bloku piaskowego (Eijkelkamp) i ustawiano próżnię -100 cm H_2O na 30 min. Następnie próbki ponownie zalewano na głębokość 3 cm nad próbką, moczono przez 24 h ± 2 h i przystąpiono do oznaczania właściwości powietrzno–wodnych w zakresie próżni 0–100 cm H_2O, stosując 24-godzinny czas ustalenia równowagi wodnej na każdym z 5 poziomów podciśnienia (-4,5, -10, -32, -50 i -100 cm H_2O). Po zakończeniu oznaczeń aparatem piaskowym próbki suszono w temperaturze 103°C ± 2°C i określano kurczliwość podłoży poprzez określenie ubytku objętości. Zgodnie z normą PN-EN 13039 (2011) oznaczono także zawartość materii organicznej i popiołu, niezbędną do obliczenia porowatości całkowitej zgodnie z normą PN-EN 13041 (2011).

3.4.2. Parametry morfologiczne roślin

W celu pomiaru tygodniowego przyrostu pędu na długość, mierzono odległość od wierzchołka pędu do miejsca zaznaczonego na sznurku, gdzie znajdował się wierzchołek pędu 7 dni wcześniej. Wynik podawano w cm. Średnicę pędu mierzono elektroniczną suwmiarką w mm w dwóch miejscach pędu: pomiędzy 4. i 5. oraz 9. i 10. w pełni rozwiniętym liściem, licząc od wierzchołka rośliny. Długość i szerokość oraz długość ogonka liściowego piątego i dziesiątego liścia podano w cm. Przybliżoną powierzchnię liścia 5. i 10. obliczono z iloczynu długości i szerokości liścia, wynik podano w cm^2. Określono także tygodniowy przyrost liczby liści na roślinie (szt./tydzień).

3.4.3. Wymiana gazowa i fluorescencja chlorofilu

Względną zawartość chlorofilu w liściach określono testem SPAD (Soul Plant Analysis Systems) przy użyciu przenośnego miernika Minolta SPAD-502 Plus. Pomiaru indeksu SPAD dokonano na 5. i 10. w pełni rozwiniętym liściu, licząc od wierzchołka pędu rośliny. Szybkość fotosyntezy netto (PN), przewodność szparkową (gs) i szybkość transpiracji (E) zmierzono przy użyciu systemu fotosyntezy LI-6400 (LI-COR, Inc., Lincoln, NE, USA) wyposażonego w 6400-40 fluorometr z komorą liściową i mieszalnik CO_2 6400-01. Pomiary wykonano przy referencyjnym stężeniu CO_2 (500 $\mu mol \cdot s^{-1}$), stałym natężeniu przepływu (400 $\mu mol \cdot s^{-1}$), wilgotności względnej pomiędzy 30% a 50% i gęstości strumienia fotosyntetycznego fotonów (PPFD, 1000 mmol m^{-2} s^{-1}). Fluorescencję chlorofilu mierzono przy użyciu przenośnego systemu monitorowania fluorescencji chlorofilu z modulacją impulsów FMS-2 (Hansatech Instruments Ltd., King's Lynn, Norfolk, Wielka Brytania), mierząc parametry takie jak: Fs – stan wydajności fluorescencji, Fm' - maksimum fluorescencji dostosowanej do światła i ΦPSII - maksymalna wydajność kwantowa PS II. Maksymalną wydajność fotosystemu PS II w ciemności (Fv/Fm) mierzono po 30-minutowej adaptacji liści do ciemności. Do pomiaru fluorescencji bezpośredniej zastosowano przenośny miernik fluorescencji PEA (Hansatech Instruments Ltd., King's Lynn, Norfolk, Wielka Brytania).

3.4.4. Zawartość makro- i mikroelementów w liściach ogórka

Liście pobierane do analiz były bez oznak uszkodzeń, chorób i szkodników, wykształcone prawidłowo o właściwej barwie. Pobierano je losowo z każdej kombinacji w liczbie trzech liści z wysokości 4.-5. i trzech liści z wysokości 9.-10. liścia na pędzie, licząc od wierzchołka pędu ogórka. Blaszki liściowe suszono w temperaturze 60°C, w suszarce laboratoryjnej z obiegiem powietrza, a następnie mielono w młynku Bosch TSM6A013B. Zmielony materiał roślinny spalano w HNO_3. Pierwiastki (P, K, Mg, S-SO_4, Na, Ca, Fe, Mn, Cu, Zn, B,) oznaczono za pomocą spektrometru plazmowego ze sprzężeniem indukcyjnym (ICP Model OPTIMA 2000DV, Perkin Elmer, Waltham, MA, USA), uzyskując wyniki w $mg \cdot kg^{-1}$ s.m. W celu oznaczenia azotu całkowitego materiał roślinny trawiono w stężonym kwasie siarkowym w obecności katalizatora miedziowo-potasowego. Zawartość azotu oznaczano za pomocą aparatu Kijeldahla (Vapodest, Gerhardt, Königswinter, Niemcy). Po destylacji azotu w postaci NH_3 zawartość N oznaczono metodą miareczkowania (AOAC 2012), uzyskując wyniki w % suchej masy.

3.4.5. Plon i jakość owoców

Owoce ogórka dojrzałe do zbioru zbierano co dwa dni (w godzinach porannych). Określono liczbę i masę wszystkich zebranych owoców, owoców handlowych i niehandlowe. Mianem owoców niehandlowych określano takie owoce, które posiadały wady rozwojowe oraz uszkodzenia mechaniczne występujące podczas pielęgnacji roślin. Oszacowano także sumę zawiązków owoców i zawiązków owoców „zrzuconych”. Do badań jędrności oraz barwy owoców wybierano losowo owoce handlowe. Jędrność owoców mierzono twardościomierzem HPE o średnicy trzpienia 5 mm, ustawionego pod kątem 90° do owocu, uśredniając wynik z 3 pomiarów: przy szypułce, w środku owocu i w części przykwiatowej. Wyniki podano w skali HPE od 0 do 100 jednostek. Barwę owoców mierzono za pomocą przenośnego spektrofotometru światła odbitego MiniScan XE PLUS D/8-S skalibrowanego na standardowej białej płytce, a wyniki podano w skali CIE Lab: zmiany udziału barwy zielonej i czerwonej reprezentuje parametr a*; barw niebieskiej i żółtej parametr b* i jasność barwy parametr L*. Z uzyskanych danych wyliczono także współrzędne biegunowe nasycenia C* = (a* 2 + b* 2) ½ , intensywność koloru (kąt barwy) H* = tan −1 (b*/a*) i wskaźnik barwy (stosunek a*/b*). Barwę i jędrność owoców mierzono w 3 powtórzeniach.

3.4.6. Zawartość suchej masy i barwników fotosyntetycznych w liściach oraz związków bioaktywnych w owocach ogórka

Liście pobierane do analiz były bez oznak uszkodzeń, chorób i szkodników, wykształcone prawidłowo o właściwej barwie. Pobierano losowo z każdej kombinacji po 3 liście. Zawartość suchej masy w liściach oznaczono metodą wagową w temperaturze 105°C. Tak samo oznaczano zawartość suchej masy w owocach, po wcześniejszej homogenizacji losowo wybranych owoców. Zawartość *β*-karotenu, luteiny oraz chlorofilu *a* i *b* w liściach i owocach oznaczono metodą wysokosprawnej chromatografii cieczowej HPLC (Shimadzu Scientific Instruments). Materiał analityczny ogórka homogenizowano z dodatkiem 2 g Na_2SO_4 na 100 g^{-1} próbki. Tak przygotowany materiał homogenny odważano na wadze laboratoryjnej w ilości 2 g (liście) i 5 g (owoce), a następnie rozcierano w moździerzu z zimnym acetonem (-20°C) i piaskiem kwarcowym. Wyekstrahowane próbki przeniesiono ilościowo do kolb miarowych o pojemności 50 ml i uzupełniano do objętości 50 ml zimnym acetonem. Próbki odwirowywano w probówkach (15 000 obr/min), a powstały supernatant przefiltrowano przez filtr strzykawkowy 0,22 µm (Supelco IsoDisc™ PTFE 25 mm x 0,22 µm). Ekstrakty umieszczono w 1 ml pojemnikach w automatycznym podajniku próbek SIL-20AC HT (temperatura tacy 4°C). Ekstrakt o objętości 5 µl naniesiono na kolumnę chromatograficzną Kinetex 2,6 µm C18 100 Å 100 mm x 4,6 mm firmy Phenomenex. Rozdzielenie związków uzyskano stosując elucję izokratyczną metanolem w temperaturze 40°C. Zakres długości fal wynosił odpowiednio dla *β*-karotenu, chlorofilu a i b: 450 nm, 430 nm i 470 nm. Z otrzymanych wyników dla chlorofilu *a* i *b* obliczono sumę chlorofilu *a* i *b*. Wszystkie analizy przeprowadzono trzykrotnie w trzech powtórzeniach każde.

3.4.7. Zawartość azotanów i TSS w owocach

Do oznaczenia zawartości azotanów w owocach wybierano losowo z każdej kombinacji owoce handlowe, próbka owoców o przybliżonej masie łącznej około 1 kg. Następnie poddano je homogenizacji. Z tak przygotowanej próbki mieszanej, pobrano trzykrotnie próbkę zhomogenizowanych owoców o masie 10 g, dodając 0,5 g węgla aktywnego i 100 ml 2% kwasu octowego, a następnie wytrząsano na wytrząsarce laboratoryjnej. Po 30 minutach powstały roztwór przesączono przez filtr karbowany. Zawartość azotanów w mg $NO_3 \cdot kg^{-1}$ świeżej masy w owocach oznaczono spektrofotometrycznie przy długości fali 540 nm za pomocą analizatora Fiastar 5000. Zawartość składników rozpuszczalnych w soku komórkowym (TSS) oznaczono refraktometrycznie używając refraktometru cyfrowego (Hanna Instruments HI-96800), podając wyniki w %.

3.4.8. 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). Ocenę owoców wykonano bezpośrednio po zbiorze owoców oraz po przechowywaniu w chłodni (5 dni) i po 5 dniach w warunkach symulowanego obrotu (po 10 dniach od zbioru). Owoce przechowywano w chłodni w temperaturze 12°C i HR 85-90%, natomiast symulując sprzedaż na półce sklepowej, owoce przetrzymywano w temperaturze 22°C i HR 60%. Próbki owoców zostały ocenione przez wykwalifikowany zespół 10 osób pod kątem wyróżników zapachu, barwy, tekstury oraz smaku, dokonano również oceny ogólnej. Do oceny owoców ogórka wykorzystano metodę ilościowej analizy opisowej (QDA) – profilowania sensorycznego. Wyróżniki oceniano na ciągłej skali graficznej od 0-10 jednostek umownych, oznaczonej odpowiednimi określeniami. Szczegółowa metodyka znajduje się w publikacji 4, stanowiącej element rozprawy doktorskiej.

3.4.9. Analiza statystyczna

Do opracowania statystycznego uzyskanych wyników badań wykorzystano między innymi program Statgraphics Centurion XVII 2016 (publikacja 1). Dane oceniano metodą analizy wariancji jedno i wieloczynnikowej (ANOVA), a różnice pomiędzy średnimi porównywano testem Tukeya (HSD) na poziomie istotności $p < 0,05$. Analizy statystyczne przeprowadzono głównie przy użyciu programu Statistica 13.3. Przed analizą danych sprawdzano, czy osiągnięto założenia ANOVA dotyczące jednorodności wariancji. Do oceny jednorodności wariancji wszystkich badanych parametrów wykorzystano test Levene'a. (publikacja 2, 3, 4, 5). Analizę regresji wielokrotnej wykonano w celu sprawdzenia związku między cechami biometrycznymi roślin a wybranymi cechami fizycznymi substratów. Dla każdej pary parametrów obliczono współczynnik korelacji liniowej (publikacja 2). W celu określenia związku między wynikami oceny sensorycznej a wieloczynnikowymi różnicami w kombinacjach podłoża i oświetlenia w publikacji nr 4 wykorzystano analizę głównych składowych (PCA).

4. WYNIKI I DYSKUSJA

4.1. Właściwości fizyczne mat z węgla brunatnego i ich wpływ na wybrane parametry wzrostu roślin oraz plon ogórka szklarniowego

Obecne problemy z rosnącym zapotrzebowaniem na żywność oraz wymagania rolnictwa, nadmierne użycie nawozów sztucznych i niewłaściwa gospodarka rolna doprowadziły do degradacji gleb w Europie (Virto i in. 2014). W związku z niekorzystnym działaniem człowieka, liczba gruntów nadających się pod uprawy spada, dlatego uprawa hydroponiczna z wykorzystaniem podłoża stałego jest dla wymagających upraw ogrodniczych korzystnym rozwiązaniem (Abdel-Farid i in. 2020, Kamran i in. 2019). Podłoże to jeden z wielu czynników determinujących powodzenie uprawy i jakość plonu. Decydując się na wybór odpowiedniego podłoża należy mieć na względzie przede wszystkim jego właściwości fizyczne, trwałość, łatwość utylizacji oraz niską cenę (Saha i in. 2016, Kraska i in. 2018, Xing i in. 2019). Analizując wpływ nowych oraz powtórnie użytych mat z wełny mineralnej oraz węgla brunatnego w uprawie ogórka, w przypadku mat nowych nie odnotowano różnic w tygodniowym przyroście pędu ogórka na długość czy długości i szerokości liści oraz ich powierzchni asymilacyjnej i długości ogonka liściowego. Stwierdzono, że powierzchnia liści oraz średnica pędu ogórka nie zależy od rodzaju zastosowanego podłoża, niezależnie od cyklu użytkowania, czy jako podłoże nowe w pierwszym cyklu, czy powtórnie użyte w kolejnym cyklu uprawy (publikacja 1). Natomiast analizując wpływ gęstości nasypowej oraz porowatości podłoża z węgla brunatnego, stwierdzono istotne zależności pomiędzy właściwościami podłoża a parametrami morfologicznymi roślin ogórka (publikacja 2). Nowe maty z węgla brunatnego charakteryzowały się dużą gęstością nasypową i niską porowatością oraz zawartością wody łatwo dostępnej dla roślin. Badając wpływ tych parametrów na rośliny, stwierdzono ujemną korelację pomiędzy gęstością nasypową mat z węgla brunatnego a przyrostem liczby liści na tydzień, średnicą pędu, długością ogonka liściowego oraz powierzchnią liści (publikacja 2). Inni badacze wskazują, że podłoże i jego właściwości nie miały wpływu na średnicę pędu roślin pomidora (Mohammadi-Ghehsareh 2015), ale powierzchnia liści i ich liczba jest istotnie zależna od pojemności wodnej i wody łatwo dostępnej dla roślin (Dannehl i in. 2015). Dodatnią korelację stwierdzono pomiędzy porowatością podłoża, a liczbą liści wyrastających na pędzie w ciągu tygodnia (publikacja 2). Stwierdzono również, że gęstość nasypowa oraz zawartość wody łatwo dostępnej dla roślin wpływa na zawartość makro- i mikroelementów w liściach ogórka. Odnotowano dodatnią korelację w zawartości Ca oraz S-SO_4 w liściach ogórka rosnącego w węglu brunatnym. Zdolność zatrzymywania wody i woda łatwo dostępna dla roślin, to czynniki mogące znacząco wpływać na parametry morfologiczne roślin i stan ich odżywienia (Mazahreh i in. 2015). Nowa mata z wełny mineralnej charakteryzowała się małą gęstością nasypową, dużą porowatością całkowitą oraz dużą pojemnością wodno-powietrzną przy potencjale −10 cm H_2O, jednakże w trakcie uprawy straciła te właściwości, co wiązało się ze wzrostem gęstości nasypowej i zmniejszeniem zawartości powietrza. W przypadku mat z węgla brunatnego po 2 cyklach uprawy nie obserwowano aż tak niekorzystnych zmian jak w przypadku wełny mineralnej. Krzywa retencji wody pokazuje, że największe zmiany zawartości wody były przy potencjale −10 cm H_2O w obu podłożach, jednak dla wełny mineralnej zmiany dotyczyły również wyższych potencjałów (publikacja 1). Zawartość składników mineralnych w podłożu podlega zmianie w czasie uprawy, a zmiany te są szybkie i zależne od sposobu nawożenia, uwodnienia maty oraz właściwości powietrzno-wodnych, a także mikroklimatu panującego w obiekcie (Argo i Biernbaum 1994; Słowińska-Jurkiewicz i Jaroszuk-Sierocińska 2011). Natomiast zmiany zawartości pierwiastków w liściach są minimalne i zachodzą powoli. Zawartość składników w liściach zależy również od pH środowiska korzeniowego, antagonizmu pierwiastków względem siebie oraz strategii nawodnieniowej (Nurzyński 2013, Machado i Serralheiro 2017, Francke i in. 2021, Tuckeldoe i in. 2023). Jak podaje literatura, właściwości fizyczne odpowiedniego podłoża dla roślin mieszczą się w przedziale: objętość wody łatwo dostępnej 20–30%, porowatość całkowita ≥85% obj. i całkowita zdolność zatrzymywania wody 10–30% objętości (Dannehl i in. 2015, Kennard i in. 2020). Pomimo niższych wartości wskazanych parametrów w matach z węgla brunatnego, odnotowano istotną zależność gęstości nasypowej oraz pojemności wodnej podłoża na liczbę i masę owoców zebranych z roślin ogórka, gdzie uzyskano o 10% wyższy plon całkowity w porównaniu do wełny mineralnej (publikacja 2). Uzyskane wyniki są zgodne z badaniami Mazahreh i in. (2015), którzy stwierdzili, że plon ogórka zależy od dostępności wody w podłożu, a Allaire i in. (2005) potwierdzili także dodatnią korelację plonu handlowego pomidora z zawartością w podłożu wody łatwo dostępnej. Analizując wpływ powtórnie użytych mat z wełny mineralnej oraz węgla brunatnego, stwierdzono większą liczbę i masę owoców pozyskanych z roślin rosnących w wełnie mineralnej w I cyklu uprawowym. Jednak w II cyklu uprawy, z powtórnym użyciem podłoży, największą masę całkowitą owoców uzyskano z roślin rosnących na powtórnie użytym podłożu z węgla brunatnego. Zmiany zawartości powietrza oraz wody w macie mogły bezpośrednio przełożyć się na uzyskany plon owoców ogórka. Może to być spowodowane osiadaniem podłoża, zjawiskiem postępującym wraz z długością okresu uprawy (Nowak 2010) lub z rozwojem i zwiększaniem masy przez system korzeniowy (Raviv i in. 2002). W trakcie dłuższej uprawy w wełnie mineralnej obserwuje się wzrost gęstości nasypowej oraz zmniejszenie porowatości całkowitej, co potwierdzono w przeprowadzonych badaniach (publikacja 1). Zmiany te bezpośrednio wpływają na wzrost roślin i owoców w dłuższym okresie uprawy (Verdonck i in. 1984, Millaleo i in. 2010, Nowak 2010). Według Luitel i in. (2012), brak odpowiedniej ilości powietrza i wody w podłożu, ogranicza oddychanie korzeni i negatywnie oddziałuje na pobieranie wody i składników odżywczych, co z kolei wpływa na liczbę, masę oraz jakość owoców. Jakość owoców zależy od wielu czynników, począwszy od wyboru odmiany i terminu uprawy, sposobu prowadzenia rośli i ich pielęgnacji, poprzez liczbę owoców na roślinie, aż po parametry klimatu i właściwości podłoża (Gómez-López i in. 2006, Gajc-Wolska i in. 2010, Kraska i in. 2018, Yang i in. 2023). W przedstawionych badaniach stwierdzono silnie dodatnią korelację gęstości nasypowej i pojemności wodnej podłoża na jędrność oraz barwę skórki owoców ogórka (publikacja 2). Natomiast Dannehl i in. (2015). badając podłoża organiczne takie jak wełna owcza, włókno konopne oraz torf nie potwierdzili ich wpływu na jakość owoców pomidora.

4.2. Wpływ mat z węgla brunatnego i wybranych czynników uprawy na parametry morfologiczne i intensywność fotosyntezy roślin, fluorescencję chlorofilu oraz plon i jakość owoców ogórka

4.2.1. Wysokie EC pożywki

Pomimo kontroli wszystkich parametrów wzrostu w uprawach hydroponicznych może dochodzić do nadmiernego stężenia jonów w podłożu, co w konsekwencji negatywnie wpływa na wzrost i rozwój roślin. Według Chen i in. (2020) rośliny ogórka tolerują przewodność elektryczną (EC) do poziomu 2,5 $dS{\cdot}m^{-1}$, a wzrost EC o każdą jednostkę powoduje obniżenie plonu o ponad 10%. Prócz obniżenia plonu, wzrost zawartości soli w podłożu powoduje zmniejszenie syntezy pigmentów fotosyntetycznych, między innymi chlorofilu (Abdel-Farid i in. 2020, Chen i in. 2020). Według Mohsin i in. (2019) oraz Abdel-Farid i in. (2020), zbyt wysokie EC podłoża prowadzi do zakłóceń syntezy pierwotnych i wtórnych metabolitów, a także jak donoszą Kamran i in. (2019) i Mohsin i in. (2019) do nagromadzenia reaktywnych form tlenu (ROS). W badaniach, używając do fertygacji roślin ogórka rosnących w matach z wełny mineralnej, EC pożywki w wysokości 7,0 $dS·m^{-1}$, uzyskano skrócenie całkowitej długości pędu oraz zmniejszenie średnicy pędu ogórka w porównaniu do roślin nawożonych pożywką o standardowym EC dla ogórka. W przypadku roślin rosnących w podłożu z węgla brunatnego wysokie EC wpłynęło na 20% spadek masy liści i pędów w porównaniu do standardowego EC pożywki, jednak nie stwierdzono skrócenia pędów ogórka, jak w przypadku wełny mineralnej (publikacja 3). Podłoże z węgla brunatnego zredukowało więc negatywny wpływ na wzrost pędów ogórka po zastosowaniu eustresu w postaci wysokiego EC pożywki na poziomie 7,0 $dS·m^{-1}$. Jak donosi Chen i in. (2020) skrócenie pędów jest naturalną reakcją rośliny na wysokie EC pożywki, czego nie stwierdzono w przeprowadzonych badaniach w przypadku podłoża z węgla brunatnego. Analizując wyniki tempa fotosyntezy netto (PN), nie stwierdzono wrażliwości tego parametru w roślinach ogórka po zastosowaniu wysokiego EC pożywki, jednak pod koniec doświadczenia w kombinacji z wysokim EC pożywki u roślin ogórka rosnących w wełnie mineralnej, odnotowano silny spadek przewodnictwa szparkowego (g_s). Przy stosowaniu wysokiego EC pożywki w obu podłożach, zanotowano u ogórka również spadek szybkości transpiracji (E). Schwarz i Kuchenbuch (1998) udowodnili u roślin pomidora, że spadek szybkości transpiracji i obniżenie zawartości suchej masy rośliny zależy bezpośrednio od poziomu zasolenia. W przypadku roślin (*Brassica campestris* L. ssp. *chinensis*) odnotowano istotny spadek wspomnianych parametrów przy wzroście EC pożywki z 4,8 do 9,6 $dS·m^{-1}$ (Ding i in. 2018). W uzyskanych wynikach badań nie wykazano istotnego wpływu wysokiego EC pożywki i zastosowanego w badaniach podłoża na Fv/Fm i Fm', WUE oraz i WUE w liściach ogórka (publikacja 3**).** Jak donoszą Kamran i in. (2019) oraz Chen i in. (2020), omawiane parametry w przypadku potraktowania roślin stresem NaCl, ulegają istotnemu obniżeniu już po kilku godzinach od wystąpienia stresu. Zastosowane w badaniach wysokie EC pożywki do fertygacji roślin rosnących w podłożu z węgla brunatnego nie spowodowało dużych spadków parametrów fotosyntezy oraz wymiany gazowej, co może wskazywać na ograniczenie negatywnych skutków działania stresu przez podłoże z węgla brunatnego. Podobną tendencję zauważono w przypadku plonu owoców ogórka, gdzie podłoże z węgla brunatnego zwiększyło liczbę i masę plonu, przy jednoczesnym zmniejszeniu liczby owoców niehandlowych, w porównaniu do wełny mineralnej. Zastosowanie wełny mineralnej przy wysokim EC pożywki obniżyło wielkość i masę plonu handlowego ogórka. Jest to zgodne z wynikami takich badaczy jak Schwarz i Kuchenbuch (1998) oraz Albornoz i Lieth (2015), którzy stwierdzili obniżenie plonu wraz ze wzrostem EC pożywki w uprawie pomidora i sałaty. Zasolenie również wpływa na liczbę zawiązanych owoców na roślinie oraz masę pojedynczych owoców (Ouzounidou i in. 2016). W przedstawionych badaniach rośliny zawiązały podobną liczbę owoców, jednak przy wysokim EC pożywki stwierdzono większy udział zrzuconych zawiązków owoców przez rośliny ogórka, co przełożyło się bezpośrednio na masę plonu całkowitego. Podobne wyniki uzyskali Albornoz i Lieth (2015) w uprawie sałaty (publikacja 3). W przypadku jakości owoców, np. taki parametr jak jędrność nie uległ zmianie ze względu na zastosowane podłoże i wysokie EC pożywki. Potwierdzają to również inni badacze, gdzie nie odnotowano wpływu zasolenia na jędrność owoców ogórka (Colla i in. 2013). Stwierdzono wzrost zawartości suchej masy w owocach pochodzących z uprawy w wełnie mineralnej przy stosowaniu wysokiego EC pożywki, natomiast owoce ogórka pochodzące z roślin uprawianych w węglu brunatnym przy wysokim EC pożywki, charakteryzowały się niższym wzrostem zawartości suchej masy (publikacja 3). Schwarz i Kuchenbuch (199) oraz Sublett i in. (2018) stwierdzili także wpływ wysokiego EC na zawartość suchej masy w owocach pomidora i w sałacie. Połączenie podłoża z węgla brunatnego oraz eustresu w postaci wysokiego EC pożywki, zwiększyło zawartość luteiny, β-karotenu, chlorofilu *a, b* i chlorofilu całkowitego ($a + b$), w porównaniu do owoców pochodzących z roślin uprawianych w wełnie mineralnej. Jak zauważyli Rouphael i in. (2018b) zwiększenie szlaków metabolicznych prowadzących do wytworzenia większej ilości związków bioaktywnych w owocach za pomocą eustresu, nie może wiązać się z utratą znacznej ilości plonu. W przedstawionej pracy odnotowano zależność w połączeniu podłoża z węgla brunatnego oraz wysokiego EC pożywki, na zwiększenie zawartość pożądanych związków w owocach, bez obniżenia plonu u ogórka. Zwiększenie EC pożywki może jednak wiązać się z ryzykiem wzrostu zawartości azotanów w owocach, co nie jest pożądaną cechą. W uzyskanych wynikach potwierdzono wzrost zawartości azotanów w owocach ogórka szklarniowego w kombinacji wysokiego EC pożywki stosowanej do fertygacji roślin, natomiast owoce pochodzące z roślin uprawianych w podłożu z węgla brunatnego charakteryzowały się mniejszą zawartością tych związków (publikacja 3). Podobną tendencję zaobserwowali Ding i in. (2018), gdzie wraz ze wzrostem EC, wzrosła zawartość azotanów w liściach kapusty pak choi. Wzrost zawartości związków bioaktywnych w owocach jest pożądaną cechą z punktu widzenia dobrostanu naszego organizmu, jednocześnie należy kontrolować poziom azotanów w owocach poprzez właściwe nawożenie i zabiegi agrotechniczne (Colla i in. 2018, Rouphael i in. 2018a, 2018b).

4.2.2. Doświetlanie HPS i LED w technologii uprawy hydroponicznej oraz jakość i trwałość przechowalnicza owoców ogórka

Światło to jeden z najważniejszych czynników warunkujących wzrost i rozwój roślin. Niedostateczna ilość i jakość światła, zwłaszcza w miesiącach jesienno-zimowych, wpływa bezpośrednio na powodzenie uprawy. W celu dostarczenia odpowiedniej ilości światła do wzrostu i rozwoju roślin stosuje się lampy o szerokim widmie emisyjnym w zakresie promieniowania fotosyntetycznie czynnego PAR (Gajc-Wolska i in. 2021, Kowalczyk i in. 2022). Aktualnie w ogrodnictwie nadal stosowane są głównie lampy sodowe (HPS), które charakteryzują się dużym udziałem PAR, jednak niskim udziałem światła niebieskiego, które nie przekracza 5%. Światło niebieskie wpływa na proces fotosyntezy i jego regulację, a porównując światło słoneczne do lamp HPS, to udział w ich widmie światła niebieskiego wynosi tylko niespełna 28% zapotrzebowania roślin. Dodatkową wadą lamp HPS jest wysoka emisja ciepła, która przy niewłaściwym montażu może uszkodzić wierzchołki roślin (Islam i in. 2012, Kowalczyk i in. 2022). Coraz popularniejsze w ostatnich latach stały się diody elektroluminescencyjne LED, w których wraz z rozwojem technologicznym pojawiła się możliwość między innymi kontroli składu spektralnego, który dobierany jest bezpośrednio do danego gatunku i fazy rozwojowej roślin. Brak produkcji wysokiej ilości ciepła oraz możliwość regulacji spektrum, pozwala umieścić lampy LED pomiędzy roślinami, co wyraźnie przyczynia się do poprawy parametrów wzrostu doświetlanych roślin (Wojciechowska i in. 2015, Särkkä i in. 2017). Przeprowadzone badania nie pozwalają jednoznacznie stwierdzić, że zastosowane podłoże lub rodzaj światła wpłynęły na zróżnicowanie rozwoju morfologicznego roślin ogórka. W pierwszym roku doświadczenia potwierdzono wpływ zastosowania światła lamp LED na średnicę pędu, natomiast nie potwierdzono tego w drugim roku doświadczenia (publikacja 5). Badając wpływ światła czerwonego oraz połączenia światła czerwonego z zielonym, w uprawie hydroponicznej potwierdzono wydłużenie łodygi u pomidora, natomiast u ogórka stwierdzono skrócenie hypokotylu u młodych roślin w porównaniu do doświetlania lampami HPS (Zou i in. 2020, Hernández 2013). Uzyskane wyniki badań potwierdziły istotny wpływ doświetlania lamp LED na parametry wymiany gazowej takie jak intensywność procesu fotosyntezy (PN), przewodność szparkowa (gs) oraz intensywność transpiracji (E) w porównaniu do zastosowanych lamp HPS. Dodatkowo odnotowano wpływ podłoża z węgla brunatnego na omawiane parametry w przypadku liścia 10., licząc od wierzchołka rośliny. Podobną tendencję potwierdzono badając większość parametrów wymiany gazowej i fotosyntezy u roślin rosnących na tym podłożu (publikacja 5). Zbliżone wyniki uzyskano w pracy Gajc-Wolskiej i in. (2021), gdzie zastosowanie doświetlania lampami LED wpłynęło na wzrost parametrów wymiany gazowej u roślin ogórka. Jest to zgodne także z wynikami badań innych autorów, gdzie również potwierdzono wpływ lamp LED (oświetlenie górne i międzyrzędowe) na omawiane parametry (Elvidge i in. 2010, Kowalczyk i in. 2022, Talebnejad i Sepaskhah 2016). W badaniach Yang i in. (2023) potwierdzono wpływ podłoży organicznych z kory sosnowej i włókien drzewnych na szybkość fotosyntezy netto (PN), przewodność szparkową (gs) i szybkość transpiracji (E) w liściach ogórka, co jest zgodne z uzyskanymi wynikami badań (publikacja 5). Podłoże także istotnie wpływa na zawartość pierwiastków w liściach, ale jednocześnie nie jest jedynym źródłem zmienności, które wpływa na zawartość makro- i mikroelementów w liściach roślin (Yılmaz i in. 2014). W pracy potwierdzono istotnie wyższą zawartość S-SO_4 w liściach ogórka rosnącego na podłożu z węgla brunatnego doświetlanych lampami LED, w porównaniu do wełny mineralnej. W przeprowadzonych badaniach nie udowodniono istotnych różnic w plonowaniu ogórka w poszczególnych kombinacjach. Potwierdzono natomiast tendencję do mniejszego zrzucania zawiązków owoców ogórka w kombinacjach z doświetlaniem lampami LED w porównaniu do kombinacji, gdzie rośliny doświetlano lampami HPS. W uprawie doświetlanej LED stwierdzono także wyższy udział plonu handlowego w plonie całkowitym ogórka niż w uprawie doświetlanej HPS, bez względu na zastosowane podłoże (publikacja 5). W pierwszym roku doświadczenia uzyskano wyższy plon w kombinacji z podłożem z węgla brunatnego oraz lampami HPS, jednak w drugim roku nie potwierdzono tej tendencji. Jak donosi Särkkä i in. (2017) oraz Marcelis (1993), temperatura wpływa na szybkość przyrastania owoców ogórka oraz masę poszczególnych owoców, a wzrost temperatury pochodzi także z nadmiernego promieniowania podczerwonego lamp HPS. Jednocześnie brak możliwości zastosowania lamp HPS w doświetlaniu międzyrzędowym obniża parametry fotosyntezy liści położonych głębiej w łanie, która również wpływa na plon owoców ogórka. Prócz wielkości plonu ważna jest także jakość owoców. W przeprowadzonych badaniach nie potwierdzono wpływu zastosowanego rodzaju światła oraz podłoża na zawartość związków bioaktywnych w owocach ogórka, natomiast stwierdzono dodatni wpływ doświetlania LED oraz podłoża z węgla brunatnego na zawartość TSS w owocach. Udowodniono także wpływ podłoża z węgla brunatnego na zawartość suchej masy w owocach ogórka (publikacja 5), co potwierdzają liczne badania, gdzie na wzrost suchej masy wpływ miało podłoże organiczne (Nurzyński 2013, Valverde-Miranda i in. 2021, Lizhong i in. 2022). Podłoże oraz rodzaj zastosowanego światła może także wpływać na zawartość azotanów w zależności od podłoża oraz gatunku rośliny (Zhang i in. 2020). W przeprowadzonych badaniach najwyższe stężenie azotanów uzyskano w owocach pochodzących z roślin rosnących w podłożu z wełny mineralnej i doświetlanych lampami LED, natomiast zauważono wyraźny spadek ich zawartości tych związków w owocach ogórka pochodzących z roślin uprawianych w kombinacji z wykorzystaniem podłoża z węgla brunatnego (publikacja 5). Ważnym parametrem w przypadku owoców ogórka jest jędrność owoców. Ma to duże znaczenie w przypadku ich transportu, a także z punktu widzenia jakości przechowalniczej i trwałości owoców przeznaczonych do sprzedaży (Gómez-López i in. 2006). W przeprowadzonych badaniach potwierdzono pozytywny wpływ podłoża z węgla brunatnego oraz zastosowanego do doświetlania roślin lamp LED na ten parametr jakości owoców ogórka. Po zbiorze owoce ogórka narażone są na różnego rodzaju uszkodzenia mechaniczne, ale także na utratę jędrności, co z kolei powodowane jest przez utratę wody (Nishizawa i in. 2018, Valverde-Miranda i in. 2021). Jak podają Marcelis (1993), Nurzyński (2013), Kraska i in. (2018) oraz Gajc-Wolska i in. (2021), na jakość owoców wpływają takie czynniki jak podłoże, rodzaj zastosowanego światła, warunki klimatyczne czy odmiana. Wyraźny spadek twardości przechowywanych owoców w temperaturze otoczenia, spowodowany jest szybką utratą wody i oddychaniem. Wpływ na ten parametr ma także rodzaj opakowania (Dobrucka i Cierpiszewski 2014, Gutiérrez-Pacheco i in. 2020, Owoyemi i in. 2021). Analizując wpływ zastosowanego światła (HPS i LED), podłoża (wełna mineralna i węgiel brunatny) oraz opakowania (skrzynka HDPE, karton, worek foliowy PE) na utratę wody w czasie symulowanego obrotu owoców ogórka, stwierdzono najmniejszą utratę wody w owocach pochodzących z roślin uprawianych w matach z węgla brunatnego i doświetlanych lampami LED, które zapakowano w worek foliowy. Opakowanie z foli PE ograniczyło utratę wody w czasie przechowywania w chłodni oraz w warunkach symulowanej sprzedaży na półce sklepowej, a dodatkowo wykazano istotny wpływ podłoża z węgla brunatnego na trwałość owoców ogórka i ograniczenie strat masy owoców po zbiorze (publikacja 4). Dynamika utraty masy w czasie przechowywania w chłodni oraz w warunkach symulowanej sprzedaży na półce sklepowej wyraźnie wskazuje, że opakowanie z foli PE najskuteczniej zapobiega utracie wody. W przypadku twardości/jędrności owoców pochodzących z roślin uprawianych w węglu brunatnym, uzyskano istotnie wyższe wartości tego parametru w owocach bezpośrednio po zbiorze oraz w trakcie symulowanego obrotu. Owoce zebrane z roślin doświetlanych lampami LED, przechowywane 5 dni w chłodni oraz 5 dni w temperaturze pokojowej (symulowana sprzedaż na półce sklepowej), również charakteryzowały się wyższą twardością/jędrnością w porównaniu do owoców zebranych z roślin doświetlanych lampami HPS (publikacja 4). Wpływu podłoża na jakość przechowalniczą owoców ogórka nie potwierdzili w swoich badaniach między innymi Parks i in. (2004), Hovi-Pekkanen i Tahvonen, (2008) oraz Freitas i in. (2021). Według Gutiérrez-Pacheco i in. (2020) oraz Owoyemi i in. (2021), sposób opakowania ma wpływ na jakość przechowalniczą. Jednak uzyskane wyniki po symulowanym obrocie, wskazują na istotny wpływ podłoża z węgla brunatnego oraz lamp LED na jakości przechowalniczą owoców ogórka szklarniowego (publikacja 4). Owoce ogórka pochodzące z roślin uprawianych hydroponicznie w węglu brunatnym oraz doświetlane lampami LED, charakteryzowały się wyższą zawartością rozpuszczalnych substancji stałych w soku komórkowym (TSS) oraz wyższą zawartością suchej masy owoców. Po 5 dniach przechowywania owoców w warunkach chłodni, a także po 5 dniach przechowywania owoców na niechłodzonej półce sklepowej (10 dni warunków symulowanego obrotu), owoce pochodzące z roślin uprawianych w węglu brunatnym posiadały istotnie wyższe wartości TSS. Stwierdzono także, że owoce przechowywane w chłodni (5 dni) posiadały niższe wartości TSS w porównaniu do owoców przechowywanych 10 dni (publikacja 4). Zawartość TSS oraz suchej masy może różnić się w zależności od terminu uprawy, zbioru oraz sposobu przechowywania (Parks i in. 2004, Valverde-Miranda i in. 2021). Bahnasawy i Khater (2014) potwierdzili, że wraz ze wzrostem temperatury przechowywania rośnie stężenie TSS w owocach, jednakże inni badacze nie stwierdzili takich zależności (Kahramanoğlu i Usanmaz 2019, Valverde-Miranda i in. 2021). Po przechowywaniu owoców ogórka odnotowano istotny wzrost suchej masy u owoców pochodzących z roślin uprawianych w węglu brunatnym, jednak nie stwierdzono wpływu sposobu doświetlania oraz rodzaju opakowania na zawartość suchej masy (publikacja 4). Natomiast Valverde-Miranda i in. (2021) uzyskali spadek suchej masy w owocach ogórka wraz z długością przechowywania. Tendencję spadkową odnotowano w przypadku zawartości azotanów w owocach ogórka – o ponad 50% w owocach pochodzących z roślin doświetlanych lampami LED po 5 dniach przechowywania w chłodni oraz po zakończonym procesie symulowanego obrotu. Spadek zawartości azotanów potwierdzono także w przypadku przechowywania kapusty białej w chłodni (Wieczorek i Traczyk 1995). W przeprowadzonych badaniach stwierdzono istotne zróżnicowanie jakości sensorycznej owoców ogórka. Analizą składowych głównych wyłoniono jednorodną grupę, gdzie próbki owoców pochodzących z roślin uprawianych w węglu brunatnym i doświetlanych lampami LED charakteryzowały się najlepszymi parametrami sensorycznymi, takimi jak: zapach świeżego ogórka, twardość owocu i smak słodki. Oceniający wskazali również smak i zapach obcy, który zdefiniowano jako zbliżony do melona lub/i arbuza (publikacja 4). W analizie składowych głównych, którą wykonano po symulowanym obrocie owoców, wyodrębniono dwie przeciwległe grupy. Najbardziej jednorodną grupę stanowiły owoce pochodzące z roślin uprawianych w węglu brunatnym i doświetlane lampami LED – niezależnie od opakowania. Oceniający wskazali, że próbki tych owoców charakteryzowały się smakiem słodkim i dużą twardością. Najwyższe wartości w obrębie tej grupy otrzymano dla owoców zapakowanych w worek foliowy PE. Próbki owoców pochodzących z roślin doświetlanych lampami HPS i uprawianych w wełnie mineralnej, charakteryzowały się zapachem obcym, zidentyfikowanym jako stęchły (karton oraz worek foliowy PE). Natomiast próbki owoców pochodzących z roślin uprawianych w wełnie mineralnej, ale doświetlane lampami LED, charakteryzowały się smakiem gorzkim oraz obcym, również określonym jako stęchły – niezależnie od sposobu opakowania (publikacja 4). Badania przeprowadzone na owocach ogórka przez Owoyemi i in. (2021) wyraźnie wskazują, że smak ogórka zmienia się wraz z długością przechowywania. Jak podają Miano i in. (2016), sposób opakowania również może wpływać na pozytywny odbiór przez oceniających owoców ogórka po przechowywaniu. Jednakże uzyskane wyniki wskazują, że podłoże może oddziaływać w większym stopniu na smak oraz odbiór owoców przez oceniających niż sposób przechowywania.

5. WNIOSKI

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

1. W uprawie hydroponicznej, parametry podłoża z węgla brunatnego – pojemność wodna i gęstość nasypowa, wpływają korzystnie na stopnień odżywienia roślin, zwłaszcza potasem, zawartość karotenoidów oraz na plon i jakość owoców ogórka szklarniowego.
2. Cechy morfologiczne roślin ogórka, głównie średnica pędu, długość liścia i ogonka liściowego oraz tygodniowy przyrost liczby liści na pędzie, wykazują zależność od gęstości oraz pojemności wodnej podłoża.
3. Ponowne wykorzystanie mat z węgla brunatnego w uprawie hydroponicznej nie wpływa na ograniczenie wzrostu roślin, obniżenie plonowania oraz pogorszenie parametrów jakościowych owoców ogórka szklarniowego.
4. Użycie w drugim cyklu uprawy ogórka tych samych mat z węgla brunatnego skutkuje większym plonem, wyższą jędrnością owoców oraz zawartością w owocach suchej masy, TSS i karotenoidów, w porównaniu do ogórka uprawianego w ponownie zastosowanych matach wełny mineralnej.
5. Maty z węgla brunatnego zastosowane w uprawie ogórka z dodatkowym doświetlaniem LED, w porównaniu z uprawą roślin w wełnie mineralnej ze standardowym doświetlaniem lampami HPS, wpływają korzystnie na wzrost, rozwój, parametry fizjologiczne i odżywienie roślin oraz wysoką jakość sensoryczną owoców bezpośrednio po zbiorze i po symulowanym obrocie.
6. Owoce ogórka z uprawy w podłożu z węgla brunatnego mają niższą utratę masy podczas przechowywania, wyższą zawartość TSS i suchej masy oraz niższą zawartość azotanów w porównaniu do owoców zebranych z roślin uprawianych w podłożu z wełny mineralnej.
7. Zastosowanie podłoża z węgla brunatnego w uprawie hydroponicznej ogranicza negatywne skutki stresu abiotycznego związanego z wysokim EC pożywki.
8. Stres wywołany wysokim EC pożywki w uprawie ogórka szklarniowego w podłożu z wełny mineralnej powoduje znaczące zmniejszenie średnicy pędu roślin oraz obniżenie parametrów fizjologicznych roślin ogórka, takich jak

przewodnictwo szparkowe (gs) i współczynnik transpiracji (E) ,w porównaniu do roślin zasilanych standardowym EC pożywki.

9. Wysokie EC pożywki w połączeniu z podłożem z węgla brunatnego, w porównaniu z wełną mineralną, nie wpływa negatywnie na wysokość plonu ogórka szklarniowego, natomiast podwyższa jakość owoców ogórka, zwiększając w nich zawartość chlorofilu i karotenoidów.

6. SPIS LITERATURY

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7. ARTYKUŁY NAUKOWE I OŚWIADCZENIA WSPÓŁAUTORÓW

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Effect of Re-Used Lignite and Mineral Wool Growing Mats on Plant Growth, Yield and Fruit Quality of Cucumber and Physical Parameters of Substrates in Hydroponic Cultivation

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Abstract: In hydroponic cultivation of vegetables with a solid substrate, mineral wool predominates. The pro-ecological policy and consumers' expectations cause an increase in interest in organic substrates, which, when properly used, are less harmful to the environment. The aim of this study was to determine the effect of reusing lignite substrate in hydroponic cultivation on the growth, yield and quality of cucumber fruit and on the physical parameters of the substrate. The greenhouse cucumber cultivar 'Mewa F1' with semi-long fruits and smooth skin was used for the study. The plants were grown in the 'Carbomat' lignite substrate and 'Grotop Master' rockwool in two cycles. In cycle 1, new growing mats were used, while in cycle 2 the same growing mats as in cycle 1 were used again. In the hydroponic cultivation carried out on mineral wool and in the lignite substrate, both in the new and the reused substrate, the cucumber obtained mostly similar plant growth parameters and fruit color. Cucumber grown on the new mineral wool had a higher number and weight of fruits, which were characterized by a higher content of β-carotene and lutein compared to fruits from plants grown in the new lignite substrate. On the other hand, the reused lignite substrate resulted in higher cucumber yields and fruits with higher firmness and higher carotenoid content compared to cucumber grown on reused mineral wool. At the same time, the content of dry matter and sugar extract in fruits obtained from plants growing in the new and reused lignite substrate was higher compared to fruits grown in mineral wool. Both new and reused lignite substrate were characterized by very low plant-available water content. In contrast; the air and water holding capacity of lignite after cultivation did not change as much as that of mineral wool.

Keywords: substrate parameters; water retention; air-water properties of the organic substrate; SPAD-index; total soluble salts; CIE Lab

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1. Introduction

Increasing problems with environmental pollution, excessive CO_2 emissions and difficulties in the efficient production of food of a high, standardized quality are the reasons for looking for new solutions in the technology of vegetable production under cover. Many researchers are intensively searching for new cultivation technologies, including energy-saving and pro-environmental solutions, which will ensure optimum plant yields throughout the year.

Cucumber *Cucumis sativus* L. is, after tomato, the second most important vegetable species in production under covers in Poland and worldwide [1]. Throughout the year, the demand for high quality cucumber fruit is very high and does not decrease during winter [2]. The amount and quality of the yield are affected by many factors, including temperature, humidity, light intensity, the degree of plant nutrition and the type of substrate [1,3]. The most commonly used substrate for growing vegetables in hydroponic systems is mineral wool [4,5], which is usually not recycled but disposed of after one growing cycle, leading to an accumulation of post-production waste. Annually, a production greenhouse with 1 ha of growing area leaves 150 m^3 of used mineral wool [5]. The properties of the mineral wool substrate make it possible to increase yields and production efficiency compared to conventional cultivation. Mineral wool is an inert, universal substrate and is most applicable in commodity vegetable cultivation. This does not change the fact that the amount of mineral wool waste and the problem with its utilization force the search for alternative substrates for hydroponic cultivation [5–7]. Increasingly, producers under covers are starting to use coconut fiber growing mats [8]. It is an organic substrate produced in tropical countries. It has stable physical and biological properties, but tends to accumulate minerals, leading to an increase in EC (electric conductivity) over time [9,10]. Currently tested organic substrates used for hydroponic production are, for example, post-production waste from the wood industry (bark, sawdust) or plant residues from other production departments or industries. Compost and biochar obtained from plant waste can be used as substrates for hydroponic production [11–13]. Composts often have a high variability of physical characteristics depending on the composition of the waste from which they are made [11], and the production and use of biochar in agriculture is considered too capital intensive [14,15]. Plant residues used as substrates are rye or rapeseed straw [16], *Miscanthus* [6], rice husks [17], almond and hazelnut shells [18–20], grape marc [21], oil palm waste [22] or sheep wool and hemp fibers [5]. All these products have beneficial properties for plants, but are often unstable [7], leading to a reduction in easily available water and oxygen in the root zone. Such examples are hemp and sheep wool slabs, which, as research has confirmed, are not a good substitute for mineral wool in hydroponic cultivation [5]. Often mineral substrates such as perlite, mineral wool or vermiculite are mixed with organic substrates to maintain structure and improve physical properties [23]. Studies on the reuse of almond shells have shown that this substrate can be used in tomato and melon cultivation for two years without affecting yield or fruit quality [19]. An additional benefit of using organic substrates is that they can be used after cultivation as a fertilizer in conventional crops, compost or solid fuel. Studies on the *Miscanthus* substrate have shown that the plant can be grown conventionally, then used as a substrate in hydroponic cucumber and tomato crops, and burned after use [6]. A biodegradable substrate based on lignite appears to be a similar solution. After cultivation, lignite can provide a source of organic matter for conventional crops without a detrimental effect on the environment [24]. For instance, currently, waste lignite is used for the reclamation of anthropogenically altered soils, and in agriculture, coal dust and lignite are sometimes used for soil improvement or decontamination [25–28]. World lignite resources are estimated at 512 billion tonnes, while in Poland about 23 billion tonnes. The world leader in lignite production is Germany. Poland is on the fifth place just behind Russia, Australia and the United States [25,26]. Lignite is formed from peat in the presence of high temperature and pressure. It contains many organic substances, among others, and it is a very rich source of humic and fulvic acids [27]. Lignite has good physical properties due to highly condensed organic matter, it is sufficiently porous, absorbs water well and maintains a stable homogeneous structure [28–30], and moreover it is a good absorber of mineral components necessary for plant functioning [27,30,31]. According to Kwiatkowska [28], lignite is a sustainable organic material, which can be used in agriculture and greenhouse crops. Currently, the interest in generating energy from coal is decreasing in favor of renewable energy sources, while at the same time there is an increasing interest in a diverse use of lignite in agricultural and horticultural crops [28–30].

Awareness of problems with water availability, environmental pollution and the need to produce high and monitored quality of vegetables is largely contributing to the growing interest in hydroponic crops. In these crops, mineral wool is the most popular substrate.

This also applies to the year-round cultivation of cucumbers under cover in two or three cycles in a mineral wool substrate. Increasingly, research is being undertaken to develop an effective cultivation technology with a biodegradable substrate, which would significantly reduce the use of mineral wool, which is problematic in terms of utilization.

The study investigated the suitability of reused organic lignite-based substrate for hydroponic cucumber cultivation. Changes in the properties of reused organic lignite substrate in cucumber cultivation compared to mineral wool and their effects on growth, yield and fruit quality of cucumber were investigated.

2. Materials and Methods

The research was conducted in the Department of Vegetable and Medicinal Plants at the Greenhouse Experimental Centre of the Warsaw University of Life Sciences. In the greenhouse chamber, the conditions of microclimate and fertigation of plants were computer-controlled. The cultivation substrate consisted of lignite mats (CM) Carbomat by CarboHort, measuring 100 cm × 20 cm × 8 cm, and the control consisted of mineral wool mats (MW) Grotop Master by Grodan, measuring 100 cm × 20 cm × 7.5 cm. The greenhouse cucumber cultivar 'Mewa F1' by Rijk Zwaan was used for the study. It is an early variety, tolerant to low irradiance, with uniform yielding. It produces fruits 20–24 cm long, weighing 200–240 g, with dark green, smooth skin and slight ribbing. The plants were grown in two cycles. In the first one, cucumber seedlings were planted into a new medium of mineral wool (MW new) and lignite (CM new), and in the second cycle, into mineral wool growing mats after the first cultivation cycle (MW reused) and similarly into lignite mats (CM reused). The plants, after the first cultivation cycle were removed from the cultivation mats together with the seedling cubes, and in the second cycle the seedlings were planted in places next to the removed plants. While preparing the cucumber seedlings, on both dates, seeds were sown directly into mineral wool cubes on 20 November 2019, in the first cultivation cycle, and on 26 June 2020, in the second cycle. The wool cubes were soaked in nutrient solution with pH 5.4 and EC 1.8 mS·cm^{-1}. The seedling was produced on the first date with lighting by HPS lamps (Gavita GAN 600 W) at light levels averaging 170 µmol m^{-2}·s^{-1} PPFD (Photosynthetic Photon Flux Density), 16 h per day, average temperature D/N 22/21 °C, humidity averaging 24 h RH 60–70% and CO_2 800 ppm per day. Seedling for the second cycle of cultivation was produced under natural light, where temperature averaged D/N 25/21 °C, humidity RH 65–70% and CO_2 800 ppm.

In order to prepare new growing mats for planting plants in the first cycle, both lignite and mineral wool mats were flooded with nutrient solution with pH 5.5 and EC 2.8 mS·cm^{-1} in an amount of about 8 dm^3 per mat. After 48 h in the lignite mats, 2 vertical drainage holes, each 5 cm long, were made in the foil on the longer side of each mat and about 1 cm high from the bottom. In mineral wool mats, on the other hand, drainage holes were made as standard for this type of substrate. Preparing the substrate for the second cultivation cycle, the mats were poured with water of pH 5.5 at a rate of about 4 dm^3 per mat, obtaining an EC of 1.5 mS·cm^{-1} in the mats. Before planting the seedlings in the second cycle of cultivation, 24 h earlier the mats were soaked in the medium with pH 5.5 and EC 2.8 mS·cm^{-1}.

The first cycle of cultivation was conducted for 12 weeks and the second cycle for 9 weeks. In the first cycle, the daily sum of solar radiation averaged 134.0 J/cm^2 and the cucumber plants were illuminated with sodium lamps for 16 h per day, obtaining a light level of 220 µmol m^{-2}·s^{-1} PPFD on average over the tops of the plants, the lamps switched off automatically at a solar radiation level of 250 W m^{-2}. During the second cropping cycle, the daily solar radiation averaged 1474.9 J/cm^2. The temperature during the growing period averaged D/N 24/21 °C and D/N 25/22 °C in the first and second cycles, respectively, and the humidity and CO_2 concentration averaged RH 60–70% and CO_2 800 ppm in both cultivation cycles.

In both cycles, 3 plants per mat were planted. The experiment was set up using the randomized block method, in 4 replications, with 6 plants in each. Fertilization was carried out using a fertilization computer. Concentrated medium was prepared from single or two-component mineral fertilizers designed for hydroponic cultivation. Dosatron dispensers (D25RE2 0.2–2%) were used for diluting the nutrient solution and dosing acid for pH regulation of fertigation medium. The fertigation medium contained in mg·dm^{-3}: N-NO_3 230, N-NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15 and B 0.33. In both cycles, plants were run by strings on a single shoot, removing all side shoots and tendrils from leaf corners. The first 4 fruit buds on the main shoot, in each cropping cycle, were removed and then, in order to prevent the shedding of excess fruit buds, every other fruit bud on the main shoot was removed preventively.

2.1. Morphological Examination and Chlorophyll Content of Leaves

For morphological tests performed weekly, 6 test plants from each combination were selected. The weekly growth of the cucumber shoot in length was studied by measuring the shoot growth from the height of the shoot apex of the plant, marked on a string (marker) a week before. The results allowed the total length of the cucumber shoot to be determined. The shoot diameter was measured with an electronic caliper in the middle of the internode, between the 3rd and 4th fully developed leaf, counting from the shoot apex of the plant. The length and width and the length of the petiole of the 4th fully developed leaf from the apex of growth were examined. The approximate area of the 4th leaf was determined as the product of leaf length and width. Leaf increment per shoot per week was also determined.

The relative chlorophyll content of leaves was measured using the SPAD (Soul Plant Analysis Systems) test with a Minolta SPAD-502 Plus portable meter. The measurement was carried out on the 4th fully expanded leaf counting from the growth apex. Peel color and fruit hardness were measured. The firmness was measured with the HPE firmness tester at an angle of 90° to the cucumber fruit in the middle of its length. The results are given on the HPE scale (0–100 units).

2.2. Yield, Bioactive Compounds and Colour of Fruit

Cucumber fruits were harvested every two days; the number and weight of harvested fruits were determined. Selected physicochemical parameters determining fruit quality were analyzed in cucumber fruits. For the analyses, 3 fruits were taken randomly from each repetition for each combination. All measurements were performed in three replications.

The dry matter content of the fruit was determined by the weight method at 105 °C. Total soluble solids (TSSs) were determined by refractometric method using a digital refractometer, giving the result in °Brix. The contents of β-carotene, lutein and chlorophyll a and b were determined using high-performance liquid chromatography HPLC (Shimadzu Scientific Instruments company), where cucumber fruits were homogenized with 2 g Na_2SO_4 per 100 g^{-1} fresh weight of sample. The prepared homogenate was weighed out on a laboratory balance at 5 g and then grinded in a mortar with cold acetone (−20 °C) and quartz sand. The samples were then extracted by transferring the extracts to 50 mL volumetric flasks five times and refilled with cold acetone. The samples were centrifuged in test tubes (15,000 revolutions). The resulting supernatant was filtered again through a 0.22 μm syringe filter (Supelco IsoDisc™ PTFE 25 mm × 0.22 μm), then the extract was placed in 1 mL containers into an automatic sample feeder. Using a SIL-20AC HT automatic sample feeder (tray temperature 4 °C), 5 μL of extract was applied to the chromatograph column. Compound separation was obtained using isocratic elution with methanol at 40 °C on a Kinetex 2.6 μm C18 100 Å 100 mm × 4.6 mm column from Phenomenex, flow rate 2 mL min^{-1}. Analysis time was 5 min. The wavelength range was for β-carotene, chlorophyll a and b respectively: 450 nm, 430 nm and 470 nm. From the results of chlorophyll a and chlorophyll b, the sum of chlorophyll a + b was calculated.

Fruit color was measured using the CIE Lab scale (MiniScan XE PLUS D/8-S)—red share—a *, yellow share—b * and brightness—L. Fruit color and hardness were measured on fruit in 3 replicates at 3 locations.

2.3. Physical Properties of Substrates

The use of two different types of substrates (mineral wool mat and loose lignite) requires the use of appropriate analytical methods, differing in the method of sample preparation for analysis of physical properties.

The physical properties of the lignite substrate before and after two cycles of cucumber cultivation were determined according to the PN-EN 13041 standard [32]. The determinations were made in cylinders of 10 cm diameter and 5 cm height. The specific and most important element of this method is sample preparation based on natural settlement of 10 cm layer (double ring) of loose substrate brought previously to water potential −57 cm H_2O. The water–air properties were tested on an 'Eijkelkamp' sand apparatus in the vacuum range of 0–100 cm H_2O, using a 24-h water equilibrium establishment time at each of 5 vacuum levels (−3.2, −10, −32, −50 and −100 cm H_2O). After completion of the sand apparatus determinations, the samples were dried at 105 °C and the shrinkage of the substrates was determined by determining the volume loss. The organic matter content was determined after sample incinerating in accordance with PN-EN 13039 [33]. Porosity, substrate density and water and air content were calculated in accordance with PN-EN 13041.

The physical properties of mineral wool mats were determined using a method developed at the experimental station in Naaldwijk, the Netherlands [32–36]. From the mats, samples of 15 cm × 15 cm were cut with a sharp knife. The prepared samples were placed in a box on a grate (3 cm from the bottom), then the box was filled with distilled water above 1 cm above the sample. The samples were soaked for 24 h ± 2 h, then the water was drained and the samples were left like this for 3 h. After this time, the samples were again flooded with distilled water in the same box for 30 min, then immediately after draining the water they were transferred to a sand block (Eijkelkamp) and a vacuum of −100 cm H_2O was set for 30 min. The samples were then flooded again at 3 cm above the sample, soaked for 24 h ± 2 h and proceeded to the determination of air–water properties, in the vacuum range 0–100 cm H_2O, using a 24 h time to establish water equilibrium at each of the 5 vacuum levels (−4.5, −10, −32, −50 and −100 cm H_2O). After completion of the sand apparatus determinations, the samples were dried at 103 °C ± 2 °C and the shrinkage of the substrates was determined by determining the volume loss. The content of organic matter and ash was also determined in PN-EN 13039 [33], which is necessary for calculating the total porosity in PN-EN 13041 [32].

2.4. Statistical Analysis

The results were statistically processed using Statgraphics Centurion XVII 2016. The one-way analysis of variance (ANOVA) was performed and mean values were compared using the Tukey's HSD test (HSD) at a significance level of $\alpha = 0.05$.

3. Results and Discussion

Current research directions include the search for an organic substrate that could provide efficient plant yields comparable to the standard substrate, which in hydroponic cultivation is mineral wool [6,16,24]. The results obtained indicate that the lignite substrate used for the hydroponic cultivation of cucumber can be used as a new substrate and reused in the next cultivation cycle just as the mineral wool growing mats (Figure 1).

On the basis of morphological measurements, it was found that cucumber plants grown hydroponically on both the lignite and mineral wool substrates were characterized by similar growth parameters such as the weekly shoot length increment, leaf length and width, leaf area and petiole length (Table 1). Both in cultivation carried out in cycle 1, when plants were grown on a new substrate, and in cycle 2, when plants were grown on a used substrate, leaf blade area and cucumber shoot diameter did not depend on the type of substrate. There were also no significant differences in shoot length in the lignite combination compared to mineral wool cycle 1 and 2. A study on tomato growing in organic media showed no significant differences in the case of number of leaves per plant or stem length, while a significantly higher stem diameter was recorded in plants growing on mineral wool [37]. For cucumber plants growing on date palm waste substrate and perlite, stem diameter and stem length were significantly higher in date palm substrate compared to perlite [38]. Alifar et al. [39] investigating the effect of five substrates (coconut fiber, coconut fiber-perlite, coconut fiber-perlite-peat and perlite-peat) on morphological parameters and yield of cucumber obtained the highest stem diameter and the highest number of fruits in plants grown in coconut fiber.

(a) (b)

Figure 1. Cucumber plants of 'Mewa F1' growing in cycle 1: (a) in mineral wool substrate. Photo by R. Łaźny; (b) growing in lignite substrate. Photo by R. Łaźny.

Table 1. Selected morphological parameters of cucumber in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Weekly increment shoot to length	(cm)	51.8 ± 1.58 a *	51.4 ± 1.60 a	52.6 ± 1.22 a	52.9 ± 1.10 a
Shoot length	(cm)	213.6 ± 3.22 a	212.1± 3.07 a	423.1 ± 2.22 a	451.1 ± 3.00 b
Shoot diameter	(mm)	5.8 ± 0.07 a	5.8 ± 0.02 a	6.6 ± 0.97 a	6.5 ± 1.10 a
Number of leaves per week	(pcs·plant^{-1})	4.0 ± 0.70 a	4.2 ± 0.37 a	3.5 ± 0.53 a	4.0 ± 0.69 a
Leaf length	(cm)	22.2 ± 1.68 a	22.8 ± 1.90 a	18.7 ± 1.95 a	18.2 ± 1.41 a
Leaf width	(cm)	25.5 ± 1.71 a	26.0 ± 1.31 a	24.3 ± 1.47 a	22.6 ± 1.57 a
Leaf area	(cm^2)	600.0 ± 13.5 a	629.0 ± 12.1 a	455.2 ± 10.03 a	438.3 ±11.18 a
Petiole length	(cm)	11.4 ± 1.56 a	10.7 ± 1.39 a	12.5 ± 1.78 a	12.9 ± 1.34 a
SPAD leaf 4	SPAD	37.1 ± 1.24 a	37.7 ± 1.12 a	40.1 ± 1.10 a	40.6 ± 1.06 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

In the study, higher total number of fruits per plant and higher total fruit weight were recorded in plants grown on mineral wool in the 1st cropping cycle (Table 2). For the second cropping cycle, the highest total fruit weight was obtained from plants growing on reused lignite substrate compared to reused mineral wool. This is probably due to more favorable conditions for the activity of the cucumber root system (uptake of water and mineral nutrients) as fertigation was similarly carried out for both substrates. Fruits in the second cropping cycle grew faster, which may have been influenced by the date of cultivation and more favorable microclimatic conditions (Table 2).

Table 2. Total yield and average weight of cucumber fruit in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral wool	Lignite	Mineral wool	Lignite
Number of fruits of the total crop	(pcs·plant^{-1})	14.8 ± 0.84 b *	13.8 ± 0.91 a	15.2 ± 1.10 a	15.6 ± 1.17 a
Total weight of yield	(g·plant^{-1})	2923.0 ± 24.20 b	2617.9 ± 14.40 a	3599.8 ± 15.00 a	3783.0± 15.10 b
Average weight of fruit	(g·fruit^{-1})	197.5 ± 20.51 a	189.7 ± 18.00 a	236.8 ± 11.4 a	242.5 ± 10.00 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

No differences were found for relative chlorophyll content in cucumber leaves SPAD index, both on new and reused substrates (Table 1). The numerical value of SPAD is proportional to the chlorophyll content. The higher the numerical value of SPAD, the better the plant nutrition, because the chlorophyll content increases with increasing nitrogen [40].

Dyśko et al. [29] investigating the effect of lignite substrate on the yield of tomato cv. 'Growdena F1', did not obtain differences in yield compared to mineral wool. Other researchers, comparing organic substrates to mineral substrates also reported no significant differences in vegetable yield at optimal plant nutrition [6,29,38]. Different results were obtained comparing the yield of cucumber grown on mineral wool substrate and perlite to coconut fiber, where the yield in the combination with coconut fiber was found to be lower [41]. The number of buds and hence fruits per plant can be influenced by the cultivation date, number of leaves and solar radiation efficiency [42].

Many authors report that fruit dry matter content depends on climate, excessive temperature rise and regulation of the number of buds per plant [42–44]. The dry matter content of fruit can also be affected by the substrate, which is confirmed by the results of the study in cycle 1, where higher fruit dry matter content was found in plants grown on new lignite compared to mineral wool (Table 3). Nurzyński [16] also obtained a significantly higher dry matter content in tomato fruits grown on rape straw substrate compared to mineral wool. Analyzing the obtained results, organic substrate such as lignite also influenced the concentration of TSS in cucumber fruits. In the present study, a significantly higher TSS content in cucumber fruits was recorded in the combination with lignite in cycle 1. In cycle 2 of cultivation, on the substrates used again, the TSS content in fruits was also higher in the combination with lignite than with mineral wool (Table 3). As reported by Peet et al. [44], yield and especially fruit quality (e.g., Brix value) depend on cultivar and cultivation method, but the effect of substrate on these parameters is difficult to determine unequivocally.

Biologically active components are particularly valuable for humans and are needed to maintain proper functioning of the body [45]. In case of the first cultivation cycle, significantly higher contents of β-carotene, lutein, chlorophyll a and the sum of chlorophyll a and b were recorded in fruits of plants grown on a new mineral wool substrate as compared to lignite. This tendency is not confirmed by the results obtained in cycle 2, where the contents of β-carotene, lutein and chlorophyll a, b and the sum of chlorophyll a and b were higher in the fruits obtained from plants grown on the reused lignite substrate compared to mineral wool (Table 3).

Table 3. Contents of dry matter and selected chemical components in cucumber fruit in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Dry matter	(%)	3.2 ± 0.01 a *	3.4 ±0.05 b	3.7 ± 0.06 a	3.8 ± 0.09a
β-carotene	(mg 100 g^{-1} FW)	6.3 ± 0.11 b	6.1 ± 0.13 a	5.5 ± 0.16 a	6.2 ± 0.42 b
Lutein	(mg 100 g^{-1} FW)	9.5 ± 0.10 b	9.2 ± 0.13 a	10.7 ± 0.25 a	13.2 ± 1.14 b
Chlorophyll a	(mg 100 g^{-1} FW)	86.2 ± 0.70 a	82.7 ± 0.66 a	73.2 ± 1.72 a	98.6 ± 1.81 b
Chlorophyll b	(mg 100 g^{-1} FW)	35.2 ± 1.90 a	35.4 ± 0.33 a	33.1 ± 1.59 a	49.3 ± 2.84 b
Total chlorophylla + b	(mg 100 g^{-1} FW)	121.4 ± 1.61 b	118.1 ± 0.99 a	106.3 ± 1.40 a	147.9 ± 1.62 b
TSS	(°Brix)	3.1 ± 0.05 a	3.4 ± 0.10 b	3.6 ± 0.05 a	3.9 ± 0.10 b

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

Studies on tomatoes grown in organic substrates (pine bark, rapeseed straw, high peat and their mixtures) proved a higher content of vitamin C and nitrogen in fruits compared to fruits obtained from plants grown on mineral wool [16]. This is also confirmed by the study of Kowalczyk et al. [46]. A higher content of dry matter and chlorophyll in SPAD units was obtained by Nerlich and Dannehl [40] in lettuce growing in hemp substrate in comparison to mineral wool, wood shavings and peat. In contrast, the highest concentrations of secondary metabolites were obtained in lettuce grown on hemp and wood sawdust substrates. Tzortzakis and Economakis, [47] adding shredded corn stalks to perlite, showed an increase in total TSS and carotenoid content in cucumber fruits compared to fruits obtained from plants grown in perlite and pumice.

Salad cucumber fruits are eaten raw. For this vegetable, hardness is the first important parameter indicating their quality [48]. The conducted statistical analysis proved the absence of differences in the case of hardness of cucumber fruits obtained from plants grown in new substrates in one cultivation cycle. Fruits of plants grown in the combination with reused lignite were characterized by higher hardness in comparison to reused mineral wool (Table 4). Parks et al. [49] reported no differences in the hardness of cucumber fruits harvested from plants grown in coconut fiber and sawdust. According to many authors, skin color is the second important indicator of cucumber fruit quality [50,51]. In the present study, there was no effect of substrate on fruit color on the CIE Lab scale in the 1st and 2nd cycle (Table 4). The CIE Lab scale is a mathematical transformation of the CIE XYZ space. Perpendicular to the ab plane at the achromatic color point is the color brightness axis L with a scale from 0 (black) to 100 (white). The coordinates a and b can take either positive or negative values. Positive values for a indicate red, negative values indicate green. Positive values of the b coordinate refer to the proportion of yellow color and negative values to blue color [52]. Schoutena et al. [53] in their study confirmed the effect of maximum plant nutrition or adequate crop density on maximum/proper cucumber fruit color. However, skin color also depends on varietal characteristics [51,53]. The obtained results of the study do not allow to unequivocally state the influence of substrate type on fruit color and hardness. No effect of applied substrates on cucumber fruit color parameters was found in the study (Table 4).

Mineral (mineral wool), organic (based on peat, coconut fiber, lignite, straw, composted bark and wood fiber) and organic–mineral (mixtures of organic with perlite, expanded clay, vermiculite and sand) substrates can be used for cucumber cultivation [54–56]. The physical properties, especially air–water properties of these substrates differ significantly [5]. The recommended basic physical parameters for substrates intended for cucumber cultivation such as volumetric density, porosity or water and air capacity at −10 cm H_2O are within a very wide range, i.e., volumetric density 30–1400 kg·m^{-3}, total porosity 45–99 (% vol), water holding capacity at −10 cm H_2O 15–85 (% vol) and air holding capacity at −10 cm H_2O 20–80 (% vol). Such discrepancies give great scope for using many substrates for cucumber cultivation, which does not necessarily translate into yield quality and quantity. With such varied parameters, it is important to maintain optimal air and water properties in the substrate by controlling irrigation and fertilization [56,57].

Table 4. Cucumber fruit hardness and color in the CIE Lab system.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Hardness	(HPE)	60.9 ± 1.70 a *	61.1 ± 1.68 a	56.8 ± 1.51 a	63.6 ± 1.50 b
Color (CIE Lab)	a *	−6.6 ± 0.95 a	−6.4 ± 0.51 a	−6.6 ± 1.00 a	−6.8 ± 0.73 a
	b *	11.7 ± 2.29 a	10.9 ± 1.33 a	11.1 ± 1.41 a	12.2 ± 2.02 a
	L	32.8 ± 1.54 a	31.6 ± 1.55 a	29.8 ± 1.50 a	30.1 ± 1.51 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

The parameters characterizing the mineral wool cultivation mats used in the experiment, i.e., bulk density, total porosity, water and air capacity (after gravity water drainage and at a potential of −10 cm H_2O) were within the optimum range for this substrate. The new mineral wool before cultivation had low bulk density, high total porosity, high water and air capacity at a potential of −10 cm H_2O (Table 5). However, it lost its good properties during cultivation and a significant deterioration in physical properties was observed after cultivation compared to the new mineral wool. An increase in the bulk density of the mineral wool mat was observed after 2 cycles of cultivation compared to the new one. However, this did not affect the overall porosity of the wool, but contributed to a significant decrease in air content (Figure 2) and an increase in water content at a potential of −10 cm H_2O (Table 5). The deterioration of the air–water properties in the mat after two cultivation cycles could also have been caused by substrate settlement [34] or an expanding root system [58]. A decrease in total porosity and an increase in bulk density are observed with longer cultivation on mineral wool [34]. This has important implications for changes in air–water properties [34,59], which have a negative effect on plant growth over longer cropping periods [59–62].

Less air in the root zone can lead to abnormal uptake of nutrients, contributing to their accumulation, symptomatic of which is toxicity to plants manifested by chlorosis or necrosis of leaves [58,59]. In the case of lignite, physical properties determined after two cycles of cultivation underwent slight changes. These changes were not so unfavorable in the case of air and water capacity of the substrate as in the case of mineral wool also after two cycles of cultivation (Table 5). It was observed that the decrease in porosity in the lignite substrate after two cultivation cycles of cucumber was associated to a greater extent with a decrease in air content, to a lesser extent with water content at a potential of −10 cm H_2O. Thus, no such changes in air–water properties as in other organic substrates were observed [56,57]. The water retention curve (Figure 3) shows that at the end of cultivation the water content changed to a greater extent in mineral wool than in lignite. The largest fluctuations were observed at a potential of −10 cm H_2O in both substrates and for mineral wool at higher potentials (from −30 to −100 cm H_2O). No such significant differences in water retention were observed in the lignite substrate. However, the retention curves show that the substrates used in the experiment differed significantly in terms of plant-available water content.

Table 5. Physical and air–water properties of mineral wool and lignite mats, new and after second cucumber cultivation cycles.

Parameter	Units	Mineral Wool		Lignite	
		New Substrate	Substrate after 2nd Cultivation Cycle	New Substrate	Substrate after 2nd Cultivation Cycle
Organic matter content	(% of dry matter)	2.2 ± 0.10 a *	7.0 ± 0.69 b	85.0 ± 0.52 a	84.6 ± 0.98 a
Bulk density	(kg m^{-3})	58.5 ± 0.64 a	65.4 ± 2.00 b	394.3 ± 8.90 a	429.1 ± 11.50 b
Total porosity	(% vol)	97.8 ± 0.02 b	97.5 ± 0.17 a	76.1 ± 0.55 b	74.0 ± 0.76 a
Shrinkage	(% vol)	-	-	13.0 ± 1.25 a	10.1 ± 2.36 a
Water content after drainage of gravity water	(% vol)	94.0 ± 0.51 a	94.7 ± 1.49 a	56.9 ± 1.66 a	51.4 ± 2.87 a
Water content pressure at −10 cm H_2O	(% vol)	77.9 ± 0.51 a	87.7 ± 0.82 b	46.6 ± 1.35 a	41.9 ± 1.80 a
Air content after drainage of gravity water	(% vol)	3.8 ± 0.54 a	2.7 ± 0.61 a	19.1 ± 2.16 a	21.9 ± 4.49 a
Air content at −10 cm H_2O	(% vol)	19.9 ± 0.53 b	9.7 ± 1.02 a	41.9 ± 4.80 b	31.9 ± 4.70 a
Easily available water	(% vol)	51.4 ± 0.88 a	69.8 ± 0.97 b	8.1 ± 0.19 a	6.9± 0.11 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

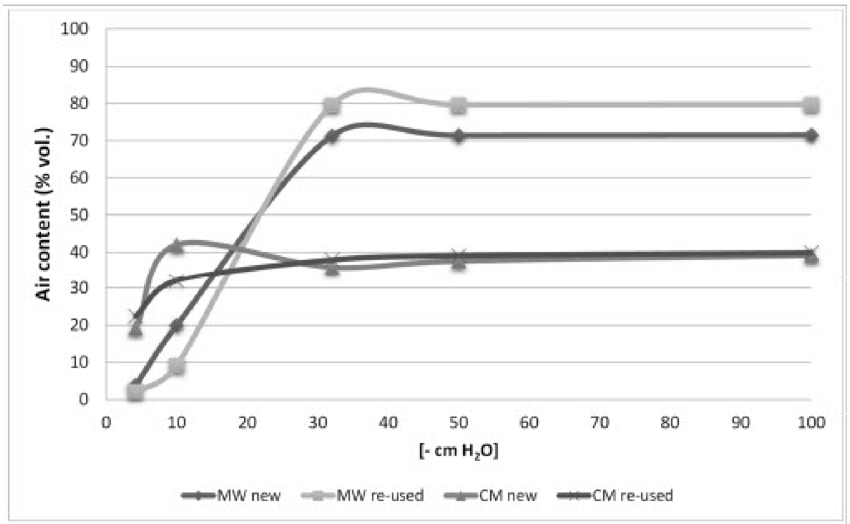

Figure 2. Air content for mineral wool and lignite substrate before and after two cycles of cucumber cultivation.

Easily available water is the water content between the water potential of −10 and −50 cm H_2O [63]. The lignite substrate was characterized by a very low content of plant-available water, which before cultivation in the new substrate was 8.12% and after two cultivation cycles was 6.99%. In mineral wool, the easily available water content was much higher and in the mat before cultivation it was 51.39% and after two cycles it was 69.80%. The type of substrate and their sorption properties have a significant effect on large differences in the easily available water to plants. The structure of the mineral wool mat, i.e., the horizontal arrangement of the fibers and the different density depending on the height of the mat, favors water retention in low negative pressures (from 0 to −10 cm

H_2O), which has a significant impact on its content at the standard potential of −10 cm H_2O. At higher negative pressures (from −10 to −50 cm H_2O), water is less retained and more available for plants, thus significantly increasing the easily available water. Lignite, as an organic substrate, has different properties compared to mineral wool (Table 5). It is a heavier substrate and, depending on the fragmentation of carbon particles and their diameter, has different porosity, which significantly affects the water and air content in the substrate. Unfortunately, these properties are more unfavorable for water (Figure 3), which, at low porosity, is more strongly bound by carbon particles, reducing the content of easily available water. Verdonck et al. [64] report that 30–45 (% vol) of water defined as easily available is needed for optimum plant growth. The content of easily available water in lignite substrate is therefore much lower than that needed for proper plant growth. In fact, not all of this content is used by plants, as a large part of the water during plant growth is lost through evaporation and this amount reaches up to 30% of the total water supplied during irrigation [65,66]. Therefore, the content of easily available water in substrates is of great importance. In order to improve the availability of air and water in the substrate for hydroponically grown plants, an effective fertigation taking into account the properties of the substrates is very important.

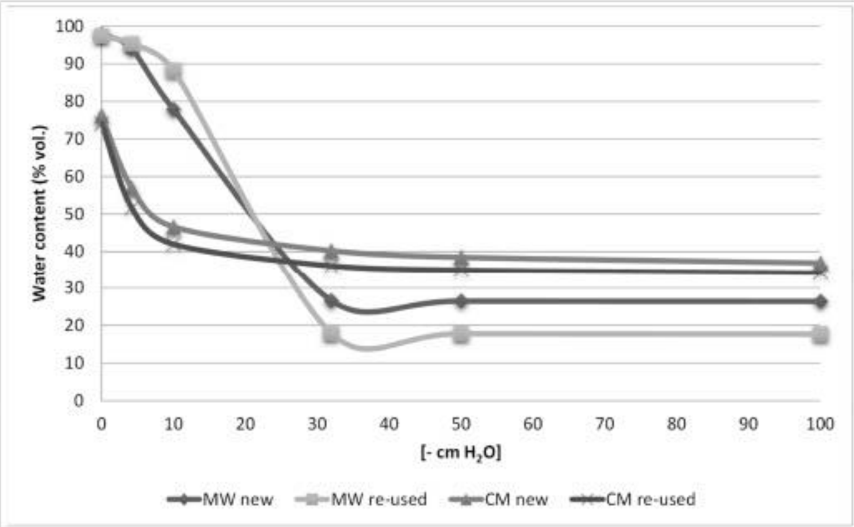

Figure 3. Water content for mineral wool and lignite substrate before and after two cycles of cucumber cultivation.

4. Conclusions

The reuse of lignite substrate in hydroponic cultivation did not reduce cucumber growth, yield and fruit quality compared to the reuse of mineral wool substrate. In addition, the reuse of lignite substrate resulted in higher cucumber yields and fruits with higher firmness and higher dry matter and sugar extract and carotenoid content compared to cucumber grown on reused mineral wool. In spite of the fact that the lignite substrate was characterized by a very low plant-available water content, after its reuse in cucumber cultivation the deterioration of air–water properties was not as high in relation to the parameters of the new substrate as in the case of mineral wool. It was observed that the reduction in porosity in the lignite substrate after two cycles of cucumber cultivation was related more to the reduction in air content and less to the difference in water retention. The results obtained indicate that the biodegradable lignite mat substrate can be reused in hydroponic cucumber cultivation. With the reuse of lignite in cucumber cultivation and appropriate fertigation management, good quality and high yield of cucumber can be obtained compared to the reused mineral wool substrate. The reuse of lignite substrate is pro-environmental and increases its effectiveness in comparison to substrates traditionally used in hydroponic cultivation of cucumber.

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Szkoły Głównej
Gospodarstwa Wiejskiego
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Effect of Selected Physical Parameters of Lignite Substrate on Morphological Attributes, Yield and Quality of Cucumber Fruits Fertigated with High EC Nutrient Solution in Hydroponic Cultivation

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Abstract: Environmentally friendly substrates that are biodegradable may provide an alternative to mineral wool, which is commonly used in hydroponic growing technology. Little is known about the relationship between the physical characteristics of lignite substrate and cucumber yield. The study analyzed the effect of bulk density and water holding capacity of lignite substrate in comparison to mineral wool and EC of nutrient solution on plant morphological parameters, yield and fruit quality of greenhouse cucumber. A positive relation was found between the bulk density of lignite mats and the increase in the number of leaves per week, shoot diameter as well as leaf length and leaf area (calculated as the product of leaf length × width) in cucumbers grown in this medium. Bulk density of lignite growing mats also affected the macro- and micro-nutrient content of cucumber leaves. The physical properties of the substrate and the high EC of the medium had a significant effect on the hardness, color and lutein content of cucumber fruits. The content of biologically active compounds in cucumber fruits depended on the water holding capacity of the medium and the water readily available to plants; these parameters were lower in the lignite medium compared to mineral wool. However, when the lignite substrate was used in hydroponic cucumber cultivation, for a period of 51 days after planting (DAP) there was an increase of more than 23% in the bulk density of the substrate and an increase of nearly 55% in the water readily available compared to the new lignite mats.

Keywords: organic substrate; correlation coefficient; marketable yield; concentration of minerals in leaves; fruit quality

1. Introduction

The world population has already reached 7 billion and will reach 9.7 billion by 2050 [1]. As the population grows, so does the demand for arable land and high quality food all year round. To meet this, fertigation is used in conventional farming, which entails problems of excessive soil salinization. Common causes of excessive salinity also include poor agricultural practices, the use of excessive mineral fertilizers and a hot climate [2,3]. The solution to these problems in most countries of the world is soilless cultivation using mineral and organic substrates, inert to plants. Soilless cultivation has many advantages, one of which is isolation of the plant from the soil, which is often heterogeneous. Intensively exploited, the soil may be degraded, become a habitat of pathogenic pathogens, and in addition is often excessively saline [2–4]. Controlled growing conditions in hydroponic systems allow a significant increase in production efficiency compared to conventional methods [4]. High efficiency and healthiness of cultivation are ensured by a substrate with appropriate, stable physical properties [1,5]. This is usually mineral wool, which is a versatile substrate, widely used in the commercial cultivation of vegetables and other plants. Mineral wool in year-round cultivation is usually used for one season, which leads to the creation of a large amount of post-production waste, of which only a small part is recycled or reused for cultivation [6–9]. The process of utilization of mineral wool after cultivation itself is expensive and is not neutral for the environment, and mineral wool stored outside production facilities, without any protection, may adversely affect human health [9]. Annually, from the area of 1 ha of greenhouses, about 150 m^3 of used mineral wool remains after cultivation. The production of such an amount of mineral wool emits to the atmosphere approximately 26 tons of CO_2 [6,10]. The growing awareness of ecology and problems with mineral wool utilization have contributed to the search for new pro-ecological substrates that will be fully biodegradable [9]. New substrates being investigated for hydroponic cultivation include wood industry waste, composts or biocarbon produced from many types of waste [10–12]. Plant residues such as grape pomace and nut and almond shells are also being tested, along with many others [13–15]. These substrates are often used in mixtures with other organic or mineral substrates, such as perlite or vermiculite, in order to improve physical properties [8,16]. Another type of organic substrate is lignite, which retains a stable homogeneous structure due to its highly condensed matter. Its suitability has been studied in tomato, cucumber and other vegetable and soft fruit cultivation [17–19]. Lignite has good, stable physical properties that allow it to be used for a longer period of time [19]. Additionally, during its production, CO_2 emission is reduced by almost 40% in comparison to the production of the substrate from mineral wool [20].

Lignite mining is associated with negative social and environmental impacts, but it also has some benefits. Mining itself can cause rapid development of areas rich in coal resources by creating new jobs and developing infrastructure [21]. However, the exploitation of springs can take years, and during this period, negative effects on agriculture and the environment can occur, as well as have a negative impact on the mental and physical health of neighboring residents [22]. Positive public attitudes about lignite mining are linked to perceptions of employment opportunities, cheaper fuel and energy [23,24]. The increase in CO_2 and greenhouse gas emissions from the electricity sector has forced a gradual shift away from the use of lignite as a fossil fuel. Coal extracted from low seams can be used for food production, is not used as a fuel, and, therefore, does not emit CO_2 or greenhouse gases. Detman et al. [25] found that lignite is difficult to recycle, and it has been treated as problematic waste. From an agricultural point of view, it is organic matter that contains cellulose, lignin, humins or humic acids and can be used as organic fertilizer in conventional crops. The compounds contained in brown coal (huminous acids, humic acids) play an important role in the absorption of nutrients by plants and act as chelates, preventing leaching and degradation of nutrients. This also contributes to reducing the use of artificial mineral fertilizers. Humic acids have also been found to contain substances such as auxins and gibberellins, which are essential for proper plant growth and development. It has also been proven that soil fertility is improved by the use of humic acids, whose sources include lignite [26,27]. With this in mind, lignite after several seasons of hydroponic cultivation can be intended as an organic fertilizer containing humic acids that improve soil properties. This is a type of cascade proposal for the use of lignite, which was proposed using a substrate of *Miscanthus* [7], but without combustion, which reduces greenhouse gas emissions.

Despite strictly controlled conditions in hydroponic cultivation, both mineral and organic substrates result in excessive accumulation of salts and ions in the substrate [28]. The accumulation of ions in the substrate and the increase in EC electrolytic conductivity affect plant morphology, may lead to a reduction in leaf area and root and shoot length, and affect the amount of fresh and dry matter of the plant [3,29]. Salinity stress, where there is also a high EC of the substrate, affects physiological activity through changes in the transport of primary and secondary metabolites and disturbances of photosynthesis, including disturbances of the proper functioning of photosynthetic pigments [2,29,30]. The environmental pollution that results from hydroponic cultivation using mineral medium is one of the problems to be solved. Another challenge is to increase the quality of fruits and vegetables by increasing the content of biologically active substances. One way to obtain an increased amount of secondary metabolites and biologically active substances is to apply eustressors in the form of salt stress and high EC of the substrate [20,31–33]. Salinity stress can affect the color of cucumber fruit [34], increase the content of vitamin C [35], carotenoids, phenols [36], or acids and antioxidant compounds [37]. On the other hand, salt stress is considered to strongly reduce plant yield [2,33]. By applying salt stress to obtain an increase in biologically active compounds, a strong reduction in yield can be induced [2,36,38] and lead to adverse physical changes, such as the ability to retain water and minerals in the soil [9,39]. Increased nutrient solution ion concentration (high EC) in hydroponic cultivation using lignite substrate increases cucumber fruit quality parameters without significantly reducing yield [20].

There have been no reports to date on the effects of the physical properties of lignite substrate on morphological parameters and plant nutritional status, as well as cucumber fruit yield and quality. The results obtained will help direct research into improving the universal lignite substrate and the use of meters to measure changing physical parameters of the substrate during cultivation. Such solutions will allow future control and management of plant growth and yield in hydroponic crops with lignite substrate.

The aim of this study was to investigate the correlation between bulk density and water holding capacity of the substrate and morphological parameters, macro- and micronutrient content of leaves, and cucumber fruit yield and quality in hydroponic cultivation.

2. Materials and Methods

The trials were conducted at the Greenhouse Experimental Center of the Warsaw University of Life Sciences in the growing rooms of the Department of Vegetable and Medicinal Plants in 2020 and 2021. For testing, we selected greenhouse cucumber (*Cucumis sativus* L.) cultivar "Mewa" F1 by Rijk Zwaan, which has marketable fruits growing up to 24 cm in length and weighing 200–220 g, with dark, slightly glossy skin. The organic substrate for hydroponic cultivation, carbomat lignite mats from CarboHort, measuring $100 \times 20 \times 8$ cm, further denoted by the symbol L, were tested. The controls were Grotop Master mineral wool mats from Grodan, measuring $100 \times 20 \times 7.5$ cm, further denoted by the symbol MW. The microclimate in the growing rooms was controlled with the Hortimax system. Fertilization was controlled using a DGT Volmatic controller with Dosatron dispensers. Before starting the cultivation, new growing mats were flooded with nutrient solution at pH 5.5 and EC 2.6 $dS{\cdot}m^{-1}$, at a rate of approximately 8 dm^3 per mat. After 48 h, two 5 cm drainage holes were made in the lignite mats on each side of the longer sides of the mat [19], while in the mineral wool mats, four drainage holes were made (two horizontal in each of the shorter sides of the mat and two vertical in each of the longer sides of the mat). Cucumber seedlings, 28 days after sowing (DAS) plants, in the first year of the study were planted into the growing mats on 10 July 2020, and in the second year, on 12 July 2021, at a rate of 3 per mat. The crop was grown until the 35th week of the year. In 2020, during the growing season, the average daily solar radiation sum was 1474.9 J cm^{-2}, while the average temperature D/N was 25/23 °C, and the experimental camera humidity and CO_2 concentration were about 70% and 800 ppm, respectively. In the second year of the experiment, the mean daily solar radiation was 1407.0 J cm^{-2}, D/N temperature 25/22 °C, and humidity at the experimental camera and CO_2 concentration were about 70% and 800 ppm, respectively. Plants in the experiment were fed with cucumber standard medium with EC 3.1 $dS{\cdot}m^{-1}$ and pH 5.5–5.8, designated as control EC. In each year of the 7 days after planting (DAP) experiment, the EC of the nutrient solution was varied for half of the plants in the experiment by dosing capillary medium with an EC of about 7 dS·m^{-1} and pH 5.5–5.8, designated as high EC. Four treatments of the experiment were compared: (1) MW/control EC—mineral wool and medium with EC 3.1 dS·m^{-1}, (2) L/control EC—lignite and medium with EC 3.1 dS·m^{-1}, (3) MW/high EC—mineral wool and medium with EC 7 dS·m^{-1}, (4) L/high EC—lignite and medium with EC 7 dS·m^{-1}. The experiments were established using the randomized block method, in 3 replications, with 9 plants in each repetition. The fertigation medium was prepared from one- and two-component mineral fertilizers designed for hydroponic cultivation. The nutrient solution in the control contained (mg·dm^{-3}): N-NO_3 230, N-NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15 and B 0.33. Dosatron dosing devices (D25RE2 0.2–2%) were used for diluting the concentrated nutrient solution and for nitric acid to adjust the pH of the working medium. Working medium parameters (pH and EC) were measured daily using a Senmatic portable measuring device. The nutrient solution was dosed into the plants using a capillary system at a rate of 0.5 to 2.5 dm^3 per day per plant. The amount and frequency of the nutrient solution applied during the day depended on the developmental stage of the plant and the current solar radiation and humidity of the substrate. Irrigation was started 30 min after sunrise, and the last cycle was started 2 h before sunset. After planting the cucumber seedlings on the growing mats, the first 4 buds were removed from each plant. Plants were string trained, using the one-leader method, in which all side shoots and clinging tendrils were removed.

2.1. *Physical and Physico-Chemical Properties of the Substrate*

During the experiment, the pH and EC of the substrate were tested in triplicate from each treatment by taking the solution from the cultivation mats, the so-called mat extract, with a syringe at several places on the mat, at a height of 2, 4 and 6 cm, counting from the top surface of the mat—further defined as the top, middle and bottom of the mat, respectively. For the study, medium samples were taken from the substrate (mat extract) with a volume of approximately 100 cm^3 (single sample). Measurements were carried out 2 times a week 3 times a day at 9:00 a.m., 12:00 p.m. and 3:00 p.m. The method of preparing the substrate samples for evaluating the physical properties of the growing mats depended on the type of substrate. The physical properties of the lignite substrate were determined in accordance with the current standard PN-EN 10041 [40]. An important element of this method is the method of sample preparation, which is based on the natural settling of a loose substrate (10 cm layer), brought to a water potential of −57 cm H_2O. The determination of physical properties of lignite mats was carried out in cylinders of 10 cm diameter and 5 cm height (Figure S1a Supplementary Material) in a sand block (Eijkelkamp) (Figure S1b Supplementary Material). The determination of air–water properties in the vacuum range of 0–100 cm H_2O was conducted using a 24 h time to establish water equilibrium at each of the 5 vacuum levels (−4.5, −10, −32, −50 and −100 cm H_2O). The samples were dried at 105 °C, and the shrinkage of the media was determined by measuring volume loss. The organic matter content after incineration was determined in accordance with PN-EN 13039 [41] (results are given in % DM), while porosity, bulk density of the substrate, referred to in the paper as BD, and water content were calculated according to the current standard PN-EN 13041 [40]. Physical properties of mineral wool mats, both new and after the experiment, were determined by the method developed at the experimental station Naaldwik in the Netherlands [40–44]. With a sharp knife, 15 cm × 15 cm substrate samples were cut from the mats, placed in a grid box (Figure S1c Supplementary Material) 3 cm from the bottom and filled with distilled water to a level above 1 cm above the samples. The samples were kept in the water for 24 h and then, after removing the water, allowed to stand for 3 h before being flooded again with distilled water. After 30 min, the water was drained, and the samples were transferred to a sand block (Eijkelkamp), establishing a vacuum of −100 cm H_2O for 30 min. The samples were then once again flooded with distilled water 3 cm above the surface of the wool for 24 h, and then we proceeded to determine air–water properties in the vacuum range of 0–100 cm H_2O, using the 24 h time to establish water equilibrium at each of the 5 vacuum levels (−4.5, −10, −32, −50 and −100 cm H_2O). After the sand block determinations were completed, the samples were dried at 103 °C in a laboratory fan dryer, and the shrinkage of the substrate was determined by measuring volume loss. Organic matter and ash content were also determined (PN-EN 13039) [41] in order to calculate the total porosity (PN-EN 13041) [40].

The basic physical parameters of the substrate that have a significant effect on plant growth and yield are bulk density, porosity and air–water properties. These characteristics are closely correlated with each other (density–porosity; water capacity–air capacity), so volumetric density and water capacity were selected for comparison. The volumetric density (BD) results are presented in (kg m^{-3}), while the results for the other substrate parameters including water content pressure at −10 cm H_2O, referred to in the paper by the abbreviation WHC, are presented in % vol.

2.2. Morphological Studies

Morphological measurements were made on 9 plants from each treatment, every 7 days to 49 DAP. Weekly cucumber shoot growth in length was studied. For this purpose, the distance from the shoot apex to the location of the shoot apex 7 days earlier (location marked on the string) was measured in cm. The diameter of the shoot was measured with a caliper in mm at two places on the shoot: between the 4th and 5th and 9th and 10th leaves, counting from the top of the plant. The length and width, and the length of the petioles, of the 5th and 10th leaves were measured in cm. The approximate leaf area of the 5th and 10th leaves was calculated as the product of leaf length and width, giving the result in cm^2. The weekly increment in the number of leaves per plant (pcs/week) was also determined. The results obtained from the measurements of the 5th and 10th leaves and the shoot diameter measured at two shoot locations were averaged. The results presented in the tables are averages over the 2 years of the study.

2.3. Macro- and Micronutrient Content in Cucumber Leaves

The macronutrient and micronutrient contents of cucumber leaves were examined twice at 20 and 45 DAP; results are given as averages of the two dates. For the study, each time, 3 leaves located at the height of 4.-5. and 3 leaves located at the height of 9.-10. leaf on the shoot, counting from the shoot apex of the plant, were taken randomly from plants in each treatment. Leaf blades were dried at 60 °C in a laboratory air dryer and then ground in a Bosch TSM6A013B grinder. The ground plant material was incinerated in HNO_3. Elements (P, K Mg, Na, Ca, Fe, Mn, Cu, Zn, B) were determined using an inductively coupled plasma spectrometer (ICP Model OPTIMA 2000DV, Perkin Elmer, Waltham, MA, USA), giving results in mg·kg^{-1} DW. For determination of total N, plant material was digested in concentrated sulfuric acid in the presence of copper-potassium catalyst. Nitrogen content was determined using a Kijeldahl apparatus (Vapodest, Gerhardt, Königswinter, Germany). After distillation of nitrogen as NH_3, the N content was determined by titration (Official Methods of Analysis of AOAC International. 19th Edition, 2012) [45], giving the results in % DW.

2.4. Fruit Yield and Quality

Cucumber fruits were harvested every 2 days (start of harvest from 15–18 DAP). The number and weight of all harvested fruits, marketable fruits and off-selected fruits were determined. The number of fruits dropped was also estimated. Fruits for the study were collected twice, at 29 and 45 DAP. For the study, marketable fruits were taken randomly, 3 from each treatment. Fruit firmness was measured using an HPE hardness meter with a 5 mm shank diameter, at an angle of 90° to the fruit, averaging the result from 3 measurements: at the peduncle, at the center of the fruit and at the post-flowering part. Results were given on the HPE scale from 0–100 units. Fruit color was measured using a portable reflected light spectrophotometer MiniScan XE PLUS D/8-S calibrated on a standard white plate, on the CIE Lab scale: red share, a*; yellow share, b*; and brightness, L. From the data obtained, the polar coordinates of chroma (saturation) $C^* = (a^{*2} + b^{*2})^{\frac{1}{2}}$, color intensity (hue angle) $H^* = \tan^{-1}(b^*/a^*)$ and color index (ratio a^*/b^*) were calculated [46–48]. Fruit color and firmness were measured in 3 replicates.

2.5. Bioactive Compounds, Nitrate Content, Dry Matter and TSS in Fruit

Fruits for analysis were sampled randomly from the marketable yield at 29 and 45 DAP. In cucumber fruits, β-carotene and lutein contents were determined by high-performance liquid chromatography (HPLC) (Shimadzu Scientific Instruments Company), reporting results in mg of 100 g^{-1} FW. Three randomly sampled fruits from each treatment were homogenized with 2 g Na_2SO_4 per 100 g^{-1}. After weighing 5 g of homogenized material on a laboratory balance to the nearest 2/100 g, the samples were ground in a mortar with cold acetone (−20 °C) and the addition of a small amount of quartz sand. The samples were extracted five times by transferring them into 50 mL volumetric flasks and topping up with cold acetone. The samples in the flasks were then centrifuged (15,000 revolutions), and the resulting supernatant was filtered through a 0.22 µm syringe filter (Supelco IsoDisc™ PTFE 25 mm × 0.22 µm) into 1 mL containers placed in a SIL-20AC HT automatic sample feeder (tray temperature 4 °C). A 5 µL extract was applied to a chromatography column, where compound separation was achieved by isocratic elution with methanol at 40 °C on a Kinetex 2.6 µm C18 100 Å 100 mm × 4.6 mm column from Phenomenex, flow rate 2 mL min^{-1}. In this article, lutein and β-carotene were considered for study. The other compounds analyzed in the fruit are presented in the published article that follows [20]. The retention times for lutein, chlorophyll b, chlorophyll a and β-carotene were 0.75, 1.27, 1.80 and 4.20 min, respectively. The wavelengths at which the signals of the individual mixture components were integrated were 445, 470, 430, 445 and 450 nm. The analysis time was 5 min.

Four marketable fruits with a total weight of about 1 kg were randomly selected for determination of nitrate content in fruits. They were then subjected to homogenization. From the mixed sample prepared in this way, a 10 g sample of plant material was taken three times by adding 0.5 g of activated carbon and 100 mL of 2% acetic acid, and then shaken. After 30 min, the resulting solution was filtered through a fluted filter. Nitrate content in mg $N\text{-}NO_3/100\ g^{-1}$ FW of fruits was determined spectrophotometrically at 540 nm using a Fiastar 5000 Analyzer. The dry matter content of the fruits was determined by the dry-weighing method at 105 °C, giving the results in %.

The content of soluble components in TSS cell sap was determined using a digital refractometer (Hanna Instruments HI-96800), reporting the results in %.

2.6. Statistical Analysis

Results were analyzed as the average of 2 years of study. The results of the study were statistically processed using Statistica 13.3 software. Data were analyzed for normal distribution and homogeneity of variance, followed by multiple regression analysis for the relationship between plant biometric traits and selected physical characteristics of the substrates. Linear correlation (z) coefficient was calculated separately for each pair of parameters. Numerical data for pH and EC of the mat extracts were checked for homogeneity of variance for the mentioned parameters (Levene's test), and then analysis of variance (ANOVA) was performed. The means were compared using Tukey's test (HSD) at a significance level of $p < 0.05$.

3. Results

The physical properties of mineral wool and lignite mats before and after cucumber cultivation are shown in Table 1. The new mineral wool mat has good physical properties typical of this substrate: density 61.13 kg m^{-3}, porosity 97.70% and high content of readily available water. The air–water properties were favorable for greenhouse cucumber cultivation, and after cultivation (51 DAP), changes were observed in both physical properties and changes in organic matter content compared to the new substrate. There was a 58.7% increase in organic matter in mats after cucumber cultivation fed with standard MW/control EC medium and a 123% increase in MW/high EC mats fed with high EC medium compared to new mats (Table 1). Water content at a potential of −10 cm H_2O increased by nearly 19% in MW/control EC mats and by 27.3% in MW/high EC mats. The plant-available water content also increased by an average of about 41%. These changes reduced the air content of the mat by more than 30% in the MW/control EC treatment and by 43% in the MW/high EC treatment, but it was still within the range of optimal levels for cucumber. The results indicate that mat water content increased toward the end of cultivation at the expense of air content. Higher EC did not cause much change compared to the control (Table 1).

Table 1. Physical properties of mineral wool and lignite mats before and after cucumber cultivation (average of 2 years).

Physical Parameter of the Substrate	New MW	MW/Control EC	MW/High EC	New L	L/Control EC	L/High EC
Organic matter content	3.17	5.03	7.07	85.55	85.50	85.07
Bulk density (BD)	61.13	60.78	61.89	378.15	384.60	391.96
Total porosity	97.70	97.67	97.59	77.07	76.68	76.29
Shrinkage	-	-	-	25.48	20.15	19.74
Water content after drainage of gravity water	92.01	93.08	93.74	50.57	62.41	76.29
Water content pressure at −10 cm H_2O (water holding capacity) (WHC)	59.91	71.66	76,24	41.32	51.05	50.98
Air content after drainage of gravity water	5.68	4.60	3.85	26.50	14.27	15.92
Air content at −10 cm H_2O	37.78	26.01	21.35	35.74	25.62	25.31
Readily accessible water	30.49	40.95	45.04	6.55	10.66	9.62

New lignite mat (New L) had high bulk density (378.15 kg m^{-3}) and low porosity (77.07% vol). Its water holding capacity was low (41.32% vol) and it gave up water quickly, which promoted aeration of the mat and was reflected in the high air content regardless of the potential tested (Table 1 and Figure 1a–d). There was a 0.3% decrease in organic matter in mats after cucumber cultivation compared to new lignite mats. The lignite was also characterized by low plant-available water content, which was about 78.7% lower compared to the New MW mats. A beneficial feature of the amendments was the decrease in shrinkage of lignite during cultivation by 20.9% in the L/control EC treatment substrate and by 22.5% in the L/high EC treatment substrate compared to the New substrate (Table 1).

Substrate parameters, measured in the mat extract, depended on substrate type and medium EC. The mineral wool substrate, when cucumbers were fed with standard nutrient solution (MW/control EC), had approximately 14% higher pH compared to the lignite substrate (L/control EC) and 5% higher pH for plants fertilized with high EC nutrient solution, regardless of mat height (Figure 2a,c,e). For ion concentration in the substrate, mineral wool and lignite, when fed capillary nutrient solution with higher EC (7 dS·m^{-1}), had higher EC at the top, middle, and bottom of the growing mat compared to mineral wool and lignite mats fed control nutrient solution (Figure 2b,d,f). The lignite mats in which the growing cucumber was fed with a high EC medium only had higher EC in the upper part compared to the mineral wool, where the cucumber was also fed with a higher EC medium (Figure 2b). In contrast, the middle and lower parts of the lignite mats at high EC of the nutrient solution had lower EC of the substrate compared to the EC of the mineral wool substrate also fed with high EC (Figure 2d,f). The lignite substrate where cucumbers were fed with high EC medium (L/high EC) had about 15% higher EC compared to mineral wool mats, where cucumbers were also fed with high EC medium (Figure 2b). At the middle height and bottom of the mat, the highest substrate EC values were found in the MW/high EC treatment and were 10.5% and 9.3% higher, respectively, compared to L/high EC (Figure 2d,f).

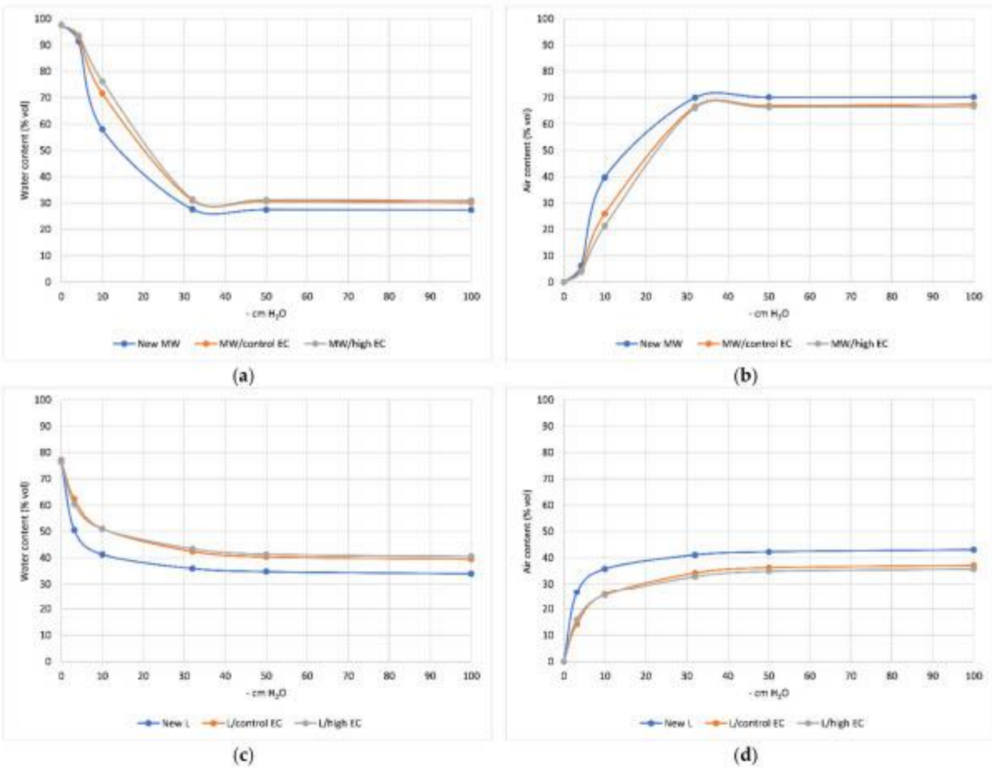
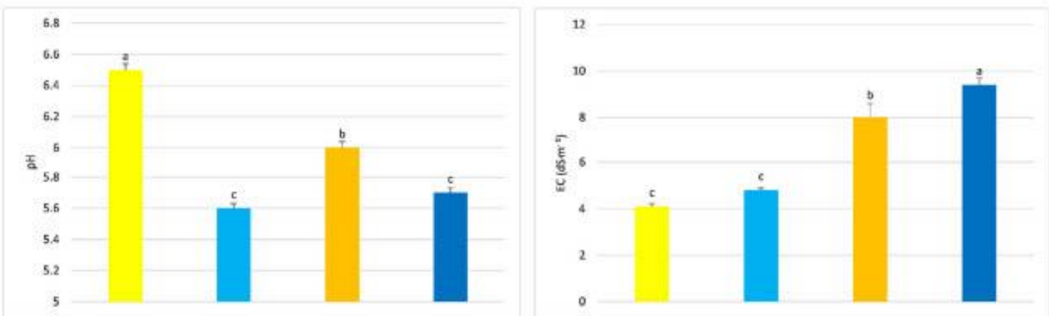
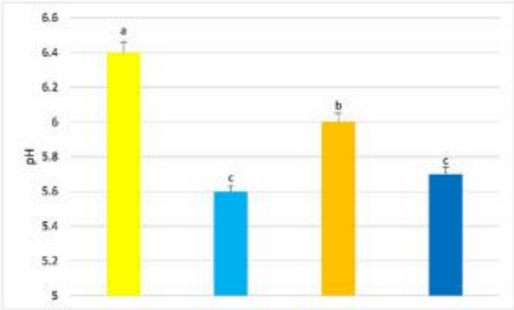


Figure 1. Air and water content of mineral wool (**a**,**b**) and lignite substrate (**c**,**d**) before and after cucumber cultivation.

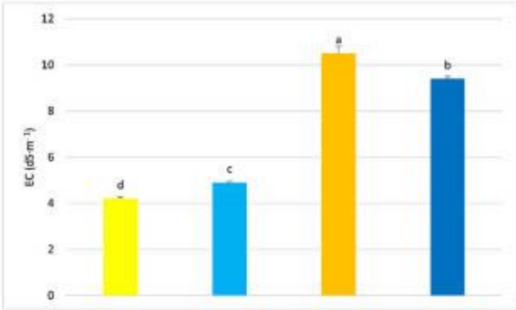


(**a**) (**b**)

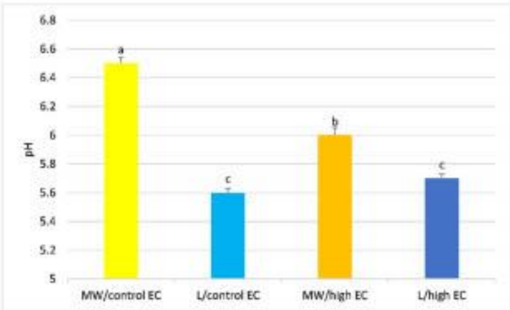
Figure 2. *Cont.*



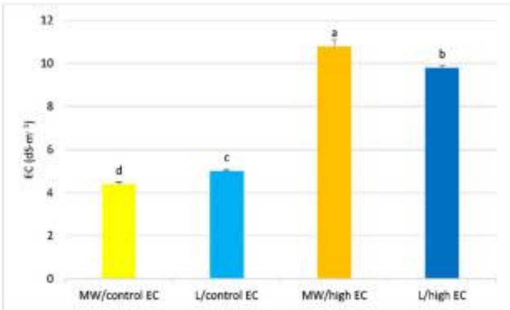
(c)



(d)



(e)



(f)

Figure 2. pH and EC of mineral wool and lignite mat extracts, taken from the top (**a**,**b**), middle (**c**,**d**) and bottom of the mat (**e**,**f**), respectively. Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Vertical bars indicate ± standard deviation.

3.1. Morphological Studies

Analyzing the results of linear correlation, there was a significant effect of water capacity on the number of leaves emerging per week and petiole length of cucumber in plants grown in mineral wool with both standard and high EC of nutrient solution (Table 2). The high coefficient of determination confirmed these relationships of the studied physical characteristics of mineral wool on the average number of leaves emerging per week (75.19%) and petiole length of cucumber (72.43%) (Table 3).

A significant negative correlation was found between the bulk density of lignite growing mats in which cucumber was grown and plants were fed with standard EC (L/control EC) and the number of new leaves per week per shoot, shoot diameter, leaf length and leaf area and petiole length (Table 2). This was confirmed by the high coefficient of determination (D), where physical characteristics had a significant effect on the discussed morphological traits of plants (Table 3). On the other hand, a positive correlation was found between the water holding capacity, both of mineral wool when standard EC and high EC of capillary medium were applied, and the water holding capacity of lignite in the treatment with high EC, and the number of leaves growing weekly on the cucumber shoot. The petiole length of cucumber leaves also depended on the water holding capacity of the mineral wool mats regardless of the EC of the capillary medium (Table 2). When high EC of nutrient solution was applied in lignite substrate, a significant effect of water holding capacity on the number of leaves growing per week was shown as evidenced by the coefficient of determination for this parameter, which was 72.98%. At the same time, other treatments showed a high effect of BD and WHC on the weekly increase in number of leaves in cucumber (Table 3).

Table 2. Linear correlation coefficient[(z)] between selected morphological parameters of cucumber and physical properties of medium (BD, WHC) depending on medium type and medium EC.

Treatment	Physical Parameter of the Substrate	Shoot Length Increase Per Week	Leaf Number Per Week	Shoot Diameter	Leaf Length	Leaf Width	Leaf Area	Petiole Length
MW/control EC	BD	0.4667	0.2848	0.6429	0.4736	0.4376	0.4431	042.53
	WHC	0.2255	0.8476 *	0.3794	0.7326	0.6361	0.7273	0.8508 *
L/control EC	BD	−0.0145	−0.5190 *	−0.8082 *	−0.7648 *	−0.5544	−0.6573 *	−0.7552 *
	WHC	0.1066	0.2659	−0.1366	−0.0405	0.0168	−0.0039	−0.0232
MW/high EC	BD	0.4017	0.0680	0.4244	0.3765	0.3124	0.3360	0.3283
	WHC	0.3186	0.7968 *	0.3476	0.6339	0.4884	0.6060	0.8594 *
L/high EC	BD	0.3348	0.6103	−0.2252	0.3156	0.2001	0.3115	0.5180
	WHC	0.3143	0.8402 *	0.0748	0.6068	0.4080	0.5651	0.6967

* significant at $p \leq 0.05$.

Table 3. Multiple correlation coefficient (R) and coefficient of determination (D) for selected morphological parameters of cucumber plants and type of medium and EC.

Parameter	MW/Control EC		L/Control EC		MW/High EC		L/High EC	
	R	D (%)	R	D (%)	R	D (%)	R	D (%)
Stem length increase per week	0.4672	21.82	0.4263	18.17	0.1245	1.55	0.3412	11.64
Leaf number per week	0.8671 *	75.19	0.8749 *	76.54	0.7393 *	54.71	0.8543 *	72.98
Diameter shoot	0.6451	41.62	0.4546	20.67	0.8366 *	69.99	0.5194	26.98
Leaf length	0.7406	54.85	0.6576	43.24	0.8223 *	67.62	0.6937	48.12
Leaf width	0.6483	42.03	0.4962	24.62	0.6166	38.02	0.4771	22.76
Leaf area	0.7312	53.47	0.6027	36.32	0.7198 *	51.81	0.6312	39.84
Petiole length	0.8510 *	72.43	0.8650 *	74.83	0.8188 *	67.05	0.7049	32.91

* significant at $p \leq 0.05$. D < 25%—low impact, 25–45%—average impact, 46–100%—high impact.

3.2. *Effect of Bulk Density and Water Capacity of the Substrate on Macro- and Micronutrient Content in Cucumber Leaves*

Linear correlation analysis of the relationship between macronutrient content and physical properties of substrates showed a high positive correlation of K content in leaves of cucumber plants grown in mineral wool and fertilized with standard EC nutrient solution, and BD of mineral wool and WHC substrates. No significant relationships of macronutrient concentration in cucumber leaves were found with DB and WHC of mineral wool when high EC of capillary nutrient solution was applied (Tables 4 and 5). However, in the case of lignite and application of control nutrient solution in cucumber cultivation, a positive relationship was found between K concentration in cucumber leaves and WHC of lignite cultivation mats (Table 4).The significant relationship of these elements was confirmed by the multiple correlation coefficient R and the value of coefficient of determination (D = 96.67%) (Table 5). Significantly higher K concentration in leaves was found in cucumber grown at high EC of mineral wool substrate than at EC standard for cucumber and lignite substrate (Table S1 Supplementary Materials).

Table 4. Linear correlation coefficient[(z)] for the relationship between macronutrient content in cucumber leaves and physical parameters of the medium (BD, WHC) depending on the type of medium and EC of the medium.

Treatment	Physical Parameter of the Substrate	Macronutrient					
		N	P	K	Ca	Mg	S-SO_4
MW/control EC	BD	0.1434	0.7279	0.8977 *	−0.4575	−0.3844	−0.3217
	WHC	0.2534	0.8309	0.9284 *	−0.5629	−0.4981	−0.4277
L/control EC	BD	0.0821	−0.4286	0.4593	0.1396	0.0871	−0.0737
	WHC	0.5042	0.1423	0.9115 *	−0.3581	−0.3985	−0.4256
MW/high EC	BD	0.2919	0.2542	0.3678	−0.3863	−0.4751	−0.6346
	WHC	0.3997	0.3472	0.3582	−0.4894	−0.5737	−0.6828
L/high EC	BD	0.5357	0.7794	−0.4806	−0.8000 *	−0.5893	−0.6150 *
	WHC	0.3990	0.6296	−0.3213	−0.6539	−0.4329	−0.3402

* significant at $p \leq 0.05$.

Table 5. Multiple correlation coefficient (R) and coefficient of determination (D) for macronutrient content in cucumber leaves vs. medium type and medium EC.

Macronutrient	MW/Control EC		L/Control EC		MW/High EC		L/High EC	
	R	D (%)	R	D (%)	R	D (%)	R	D (%)
N	0.4312	18.59	0.7515	56.48	0.6896	47.56	0.6417	41.18
P	0.8648	74.79	0.6494	42.17	0.8459	71.55	0.8570	73.44
K	0.9288 *	86.27	0.9832 *	96.67	0.3690	13.62	0.6479	41.98
Ca	0.6322	39.97	0.7745	60.00	0.7345	53.96	0.8697 *	75.64
Mg	0.5953	35.44	0.8053 *	64.85	0.7268	52.82	0.7167	51.37
S-SO_4	0.5279	27.86	0.7251	52.59	0.5775	33.35	0.9962 *	99.25

* significant at $p \leq 0.05$. D < 25%—low impact, 25–45%—average impact, 46–100%—high impact.

In cucumbers grown in lignite substrate, a significant negative correlation was found between the physical properties of the medium, both BD and WHC, and the leaf concentrations of macronutrients such as calcium and sulfate. Significant correlations were found mainly when lignite was fertilized with high EC medium (Table 4), which was confirmed by multiple correlation analysis and coefficient of determination for these parameters (Table 5). The concentration of calcium, and especially sulfur, in cucumber leaves was higher when plants were grown in lignite substrate than in mineral wool, irrespective of the EC ion concentration of the medium. On the other hand, the concentration of magnesium in cucumber leaves depended more on the concentration of Mg ions in the capillary medium than on the characteristics of the medium because both when cucumber was grown in mineral wool and in lignite mats, more magnesium was in the leaves when plants were fertilized with high EC medium (Table S1 Supplementary Materials).

The results of linear correlation between micronutrient content in cucumber leaves and physical properties of the substrate indicated that there was a significant positive correlation between water holding capacity of the lignite substrate fed with standard EC medium and iron accumulation in cucumber leaves (Table 6). The coefficient of determination for this relationship was 64.06% (Table 7). There was also a significant positive correlation between zinc content in cucumber leaves and water holding capacity of lignite in the treatment with high EC of nutrient solution (Table 6), as confirmed by the significant multiple correlation coefficient R and coefficient of determination (D) of 74.21% (Table 7).

Table 6. Linear correlation coefficient[(z)] for the relationship between micronutrient content in cucumber leaves and physical parameters of the medium (BD, WHC) depending on the type of medium and medium EC.

Treatment	Physical Parameter of the Substrate	Micronutrient				
		Fe	Mn	Cu	Zn	B
MW/control EC	BD	−0.4407	0.4478	0.0877	−0.4108	0.4717
	WHC	0.1183	0.4784	0.3066	−0.0947	0.5699
L/control EC	BD	0.5196	0.6525	0.5430	0.4872	−0.2190
	WHC	0.7998 *	0.1002	0.0863	0.0778	0.0559
MW/high EC	BD	0.0233	−0.0005	−0.5077	−0.2007	0.3756
	WHC	−0.5472	−0.4904	−0.5977	0.1155	0.5356
L/high EC	BD	0.0613	−0.0184	−0.1585	0.5994	−0.3615
	WHC	−0.1214	−0.2324	−0.4497	0.8429 *	−0.2380

* significant at $p \leq 0.05$.

Table 7. Multiple correlation coefficient (R) and coefficient of determination (D) for micronutrient content in cucumber leaves vs. media type and medium EC.

Micronutrient	MW/Control EC		L/Control EC		MW/High EC		L/High EC	
	R	D (%)	R	D (%)	R	D (%)	R	D (%)
Fe	0.6369	40.71	0.8004 *	64.06	0.6352	40.34	0.3144	9.88
Mn	0.5322	28.32	0.5595	31.31	0.6783	46.01	0.3888	15.12
Cu	0.3179	10.10	0.6480	42.00	0.5636	31.77	0.5910	34.93
Zn	0.4337	18.81	0.3147	9.90	0.5056	25.56	0.8614 *	74.21
B	0.5521	30.48	0.6058	36.69	0.2716	7.37	0.3780	14.29

* significant at $p \leq 0.05$. D < 25%—low impact, 25–45%—average impact, 46–100%—high impact.

The accumulation in cucumber leaves of iron, zinc and boron was significantly higher in plants grown in lignite substrate than in mineral wool regardless of the concentration of ions in the drip nutrient solution (Table S1 Supplementary Materials).

3.3. Effect of Bulk Density and Water Holding Capacity on Cucumber Fruit Yield and Quality

The number of harvested cucumber fruits grown in lignite substrate and fed with standard EC medium depended on both BD and WHC of the growing mat. The water holding capacity of this substrate was significantly positively correlated with both the total number of harvested cucumber fruits and the number and weight of marketable fruits and non-choice fruits. There was also a significant relationship of bulk density and water capacity of lignite to total cucumber yield (Table 8). The dependence of cucumber fruit number and fruit weight on the physical properties of lignite was confirmed by significant multiple correlation coefficients and the coefficient of determination for cucumber yield in lignite with standard medium EC. In the case of cucumber grown in mineral wool and fed with high EC of nutrient solution, such relationships were not found (Tables 8 and 9). Growing cucumber in lignite substrate only with medium of standard EC proved a significant effect of BD and WHC of this substrate on the number of dropped cucumber fruits. This relationship was shown in the positive linear correlation for both these characteristics of the lignite substrate and in the significance of the multiple correlation coefficient and the coefficient of determination for this treatment, which was 96.47% (Tables 8 and 9).

Table 8. Linear correlation coefficient[z] for the relationship between cucumber fruit yield and physical parameters of the medium (BD, WHC) depending on the type of medium and medium EC.

Treatment	Physical Parameter of the Substrate	Total Yield		Marketable Yield		Unmarketable Yield		Number of Aborted Fruits
		Number of Fruits	Weight of Fruit	Number of Fruits	Weight of Fruit	Number of Fruits	Weight of Fruit	
MW/control EC	BD	−0.5195	−0.1661	−0.1675	−0.1397	−0.6762	−0.6763	0.4606
	WHC	−0.0597	0.2209	0.0108	0.0176	−0.1017	−0.1019	0.2020
L/control	BD	0.8415 *	0.8409 *	0.6908 *	0.6373	0.9798	0.9588	0.8384 *
	WHC	0.9606 *	0.9485 *	0.8678 *	0.8239 *	0.9920*	0.9896 *	0.7560 *
MW/high EC	BD	0.3216	0.7005	0.8114	0.8097	−0.4821	−0.3462	−0.7862
	WHC	0.4177	0.7175	0.8055	0.8035	−0.3735	−0.2003	−0.7108
L/high EC	BD	0.5626	0.5961	0.7175	0.6840	0.1690	0.3498	0.0107
	WHC	0.7189	0.4632	0.5545	0.5446	0.2377	0.2578	0.3161

* significant at $p \leq 0.05$.

Table 9. Multiple correlation coefficient (R) and coefficient of determination (D) for cucumber yield versus substrate type and medium EC.

Yield of Fruit		MW/Control EC		L/Control EC		MW/High EC		L/High EC	
		R	D (%)	R	D (%)	R	D (%)	R	D (%)
Total yield	Number of fruits	0.7007	49.10	0.9999 *	99.99	0.7376	54.41	0.8164	66.65
	Weight of fruit	0.7190	51.70	0.9783	95.71	0.5647	31.89	0.6821	46.53
Marketable yield	Number of fruits	0.8119	65.93	0.9989 *	99.79	0.2729	7.45	0.8257	68.18
	Weight of fruit	0.8102	65.64	0.9820 *	96.43	0.2383	5.68	0.7631	58.23
Unmarketable yield	Number of fruits	0.9433	88.99	0.9972 *	99.44	0.9339	87.22	0.2998	8.99
	Weight of fruit	0.7972	63.65	0.9903 *	98.07	0.9339	87.22	0.4240	17.79
Number of aborted fruit		0.9577	91.73	0.9821 *	96.47	0.8571	73.47	0.8839	78.13

* significant at $p \leq 0.05$. <25%—low impact, 25–45%—average impact, 46–100%—high impact.

A significant relationship was found between cucumber fruit firmness and the physical properties of the medium in hydroponic cultivation (Tables 10 and 11). The higher the bulk density of lignite substrate fed with standard nutrient solution, the firmer the cucumber fruits were, as confirmed by the high (77.94%) coefficient of determination for this parameter (Table 11). In the case of plants grown in mineral wool and fed with high EC of nutrient solution, the increase in moisture content of this substrate had a decreasing effect on cucumber fruit hardness (Table 10). The multiple correlation coefficient in this case was (R = 0.7569) and the coefficient of determination was 57.29% (Table 11). In both treatments, when lignite growing mats were fed with standard nutrient solution and when in mineral wool mats fed with high EC nutrient solution, a statistically significant negative correlation was found between bulk density of these substrates and cucumber fruit skin color saturation (C*). This was confirmed by the coefficient of determination, which was 75.03% and 75.84%, respectively (Tables 10 and 11). Cucumber fruit skin color intensity (H*) and coloration index (a*/b*) were positively correlated with the bulk density of the medium, but only in the mineral wool medium treatment, where standard medium was used (Tables 10 and 11). In the case of lignite substrate and high EC medium, a significant multiple correlation was also found between physical properties of the substrate and color intensity (H*) and color index (a*/b*) of cucumber fruit peel (Table 11).

Table 10. Linear correlation coefficient[(z)] for the relationship between firmness of fruit, fruit skin color traits in the CIE Lab system: C* (color saturation), H* (color intensity) and a*/b* color index, and physical parameters of the medium (BD, WHC) depending on the type of medium and EC of the medium.

Treatment	Physical Parameter of the Substrate	Firmness	C*	H*	a*/b*
MW/control EC	BD	−0.0451	0.1603	0.7442 *	0.7326 *
	WHC	−0.6256	−0.2896	0.2782	0.2539
L/control EC	BD	0.6514 *	−0.8071 *	0.5791	0.5685
	WHC	−0.0824	0.0352	0.1120	0.1211
MW/high EC	BD	0.1770	−0.8633 *	−0.5064	−0.5065
	WHC	−0.6722 *	−0.4783	0.0569	0.0598
L/high EC	BD	−0.4663	0.0517	0.4614	0.4581
	WHC	−0.6221	0.1485	0.6603	0.6616

* significant at $p \leq 0.05$.

Table 11. Multiple correlation coefficient (R) and coefficient of determination (D) for firmness of fruit, fruit skin color traits in CIE Lab system: C* (color saturation), H* (color intensity) and b*/a* color index vs. substrate type and medium EC.

Parameter	MW/Control EC		L/Control EC		MW/High EC		L/High EC	
	R	D (%)	R	D (%)	R	D (%)	R	D (%)
Firmness	0.7064 *	49.91	0.8828 *	77.94	0.7569 *	57.29	0.6283 *	39.48
C*	0.4652	21.65	0.8662 *	75.03	0.8708 *	75.84	0.1959	3.84
H*	0.7550 *	57.01	0.6122	37.47	0.5957	35.48	0.6781 *	45.98
a*/b*	0.7476 *	55.89	0.6141	37.71	0.5820	33.87	0.6810 *	46.38

* significant at $p \leq 0.05$. < 25%—low impact, 25–45%—average impact, 46–100%—high impact.

3.4. Effect of Bulk Density and Water Capacity of the Substrate on Dry Matter, Tss and Bioactive Compound Content of Fruit

Using the standard EC of the medium in mineral wool mats, a negative correlation was obtained between bulk density and TSS and β-carotene content in cucumber fruits (Table 12). Coefficients of determination (D) illustrating the influence of selected physical substrate characteristics on dry matter and TSS content in fruit were low and amounted to 15.19% and 12.57%, respectively (Table 13).This indicates a slight influence of the studied substrate characteristics on the discussed parameters (Table 13). Additionally, no significant correlation was obtained between the physical properties of the substrates and the quality of fruits from plants grown in mineral wool and fertilized with high EC medium (Table 12).

There was a significant positive correlation between WHC and lutein content in fruits from plants grown in lignite substrate, both fertilized with standard and high EC medium (Table 12). It was also confirmed by high coefficient of determination (D) and value of multiple correlation coefficient R, which was 0.8411 for plants fertilized with standard EC and 0.8211 for those fertilized with high EC nutrient solution (Table 13). On the other hand, no relationship was found between cucumber fruit dry matter, TSS, β-carotene and nitrate content and physical properties of both lignite and mineral wool substrates, irrespective of medium EC (Tables 12 and 13).

Table 12. Linear correlation coefficient$^{(z)}$ for the relationship between the content of dry matter, TSS, selected bioactive compounds and nitrates (in mg N-NO_3/100 g^{-1} FW) in cucumber fruit and the physical parameters of the medium (BD, WHC) depending on the type of medium and EC of the medium.

Treatment	Physical Parameter of the Substrate	Dry Matter	TSS	β-Carotene	Lutein	Nitrates
MW/control EC	BD	0.3399	−0.3275	−0.3837	0.1806	0.2598
	WHC	0.0137	−0.0542	0.1200	0.5242	−0.1685
L/control EC	BD	0.2636	0.4665	−0.1945	−0.0304	−0.3964
	WHC	−0.2079	0.1375	0.2934	0.7782 *	0.1842
MW/high EC	BD	−0.0352	−0.3728	0.2074	0.2589	0.1367
	WHC	0.5488	−0.5961	0.1863	0.5225	−0.1066
L/high EC	BD	0.5151	−0.0803	0.6098	0.5481	−0.1091
	WHC	0.7108	−0.3257	0.2978	0.7962 *	−0.3576

* significant at $p \leq 0.05$.

Table 13. Multiple correlation coefficient (R) and coefficient of determination (D) for the content of dry matter, TSS, selected bioactive compounds and nitrates in cucumber fruit depending on the type of substrate and medium EC.

Parameter	MW/Control EC		L/Control EC		MW/High EC		L/High EC	
	R	D (%)	R	D (%)	R	D (%)	R	D (%)
Dry matter	0.3898	15.19	0.6469	41.85	0.4363	19.04	0.7232	52.30
TSS	0.3545	12.57	0.6040	36.48	0.4704	22.12	0.4704	22.13
β-carotene	0.5359	28.72	0.2296	5.27	0.4540	20.61	0.7142	51.01
Lutein	0.5351	28.64	0.8411 *	70.74	0.5226	27,31	0.8211 *	67.42
Nitrates	0.4403	19.39	0.2398	5.75	0.5504	30.29	0.4901	24.02

* significant at $p \leq 0.05$. < 25%—low impact, 25–45%—average impact, 46–100%—high impact.

4. Discussion

Lignite substrate can be applied in hydroponic cultivation of cucumber. Studies have confirmed that lignite growing mats at the beginning of their use in plant cultivation have low water holding capacity and low content of readily available water [19]. Bulk density (BD) increased in lignite mats after 51 DAP of cucumber cultivation in comparison to new cultivation mats, which was associated with a decrease in air content in mats. The effect of lowering this parameter was an increase in water holding capacity (WHC) of the substrate and water readily available to plants (Table 1). A similar trend was found when lignite substrate was used twice in hydroponic cultivation of greenhouse cucumber [19]. Water holding capacity and water readily available to plants can significantly affect plant growth and yield [19,49,50]. According to a study by Kennard et al. and Dannehl et al. [6,8] the physical properties of the substrate recommended for most plants are in the following ranges: 20–30 vol% readily available water, ≥85 vol% total porosity, and 10–30 vol% total water holding capacity. Despite the low physical parameters of lignite mats, such as water holding capacity and readily available water content, no negative effect of this substrate on plant growth and yield was observed. As shown in previous studies, the yield of cucumber grown in reused lignite mats was higher compared to reused mineral wool mats. This may be due to the better conditions for the root system in the reused growing mats [19]. The results for the nutrient extracts from the growing mats (substrate) indicated that the pH of the lignite substrate was similar to that of the mineral wool substrate. However, the EC level was lower in the lignite substrate compared to the mineral wool substrate. The sorption complex of lignite may to some extent reduce the negative effect of high EC concentration in the substrate as for cucumber (Figure 2a–f). The EC and pH values of the substrate and the physico-chemical characteristics of the plant root system environment are mainly influenced by the material of the growing medium [51,52]. In our study, a negative correlation was found between the water holding capacity of the lignite substrate supplied with the standard EC of the growing medium and the average length and surface area of the leaf. In the study, the average length of a fully developed cucumber leaf was about 22.7 cm, and the calculated leaf area was about 629.8 cm^2 (Table S2 Supplementary Materials).Other researchers also reported a negative effect of low water content on leaf area of tomato grown on sheep wool or hemp fiber substrate [6]. A negative linear correlation ($R = -0.8082$) for water holding capacity of lignite substrate in L/control EC treatment was also reported for shoot diameter of cucumber plants. In the present study, the diameter of the cucumber shoot was on average 7.0 mm (Table S2 Supplementary Materials). Other researchers report that for tomato shoot diameter, varying substrate had no effect on this parameter [53,54]. Different results were obtained by studying the effect of date palm waste substrate on shoot diameter and length of cucumber plants, where this substrate significantly affected the morphological parameters in question compared to, for example, rice husk substrate. According to Sonneveld et al. [55], the date palm substrate had the highest porosity, bulk density and water holding capacity compared to other tested substrates, which translated into good growth conditions for cucumber plants. The availability of nutrients and appropriate physical properties of the substrate affect vegetative growth, and this in turn affects the diameter of the stem. The larger the stem is, the more the vegetative plant growth is. Stems with the thickest stem diameter are less susceptible to damage and other abiotic stresses. Additionally, a thicker stem transports water and nutrients more efficiently [56]. Studies on the effect of lignite substrate on cucumber growth and yield in combination with eustress in the form of high EC showed higher plant stem diameter in the treatment with lignite substrate [20]. It is likely that the lignite substrate, due to its properties, humic acids and nutrient content [57], has a beneficial effect on stem thickness and consequently on plant growth.

In the present study, a significant correlation was found between the WHC of the medium in both MW/control EC and L/control EC combinations to K content in cucumber leaves. The potassium content of cucumber leaves grown in these combinations was 35,252.0 $mg \cdot kg^{-1}$ DM for MW/control EC and 31,741.7 $mg \cdot kg^{-1}$ DM for L/control EC. Significantly more K was contained in the leaves of plants grown in mineral wool and fertilized with higher EC of nutrient solution, where this content was on average about 42,275.0 $mg \cdot kg^{-1}$ DM. On the other hand, higher EC of the nutrient solution in the case of lignite substrate did not result in higher K accumulation in cucumber leaves, as it was only 34,358.3 $mg \cdot kg^{-1}$ DM (Table S1 Supplementary Materials). However, when using high EC of the medium in the lignite substrate (L/high EC), a significant correlation was found between the physical properties of the medium and the S-SO_4 content in cucumber leaves. As reported by Nurzyński et al. [58], the content of mineral components in the substrate changes during cultivation, while changes in the content of components in the leaves are minimal; therefore, proper fertilization and pH in the root environment are important. Similarly to the content of bioactive compounds in fruits, the content of macro- and microelements in leaves may be influenced by many factors, starting from antagonistic relationships of elements [59] through the correct pH of the solution and irrigation strategies, to the right cultivation and plant care practices [55,58]. Micronutrients are elements that are used by plants in small quantities, but a lack or excess of these elements can disrupt the life processes of the plant and consequently reduce the yield [60]. The present study showed a significant correlation of water capacity of lignite mat to Fe (L/control EC) and Zn (L/high EC) content in cucumber leaves (Table 6). Lignite mats, in spite of their stable chemical composition, low chlorine content and high humic acid content, have large amounts of micronutrients in their composition, especially Fe and Zn [17,57]. In the initial stages of cultivation, negative effects on the plant may occur, e.g., excessive accumulation of these elements in the root zone, although this phenomenon was not observed in the conducted studies. In a study by Sonneveld and Voogt [55] it was proved that different Fe concentrations in the nutrient solution had no significant effect on the content of this element in young cucumber leaves. On the other hand, in a study on Zn content in tomato and cucumber leaves, nutrient solution containing different concentrations of Zn was found to have little effect on the Zn content in tomato leaves, while Zn significantly increased in cucumber leaves with increasing concentrations in the nutrient solution. Excessive concentrations of Fe, Zn and other micronutrients may affect the availability of other elements or vice versa [61]. Similarly, salinity stress can affect elemental content in the leaves. Excessive ion accumulation in transpiring tissue may differ between younger and older leaves because the latter transpire the longest, so they accumulate ions the longest. Additionally, ion accumulation in older leaves depends on the properties of these ions and their mode of transport [62]. Despite the introduction of high EC in the nutrient solution, no significant correlation was found between the content of other micronutrients and the physical properties of the media. It is possible that the humic acids present in the lignite substrate reduced the excessive accumulation of ions in the root zone and did not lead to their accumulation in the leaves. Humic substances may mitigate the effects of salinity by altering the absorption of macro- and micronutrients, accelerating root growth and reducing damage to cytoplasmic membranes, the researchers say [59,63].

There was a significant positive correlation between water holding capacity and bulk density and cucumber fruit yield in lignite mats compared to mineral wool, where no such relationships were found. Plants grown in lignite medium fertilized with standard EC (L/control EC) obtained a 10% higher total yield compared to mineral wool (MW/control EC), while in the L/high EC combination, plants obtained a 14.8% higher marketable yield and 10% lower non-marketable yield, respectively, compared to MW/high EC. Allaire et al. [49] found a positive correlation in tomato marketable yield with the content of readily available water in the substrate and a negative correlation with the amount of air in the substrate. Other researchers also confirm that yield correlates with water buffer in the growing medium [64]. Similar results were reported by studying the yield of cucumber grown in perilla, where higher yield was dependent on the availability of water in the substrate [50]. The obtained results confirm the correlation of bulk density (BD) and water holding capacity (WHC) of the lignite substrate with cucumber yield. However, in the studies with mineral wool substrate (MW/control EC), such a correlation of BD and WHC of the substrate with cucumber yield was not proved (Table 8). Physicochemical properties of substrates affect plant yield and growth [65]. However, which parameter affects this and to what extent is difficult to determine. In a study on the yield of cucumber and tomato plants grown on *Miscanthus* substrate, there were no differences in yield compared to mineral wool [7]. Similar results were reported in tomato plants, where the substrates had no effect on fruit number or weight [54]. According to Luitel et al. [66] fruit number and weight depend on the air and water content of the substrate, because insufficient air in the soil reduces root respiration and negatively affects water and nutrient uptake.

Fruit quality is a very broad concept, and it is not possible to say unequivocally which trait affects the final yield quality more significantly. Fruit firmness, texture, color and organic content are important [32,67]. Table S3 in the Supplementary Materials contains the average values of chosen quality traits of cucumber fruits grown hydroponically in the conducted studies. Despite many studies on new substrates for hydroponic cultivation, there is still little information on the correlation of physical characteristics of the substrate with color and bioactive content. In the study, a significant correlation was found between the bulk density of mineral wool substrate and the color intensity (H*) and color index (a*/b*) of cucumber fruit peel in the CIE Lab system (Table 10). Color saturation (C*) of cucumber fruit was strongly correlated with bulk density of lignite substrate (control EC) and mineral wool (high EC) substrates. The obtained results also confirmed a strong correlation between selected physical substrate characteristics and cucumber fruit firmness. Physical characteristics of the substrate such as bulk density and water holding capacity of lignite mats (BD and WHC) were also strongly correlated with color intensity (H*) and coloration index (a*/b*) of cucumber fruit peel. Many publications indicate that there is no effect from salinity on the color and hardness of cucumber fruit [68,69]. In the case of tomato, no differences were found in the firmness of fruit from plants grown in different organic media [6]. According to Łaźny et al. [19], the substrate and its physical characteristics can affect the dry matter content and TSS in cucumber fruits. In the present study, a high correlation coefficient, but not statistically significant, was obtained between bulk density of lignite growing mats (L/high EC) and dry matter of cucumber fruits. Similar results were obtained in an experiment with twice-used lignite substrate and high EC medium in cucumber cultivation [20]. In studies conducted on tomato plants grown on organic substrates, the highest dry matter content was obtained in fruits grown in sheep wool, but no correlation was found between the physical properties of this substrate and fruit quality [6]. Different results were obtained by examining the sugar extract content (TSS) in tomato fruits, where the lowest level of TSS was in fruits from plants grown in date palm waste substrate [70]. Kraska et al. [7] obtained no differences in TSS content in fruits from tomato and cucumber plants grown in organic medium compared to mineral medium. The content of biologically active compounds may also change under the influence of the growing medium. Analyzing the obtained results, a high correlation was found between the water capacity of the lignite substrate and the lutein content in cucumber fruits (L/control EC and L/high EC) (Tables 12 and 13). It is likely that the low water content readily available in the lignite mats increased the lutein content in cucumber fruits. These results are consistent with those for carotenoid and phenolic content in tomato, where the low content of readily available water in the medium was correlated with the content of these compounds in fruit [6]. An increase in the content of bioactive compounds in fruit was also observed by studying the effect of reused lignite mats on cucumber fruit quality, where the content of readily available water in the lignite substrate was lower compared to that in mineral wool [19]. As reported by Peet et al. [71], tomato fruit quality and yield depend on the cultivar, maintenance of appropriate substrate moisture level and cultivation method. Despite the use of high EC in the nutrient solution, no significant correlation of selected physical properties with the content of other bioactive compounds in cucumber fruit was observed in both tested substrates. Studies conducted on salinity stress have shown that an appropriate level of salt concentration can lead to an increase in the concentration of carotenoids and phenols in bell pepper fruits [36] or lutein and β-carotene in romaine lettuce [72]. However, the factors affecting the content of compounds in fruit are very complex and also depend on air temperature, sunlight, cultivar or type of fertilizer used.

5. Conclusions

The growing demand for quality food is leading to a search for new alternative substrates that are fully biodegradable and do not place an undue burden on the environment. Unfortunately, many of the materials used as substrates do not have adequate physical properties for plant growth and development. Moreover, knowledge regarding their effects on the plant during the growing season is limited. In the present study, it was found that both the substrate density (BD) and water holding capacity (WHC) affect such morphological features of plants as shoot diameter, leaf and petiole length, as well as the weekly increase in the number of leaves in cucumber. A significant positive correlation was also observed between the density (BD) as well as water capacity (WHC) of the substrate and potassium content in cucumber leaves. It was also found that both the density and water holding capacity (BD and WHC) of the lignite substrate significantly affected the number and weight of fruits in greenhouse cucumber. A positive correlation between water holding capacity (WHC) of lignite substrate and lutein content in cucumber fruits in hydroponic cultivation was also confirmed. The obtained results may contribute to the development of new biodegradable hydroponic growing media, increasing the efficiency of vegetable cultivation. At the same time, they can be used to develop new methods of monitoring and controlling the parameters of the substrate in order to control the quantity and quality of the yield.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12094480/s1, Figure S1: Apparatus and substrate samples for physical properties determination: (a) lignite substrate sample (b) Eijkelkamp sand block (c) mineral wool substrate sample; Table S1: Contents of macro- and microelements in cucumber leaves; Table S2: Chosen morphological characteristics of cucumber grown hydroponically; Table S3: Chosen yield characteristics of cucumber grown hydroponically, in the period of 8 weeks after planting until the 35th week of the year; Table S4: Chosen quality characteristics of hydroponically grown cucumber fruit.

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Article

Lignite Substrate and EC Modulates Positive Eustress in Cucumber at Hydroponic Cultivation

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Abstract: Hydroponic cultivation using organic, fully biodegradable substrates that provide the right physical properties for plant growth and development is now the future of soilless production. Despite the high productivity and strict control of production conditions in this method, excessive salinity of the substrate often occurs. However, recent research results indicate that salinity at a high enough threshold can improve yield quality, while prolonged exposure to too high EC, or exceeding the safe EC threshold for a given species, leads to reduced quality and reduced or even no yield. The aim of this study was to determine the effect of biodegradable lignite substrate (L) and eustressor in the form of high EC nutrient solution (7.0 dS·m^{-1}) on morphological and physiological parameters, as well as the quality and yield of cucumber (*Cucumis sativus* L.) in hydroponic cultivation compared to the mineral wool substrate (MW). The MW/high EC combination showed a significant reduction in shoot diameter by nearly 6% compared to the MW/control EC combination. The stomatal conductance (g_s) and the transpiration rate (*E*) were also significantly reduced in this combination. The present study indicates that the effects of eustressor application vary depending on the growing medium used, and more favorable effects in terms of yield quality were obtained using biodegradable lignite substrate. The high EC of nutrient solution combined with lignite substrate (L/high EC) significantly increased in cucumber fruit the content of β-carotene, lutein, chlorophyll a, chlorophyll b and the sum of chlorophyll a + b by 33.3%, 40%, 28.6%, 26.3% and 26.7%, respectively, as compared to MW/high EC combination.

Keywords: organic substrate; eustress; photosynthetic pigment; photosynthetic efficiency; chlorophyll fluorescence; bioactive compounds

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1. Introduction

Cucumber (*Cucumis sativus* L.) is the second most economically important and widely grown species in hydroponic systems after tomato [1,2], but it is one of the vegetables sensitive to high salt concentrations in the medium. According to Chen et al. [2], cucumber plants tolerate electrical conductivity up to a value of 2.5 dS·m^{-1}, and an increase by each unit of electrical conductivity results in a decrease in the yield of more than 10%. In addition to direct effects on plant architecture and yield loss, salinity stress affects plant photosynthetic pigments (chlorophyll a and b) and chlorophyll synthesis [3–5] and leads to disruption of primary and secondary metabolite fluxes [3,6]. A decrease in photosynthetic pigment synthesis under salinity stress has been observed in plants of the genus *Pisum* [7], in the species

Vicia faba (L.) [8], and in the cucumber *Cucumis sativus* (L.) [3], among others. Excessive salinity can result in a decrease in photosynthetic efficiency and excessive production of reactive oxygen species (ROS) [6,9]. Several studies have confirmed that increasing salinity levels cause stomatal closure, deprivation of proteins and cytoplasmic membranes of the photosynthetic apparatus and destruction of chloroplast ultrastructure [4,9–11]. Stomata play an important role in gas exchange between the plant and its environment. They allow CO_2 entry and limit water loss, but are sensitive to environmental stresses [12]. Limited diffusion of CO_2 into the leaf leads to reduced stomatal and internal conductance [12,13]. After entering the leaf, CO_2 diffuses into chloroplasts through intercellular air spaces [14]. Salinity can negatively affect stomatal conductance and CO_2 diffusion, which are important factors in photosynthesis [12,13,15].

The constraints of land scarcity and a growing population have led to a search for alternatives to conventional food production. Soilless cultivation is such an alternative, but even with this cultivation method, salt accumulation in the soil can occur. [16]. In the case of hydroponic cultivation with the solid substrate, where mineral wool is mostly used, an additional problem is that this substrate after the growing season becomes waste that should be disposed [17]. Currently, stone wool is used worldwide for hydroponic cultivation of economically important vegetable species such as tomato, bell pepper and cucumber. This is mainly due to the suitable physical properties of stone wool, which allow for increased yields compared to conventional crops [18,19]. However, producing 1 m^3 of this substrate emits 167 kg of CO_2 into the environment and consumes 275 kWh [17], where the CO_2 emitted during transportation of the substrate to the customer and the disposal of stone wool waste after the production process are not taken into account. These problems have led to a search for alternative organic substrates that will reduce the use of mineral wool in hydroponic production [18,20,21]. For comparison, the CO_2 emitted during the production of 1m^3 of lignite is about 63 kg of CO_2, which allows to reduce the emitted CO_2 by almost 40%. Calculations based on the life cycle assessment (LCA) methodology [22,23] A fully biodegradable substrate that has comparable physical properties to mineral wool is lignite substrate [20], which can be used as an organic fertilizer in conventional crops after the production process. Using such substrate instead of mineral wool could help reduce the carbon footprint. In addition to the above-mentioned problems, soilless cultivation can not only provide a solution to the problem of lack of arable soil or excessive salinity but also help to improve food quality, such as an increase in bioactive compounds through the use of an elevated EC of nutrient solution combined with an organic substrate [24,25]. Following biological, chemical and physical factors that induce stress, plants switch on defense responses by producing various phytochemicals and bioactive compounds [26]. Available research results clearly indicate that salinity stress can be a tool to improve vegetable quality, including their nutritional value, which is essential for the proper functioning of the human body [25,27]. Many biotic and abiotic factors can be classified as eustressors, depending on their mode of action, composition or origin. An example of such an eustressor can be salinity [25,27,28]. The appropriate level of salinity can affect the color and firmness of cucumber fruit or increase the content of soluble solids [28] or dry matter [29]. Current food trends and processing market requirements are centered around foods with increased content of bioactive compounds [24,30]. Studies have shown that appropriate crop control, together with a stress factor applied at the right growth phase and level, can lead to an increase in bioactive compounds, affect chemical properties and the broader quality of final products [24,30]. There are several research works regarding the use of eustressor in the form of high EC of the nutrient solution (7 $dS \cdot m^{-1}$) in the cultivation of cucumber (*Cucumis sativus* L.) in biodegradable lignite medium. Perhaps the combination of a high EC nutrient solution and an organic lignite substrate will increase bioactive compounds without adversely affecting plant growth and development. The aim of the study was to evaluate the effect of the eustressor, i.e., high EC of the medium on the selected morphological, physico-chemical parameters and the activity of the photosynthetic apparatus in cucumber plants was determined. It was also examined how lignite substrate and eustress affect the yield, selected quality parameters and the content of bioactive compounds in the fruits of cucumber plants growing in lignite substrate.

2. Materials and Methods

2.1. Plant Material, Location and Experimental Conditions

The research was conducted at the Greenhouse Experimental Center of the Warsaw University of Life Sciences, in the cultivation chambers of the Department of Vegetable and Medicinal Plants following two seasons 2020 and 2021.

Microclimate conditions and fertigation were controlled by a climate computer. A greenhouse cucumber cultivar "Mewa" F1 by Rijk Zwaan, with fruits reaching 20–24 cm in length and weighing 200–240 g, was used for the study. The fruit of "Mewa" are characterized by dark, glossy skin with slight ribbing. The substrate for cultivation was made of lignite–carbomat by the CarboHort company, 100 cm × 20 cm × 8 cm (L), and mineral wool Grotop Master by the Grodan company, 100 cm × 20 cm × 7.5 cm (MW). Before cultivation, lignite and mineral wool mats were flooded with pH 5.5 and EC 2.6 dS·m^{-1} nutrient solution, at a rate of 8 dm^3 per mat. After 48 h, two 5 cm long vertical drainage cuts were made in the lignite mat covering plastic film on each of the longer sides of the mat starting at a height of 1 cm from the bottom of the mat. In the mineral wool mat, two horizontal cuts in each of the shorter sides of the mat and two 5 cm vertical cuts in the middle of the longer sides of the mat were made. In the first season, cucumber seedlings were planted on 10 July 2020. The daily solar radiation averaged 1474.9 J/cm^2, growing season temperatures were set to averaged D/N 25/23 °C (Figure 1) and the average humidity and CO_2 concentration were 70% and 800 ppm, respectively. In the second season, plants were planted on 12 July 2021 on mats prepared in the same way as in the first growing season. The daily solar radiation averaged 1407.0 J/cm^2, the D/N temperature was 25/22 °C (Figure 2), and the average humidity and CO_2 concentration were 70% and 800 ppm, respectively.

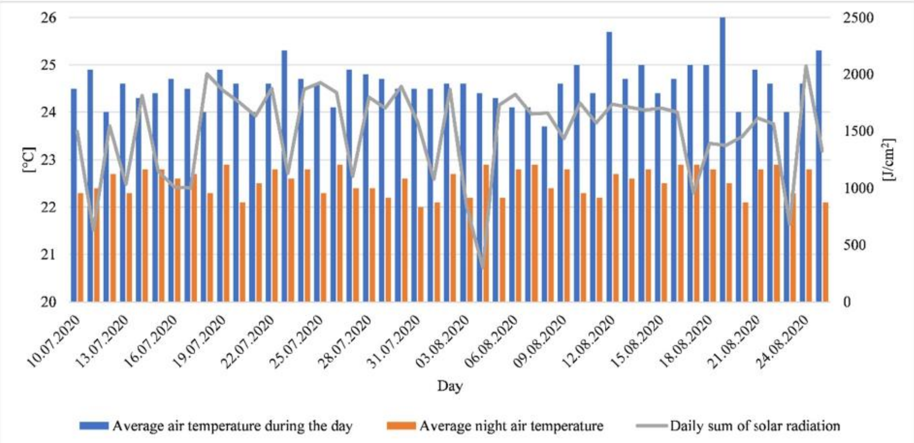


Figure 1. Climate parameters in the cultivation chamber during the experiment—season 2020.

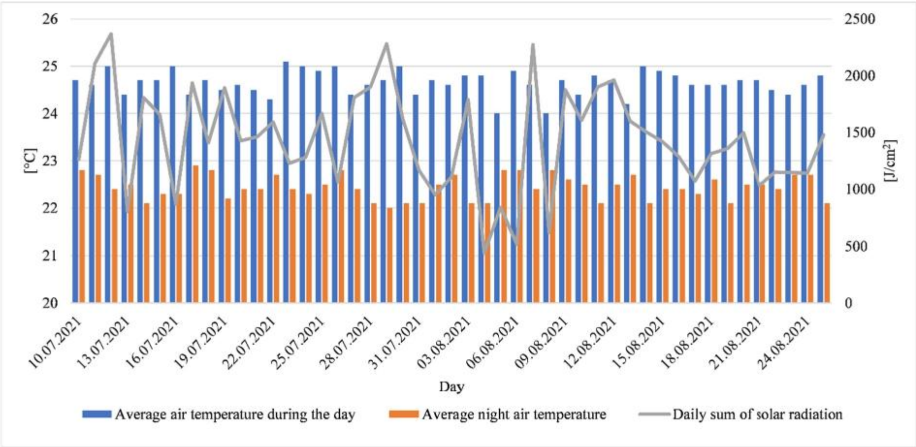


Figure 2. Climate parameters in the cultivation chamber during the experiment—season 2021.

In both seasons the research was carried out in the same way. Just after planting, the plants were fed with a control medium recommended for cucumber growing in mineral wool. Then, 7th day after planting, the experimental conditions were varied by changing the EC of the nutrient solution, for half of the growing plants. An increase in the EC of the nutrient solution was obtained by increasing the concentration of the control nutrient solution to an EC of about 7 dS·m^{-1}. The treatment tested were determined as follows: (1) MW/control EC—mineral wool substrate and control nutrient solution, (2) L/control EC—lignite substrate and control nutrient solution, (3) MW/high EC—mineral wool substrate and concentrated control nutrient solution, (4) L/high EC—lignite substrate and concentrated control nutrient solution. In combination MW/control EC and L/control the EC of the nutrient solution was 3.3 dS·m^{-1}, in combination MW/high EC and L/high the EC of the nutrient solution was 7 dS·m^{-1}. pH of the nutrient solution in all tested combinations was 5.8. The treatment was set up using the randomized block method, in 3 replications, with 9 plants in each. Irrigation was conducted using a computer, and concentrated nutrient solution and acid for pH regulation of the nutrient solution were applied using a Dosatron dispenser (D25RE2 0.2–2%). The concentrated fertilizer solution was divided into two tanks, A and B, where in tank A the following fertilizers were dissolved: calcium nitrate and potassium nitrate, while in tank B—potassium nitrate, magnesium sulphate, monopotassium phosphate and microelements in appropriate proportions. The third tank C contained concentrated HNO_3 acid to regulate the pH of the nutrient solution. Dosatron proportioners took from each of the tanks A and B appropriate, equal parts of concentrated fertilizer solutions to the mixer, where, after adding water, the nutrient solution of the desired EC was obtained. The third proportioner dispensed nitric acid from tank C to bring the nutrient solution to pH 5.8. The nutrient solution was prepared from one- or two-component mineral fertilizers The composition of the nutrient solution in the control was as follows (mg dm^{-3}): N-NO_3 230, N-NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15, and B 0.33. The nutrient solution was dosed through the drip system by computer based on actual solar radiation and substrate water content measurements. Plants were trained on a single fruiting shoot, which was wrapped with a wire-tied twine installed above the cultivation bed at a height of 2.5 m. Twice a week, all lateral shoots and clinging tendrils were removed from the fruiting shoot, as well as the 3 oldest leaves from each plant. In both the first and second year of the study, the first fruit buds up to 4 leaves were removed. Both experiments were terminated at the 35th week of the year.

Fruits and leaves for destructive physico-chemical analyses were taken twice on the 29th and 45th days after planting (DAP). At each date 3 marketable fruits and 3 young fully developed leaves from each combination were taken randomly. Fruit and leaf analyses were performed in 3 repetitions.

2.2. Morphological Measurements

In each combination, 9 representative plants were chosen and measured every 7 days. The increase in length of the cucumber shoot was measured from the point at which the top of the shoot was located 7 days before (place appropriately marked on the string). The diameter was measured at two points on the shoot (with an electronic caliper) in the middle of the internode, between the 4th and 5th and 9th and 10th fully expanded leaves, counting from the shoot top. Leaf length, leaf width, and petiole length, consecutively of the 5th and 10th leaf on the shoot counting from the shoot top, were measured with a ruler. The weight of removed leaves, lateral shoots, and tendrils from each plant was weighed to determine the total green mass-produced.

2.3. Gas Exchange and Chlorophyll Fluorescence

Relative chlorophyll content in leaves by the SPAD (Soul Plant Analysis Systems) test was determined using a Minolta SPAD-502 Plus portable meter. The measurement was performed on the 5th and 10th fully expanded leaf, counting from the shoot apex of the plant. Net photosynthetic rate (P_N), stomatal conductance (g_s) and the transpiration rate (E) were measured using a LI-6400 Photosynthesis System (LI-COR, Inc., Lincoln, NE, USA) equipped with a 6400-40 Leaf Chamber fluorometer and a 6400-01 CO_2 mixer. Measurements were made on 3 randomly selected plants from each combination at 10 am to 12 pm with relatively little change in microclimate. Measurements were made at a reference CO_2 concentration (500 μmol s^{-1}), constant flow rate (400 μmol s^{-1}), relative humidity between 30% and 50%, and photosynthetic photon flux density (PPFD, 1000 mmol m^{-2} s^{-1}). In addition, photosynthetic water use efficiency (WUE) and instantaneous photosynthetic water use efficiency (iWUE) were calculated from the P_N/E and P_N/g_s quotients, respectively. Once the device was stabilized, leaves for the experiments were taken from each plant immediately before measurements were taken so as to limit the effect of leaf ontogeny on net assimilation rate and stomatal conductance. Chlorophyll fluorescence was measured on each of 9 plants in all 4 combinations using the FMS-2 Field Portable Pulse Modulated Chlorophyll Fluorescence Monitoring System (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK), measuring parameters such as (Fs)—steady-state fluorescence yield, (Fm')—light-adapted fluorescence maximum, and (ΦPSII)—maximum quantum efficiency of PS II. Maximum efficiency of PS II photosystem in the dark—(Fv/Fm) was obtained after 30-min adaptation of leaves to the dark. A pocket PEA fluorescence meter (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK) was used to measure direct fluorescence. Chlorophyll fluorescence and gas exchange measurements were made on the 5th and 10th leaves, counting from the shoot apex of the cucumber plant, and conducted in both growing seasons every 7 days and the results were averaged.

2.4. Contents of Dry Matter and Photosynthetic Pigments in Leaves

The dry matter content of the leaves was determined by the weight method at 105 °C, after the preparation of the samples. The (5th and 10th) leaves were taken twice during the experiment, with secateurs. Leaves taken randomly from each combination were cut, and then 5 g samples of plant material were placed in a laboratory dryer. The contents of β-carotene, lutein, and chlorophyll a and b in leaves and fruits were determined by high-performance liquid chromatography HPLC (Shimadzu Scientific Instruments). Cucumber leaves were homogenized with 2 g Na_2SO_4 per 100 g^{-1} f.w. of the sample. The homogenate prepared in this way was weighed on a laboratory scales at 2 g (leaves) and 5 g (fruits) and then grinded in a mortar with cold acetone (−20 °C) and quartz sand. The extracted samples were quantitatively transferred into 50 mL volumetric flasks and made up to 50 mL with cold acetone. Samples were centrifuged in tubes (15,000 rpm), and the resulting supernatant was filtered through a 0.22 µm syringe filter (Supelco IsoDisc™ PTFE 25 mm × 0.22 µm). Extracts were placed in 1 mL containers in a SIL-20AC HT automatic sample feeder (tray temperature 4 °C). An extract of 5 µL was applied to a Kinetex 2.6 µm C18 100 Å 100 mm × 4.6 mm chromatography column from Phenomenex. Compound separation was achieved using isocratic elution with methanol at 40 °C. The wavelength range was for β-carotene, chlorophyll a and b, respectively: 450 nm, 430 nm and 470 nm. From the obtained chlorophyll a and b results, the sum of chlorophyll a and b was calculated. All analyses were performed in triplicate.

2.5. Yield Quantity and Fruit Quality

The fruit was harvested every two days, and the number and weight of fruits were determined considering marketable and unmarketable yield. Based on the results, harvest index (HI) was calculated as the ratio of total yield to the above-ground part of the plant (leaves and shoots) including fruits [31].

The color of the fruit peel was determined on three randomly selected fruits using a MiniScan XE PLUS D/8-S portable color spectrophotometer (CIE Lab-scale—red color proportion—a*, yellow color proportion—b* and brightness—L*). The polar coordinates of chroma (saturation) $C^* = (a^{*2} + b^{*2})^{1/2}$ color intensity (hue angle) $H^* = \tan^{-1}(b^*/a^*)$ and staining index (ratio a*/b*) were also determined from the obtained data [32–34]. A standard white calibration plate was used to calibrate the spectrophotometer.

Fruit firmness was determined using an HPE hardness tester with a shank diameter of 5 mm. The measurement was made at 3 points on the fruit, at an angle of 90° from its plane. The results were given on the HPE hardness scale (0–100 units).

The dry matter and β-carotene, lutein, and chlorophyll a and b content of the fruits were determined by the methods described in Section 2.4. The total soluble solids content (TSS) was determined in freshly squeezed juice from randomly selected 3 fruits, 200 mL in volume, giving the results in % using a digital refractometer (Hanna Instruments HI96801).

The nitrate content of the fruits was determined using a mixed sample of randomly selected fruits with a total weight of 1 kg, which were homogenized. From the mixed sample prepared in this way, 10 g samples of plant material were taken three times by adding 0.5 g of activated carbon and 100 mL of 2% acetic acid ($C_2H_4O_2$) and the samples were then shaken. After 30 min, the samples were filtered through a fluted filter. Nitrate content in mg N-NO_3^-/100 g f.w. of fruit was determined using a Fiastar 5000 Analyzer by reducing nitrate (V) to nitrate (III) by passing the sample solution through a cadmium column. The resulting colored solution was measured spectrophotometrically at 540 nm.

2.6. Statistical Analysis

The results are reported as the mean from a total of two experiments ± standard error (SE) values of nine biological replicates (n = 9). The SE was calculated directly from crude data. Data were evaluated by analysis of variance (ANOVA) and differences between the means were compared by Tukey's test (HSD) at a significance level of $p < 0.05$. Statistical analyses were performed using Statistica 13.3. Prior to analyses, we tested whether the assumptions of an ANOVA, homogeneity of variances were achieved. The homogeneity of variances for all the studied parameters was evaluated by Levene's test.

3. Results

3.1. Morphological Parameters

Although there were no significant differences in weekly shoot length growth between the combinations, at the high EC of the nutrient solution a significant shortening of the total length of shoot was observed in MW/high EC cucumber plants by nearly 2.6% (Table 1), moreover, this combination also recorded a smaller cucumber shoot diameter by nearly 6% compared to MW/control EC. Plants fertilized with the high EC nutrient solution and grown in lignite medium had the smallest width of the tenth leaf, compared to the control

(Table 1). The high EC of the nutrient solution reduced the total leaf and shoot weight of plants growing in lignite by nearly 20% compared to the lower EC of the nutrient solution and mineral wool. There were no significant differences in the SPAD index of cucumber leaves depending on the substrate and EC of the nutrient solution applied (Table 1).

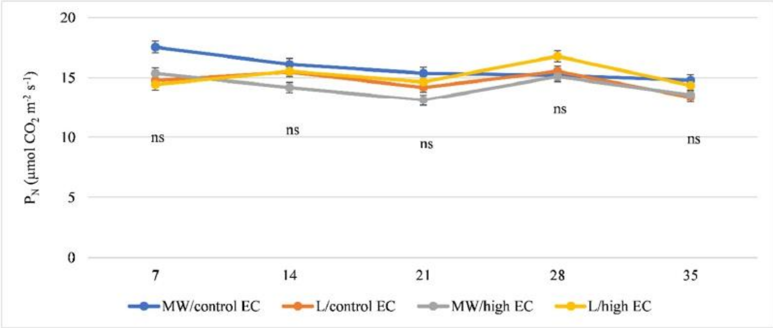
Table 1. Chosen morphological parameters of cucumber plants and chlorophyll content (SPAD) in relation to medium and nutrient solution EC (average from two years).

Parameter			Unit	Combination			
				MW/ Control EC	**L/ Control EC**	**MW/ High EC**	**L/ High EC**
Shoot	Weekly increase in length		cm	57.9 ± 1.9 ns	62.2 ± 1.7 ns	57.6 ± 1.9 ns	60.0 ± 1.7 ns
	Total length			276.8 ± 3.0 ab	286.9 ± 1.4 a	269.7 ± 3.8 b	280.4 ± 4.4 a
	Diameter under 5th leaf		mm	6.6 ± 0.1 a	6.5 ± 0.1 ab	6.2 ± 0.1 b	6.4 ± 0.1 ab
	Diameter under 10th leaf			7.7 ± 0.1 a	8.0 ± 0.1 a	7.3 ± 0.1 b	7.6 ±0.1 ab
Leaf	Number per week		pcs plant^{-1}	4.1 ± 0.1 ns	4.1 ± 0.1 ns	4.0 ± 0.1 ns	4.1 ± 0.1 ns
	5th leaf	Length	cm	20.3 ± 0.4 ns	21.2 ± 0.4 ns	20.3 ± 0.3 ns	20.0 ± 0.4 ns
		Width		23. 8 ± 0.4 ns	24.8 ± 0.5 ns	24.2 ± 0.4 ns	23.7 ± 0.4 ns
		Petiole length		14.0 ± 0.4 ns	14.2 ± 0.4 ns	13.6 ± 0.3 ns	13.6 ± 0.3 ns
		Chlorophyll content	SPAD unit	41.4 ± 0.7 ns	41.2 ± 0.6 ns	42.0 ± 0.7 ns	42.3 ± 0.7 ns
	10th leaf	Length	cm	25.3 ± 0.5 ns	25.6 ± 0.6 ns	24.0 ± 0.5 ns	24.8 ± 0.5 ns
		Width		31.5 ± 0.6 a	31.5 ± 0.6 a	30.7 ± 0.6 ab	29.2 ± 0.6 b
		Petiole length		18.2 ± 0.4 ns	18.0 ± 0.4 ns	17.7 ± 0.3 ns	17.0 ± 0.3 ns
		Chlorophyll content	SPAD unit	44.3 ± 0.4 ns	44.8 ±0.4 ns	44.8 ± 0.7 ns	44.9 ± 0.4 ns
Total leaf and shoot weight			g plant^{-1}	1267.8 ± 28.6 a	1195.7 ± 22.2 a	1164.0 ± 28.5 a	934.9 ± 28.5 b

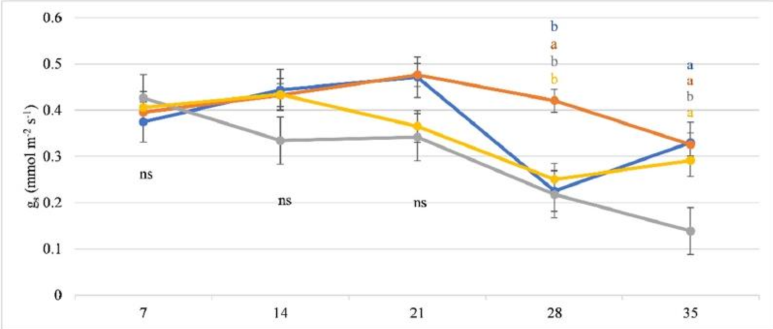
Average values marked with the same letters within the same row are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

3.2. Gas Exchange and Chlorophyll Fluorescence

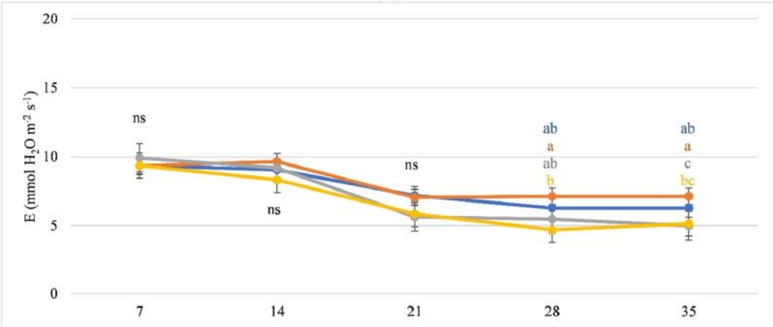
Eustressor in the form of high EC of the nutrient solution did not affect the rate of photosynthesis (P_N) in plants growing in all four combinations (Figure 3a). However, this factor reduced stomatal conductance (g_s) by more than 60% in the case of plants growing in mineral wool, which was not observed in the combination growing in lignite (Figure 3b). In the case of plants growing in the lignite substrate, stomatal conductance (g_s) started to decrease only on the 14th day of the experiment—14 DAP, 7 days after the stress factor was switched on (days after introduction of high EC 7 DAEC. Plants growing in mineral wool substrate showed a significant decrease in g_s immediately after the stress was turned on (Figure 3b). On day 28 DAEC, a temporary significant (by more than 50%) decrease in g_s was observed in plants fertilized with nutrient solution with standard EC growing in mineral wool compared to those grown on lignite (Figure 3b). At the end of the experiment, the high EC of the nutrient solution significantly reduced transpiration rate (E) in the mineral wool substrate by more than 30% (Figure 3c). During this period, an increase in photosynthetic water use efficiency (WUE) was also observed in combination with high EC of nutrient solution (MW/high EC and L/high EC) (Figure 3d). In both tested media, the eustressor (high EC) did not affect the instantaneous photosynthetic water use coefficient (WUE), while it was found to decrease significantly in combination L/control EC compared to MW/control EC by more than 8% (Figure 3e).



(**a**)

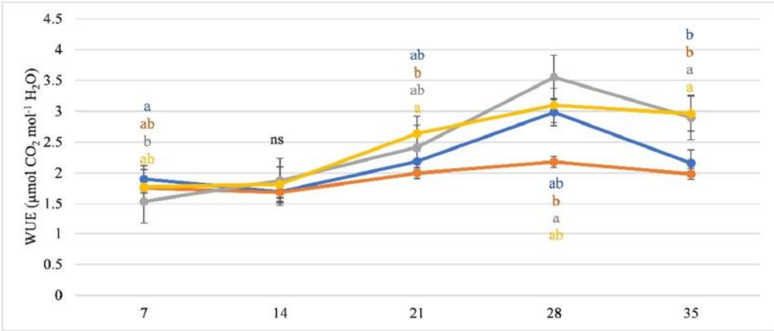


(**b**)

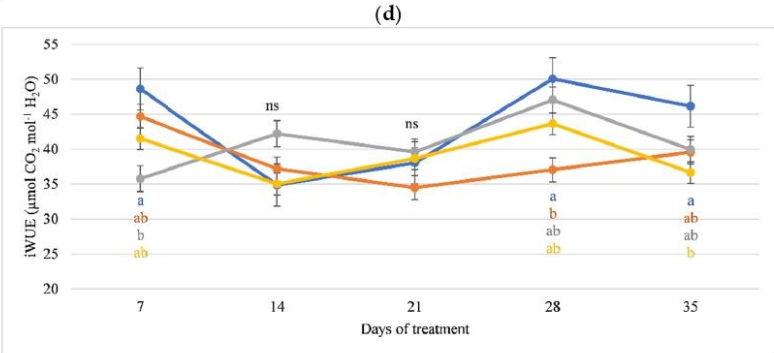


(**c**)

Figure 3. *Cont.*



(**d**)



(**e**)

Figure 3. Effect of high EC of nutrient solution on net CO_2 assimilation intensity (P_N) (**a**), stomatal conductance (g_s) (**b**), transpiration intensity (E) (**c**), photosynthetic water use efficiency (WUE) (**d**), instantaneous photosynthetic water use efficiency (iWUE) (**e**), of cucumber plants depending on the applied medium on 7, 14, 21, 28, 35 DAEC (average from two years). Vertical bars indicate ± standard deviation. Abbreviations: ns, not significant. Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$.

There was no effect of high nutrient solution EC on the maximum photochemical yield of PS II (Fv/Fm), regardless of the combination (Figure 4a). The maximum quantum yield of PS II (ΦPS II) followed a similar pattern, where no differences were obtained until day 21 DAEC of the experiment. At the end of the experiment, there was a significant reduction in ΦPS II in plants fertilized with nutrient solution of standard EC growing in lignite compared to plants growing in mineral wool of standard EC and treated with high EC nutrient solution (Figure 4c). Steady-state fluorescence yield (Fs) varied throughout the experiment. The application of eustressor did not affect this factor at the beginning and at the end of the experiment, while 14 DAEC plants growing in the combination with lignite at standard EC showed a significant increase in Fs, as compared to the other combinations by nearly 10%. On the other hand, on day 21 DAEC, plants treated with high EC of the nutrient solution showed a significant decrease in Fs in the mineral wool substrate by more than 7% compared to the combination with lignite (Figure 4d).

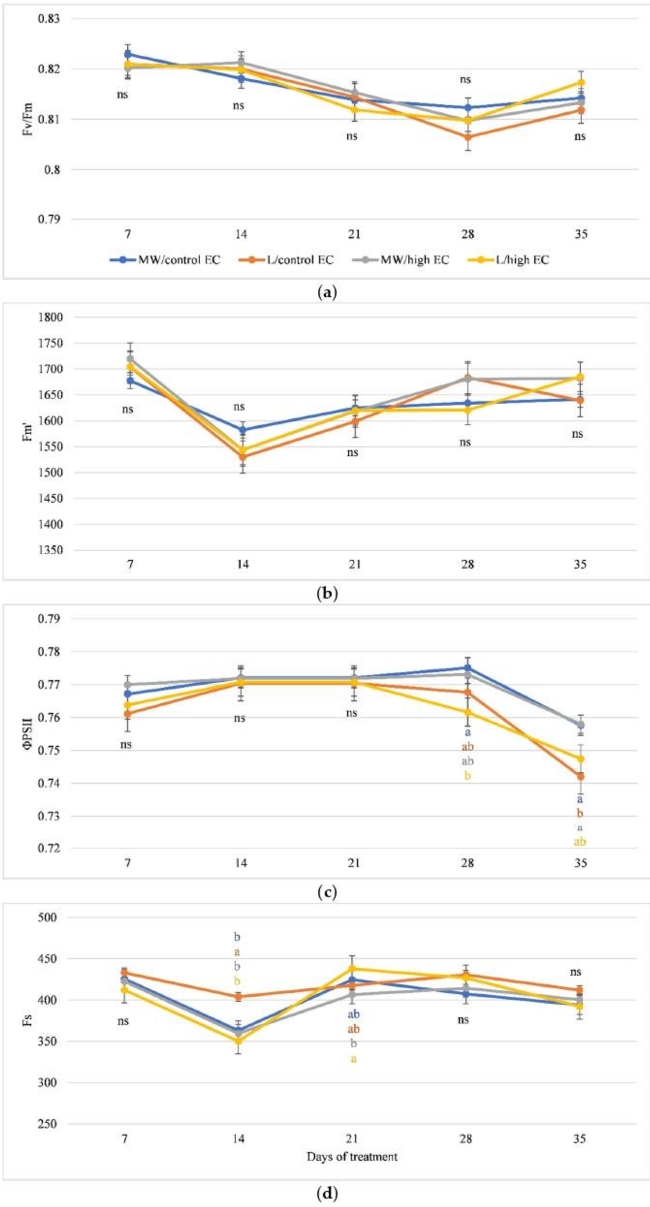


Figure 4. Effect of high nutrient solution EC on maximum photochemical yield of PSII (Fv/Fm) (**a**), maximum chlorophyll a fluorescence in dark-adapted leaves (Fm′) (**b**), the maximum quantum yield of PS II (ΦPSII) (**c**), and stationary fluorescence (Fs) (**d**) of cucumber plants depending on the medium used on 7, 14, 21, 28, and 35 DAEC (average from two years). Vertical bars indicate ± standard deviation. Abbreviations: ns, not significant. Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$.

3.3. Photosynthetic Pigment Content and Leaf Dry Matter

The highest content of lutein was recorded in plant leaves—combinations L/control EC by more than 28% compared to the MW/control EC—leaf 5. While in combination L/high EC 9% higher content of this compound was found in the tenth leaf compared to leaves from plants of the MW/high EC combination (Table 2). Higher content (by nearly 10%) chlorophyll a content was found in plants grown in combination L/high EC (fifth and tenth leaves) as compared to leaves of plants from combinations MW/high EC. Lignite medium also significantly increased chlorophyll (a + b) and β-carotene content (Table 2).

Table 2. Dry matter content and photosynthetic pigment in leaves of cucumber plants (average from two years).

Number of Leaf	Parameter	Unit	Combination			
			MW/Control EC	**L/Control EC**	**MW/High EC**	**L/High EC**
5th	Dry matter	%	11.4 ± 0.1 a *	11.0 ± 0.1 a	11.5 ± 0.2 a	11.4 ± 0.1 a
	β-carotene	$mg\ 100\ g^{-1}$ FW	16.6 ± 0.1 c	20.5 ± 0.6 b	20.4 ± 0.5 b	22.4 ± 0.3 a
	Lutein		10.6 ± 0.2 c	14.8 ± 0.3 a	13.6 ± 0.4 ab	13.2 ± 0.4 b
	Chlorophyll a		124.4 ± 1.2 c	142.9 ± 2.2 b	139.7 ± 4.0 b	155.0 ± 4.2 a
	Chlorophyll b		39.6 ± 0.4 c	49.8 ± 1.1 a	45.8 ± 1.1 b	46.0 ± 0.7 b
	Total chlorophyll a + b		164.0 ± 1.6 c	204.8 ± 5.3 a	185.5 ± 5.1 b	188.9 ± 2.9 b
10th	Dry matter	%	11.8 ± 0.1 b	12.4 ± 0.2 ab	13.1 ± 0.3 a	13.2 ± 0.3 a
	β-carotene	$mg\ 100\ g^{-1}$ FW	14.9 ± 0.1 ab	16.2 ± 0.5 ab	14.7 ± 0.3 c	16.4 ± 0.4 a
	Lutein		9.7 ± 0.1 ab	10.3 ± 0.1 ab	9.5± 0.4 b	10.4 ± 0.03 a
	Chlorophyll a		114.4 ± 0.9 ab	116.9± 2.7 ab	109.9 ± 4.7 b	122.6 ± 1.4 a
	Chlorophyll b		42.0 ± 0.5 a	38.1 ± 1.0 ab	36.9 ± 1.5 b	40.8 ± 0.9 ab
	Total chlorophyll a + b		156.5 ± 1.0 ab	155.0 ± 3.7 ab	146.8 ± 6.2 b	163.4 ± 2.3 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

3.4. Yield, Fruit Quality and Content of Biologically Active Compounds in Cucumber Fruit (Average from Two Years)

High EC reduced yield in the MW/high EC by nearly 27% and in the L/high EC combination by 22% compared to the control (Table 3). The highest number and weight of marketable fruits, with the lowest number of unmarketable fruits, were obtained from plants grown on lignite substrate—L/control EC combination produced 11% more number and nearly 9% more weight of marketable fruits. More than 9.4% fewer unmarketable fruits were obtained from the L/high EC combination compared to MW/high EC, this combination also received obtained more than 5% lower HI index compared to the other combinations. (Table 3). Plants treated with high EC nutrient solution dropped some of their buds, both in the case of mineral wool and lignite substrate but the other one had more than 12.3% fewer dropped buds compared to MW/high EC (Table 3).

Regardless of the EC of the nutrient solution and the type of substrate, no differences were observed for firmness and the L* and a* components of the CIE Lab-scale (Table 4). The high EC of the nutrient solution had an effect on reducing the parameter of the b* (by 15.5%) component of the CIE Lab-scale (L/high EC) compared to L/high EC (Table 4), which indicates a higher proportion of blue. Fruit color indices did not differ significantly after eustressor application, regardless of the applied medium (a*/b*), while cucumber fruits from plants grown in combination MW/control EC and L/control EC were characterized by a significantly lower color index by respectively 5% and 10% (Table 4).

Table 3. Cucumber fruit yield by marketable and unmarketable fruit, number of fruit abortion and harvest index (average from two years).

Harvested Fruit		Unit	Combination			
			MW/ Control EC	L/ Control EC	MW/ High EC	L/ High EC
Weight of fruit	Total fruit	$g\ plant^{-1}$	6503.2 ± 131.1 b	7004.5 ± 102.1 a	4766.0 ± 202.7 d	5471.4 ± 145.3 c
	Marketable fruit		6190.3 ± 113.5 b	6834.2 ± 83.7 a	3486.5 ± 217.8 d	4311.9 ± 150.2 c
	Unmarketable fruit		312.9 ± 71.9 b	170.3 ± 60.7 b	1279.5 ± 108.7 a	1159.5 ± 0.8 a
Number of fruit	Total fruit	$pcs\ plant^{-1}$	29.5 ± 0.8 b	32.0 ± 0.6 a	22.9 ± 0.4 d	26.1 ± 0.4 c
	Marketable fruit		27.9 ± 0.5 b	31.2 ± 0.3 a	16.0 ± 0.9 d	19.8 ± 0.7 c
	Unmarketable fruit		1.6 ± 0.3 b	0.8 ± 0.3 c	6.9 ± 0.6 a	6.3 ± 0.5 a
	Aborded fruit		0	0	7.3 ± 0.4 a	6.4 ± 0.3 a
HI index			0.84 ± 0.02 a	0.85 ± 0.02 a	0.80 ± 0.02 b	0.85 ± 0.02 a

Average values marked with the same letters within the same row are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

Table 4. CIE Lab-scale color and firmness of cucumber fruit (average from two years).

Parameter	Unit	Combination			
		MW/ Control EC	L/ Control EC	MW/ High EC	L/ High EC
Firmness	HPE	63.1 ± 0.8 ns	63.7 ± 0.5 ns	61.8 ± 0.4 ns	63.9 ± 0.6 ns
Colour	a*	−7.2 ± 0.3 ns	−7.0 ± 0.2 ns	−6.7 ± 0.2 ns	−6.6 ± 0.2 ns
	b*	12.7 ± 0.7 ab	12.9 ± 0.5 a	11.2 ± 0.3 ab	10.9 ± 0.3 b
	L*	32.1 ± 1.1 ns	33.4 ± 0.9 ns	31.7 ± 0.3 ns	32.0 ± 0.8 ns
	C*	14.6 ± 0.8 ns	14.7 ± 0.6 ns	13.0 ± 0.4 ns	12.7 ± 0.4 ns
	H*	124.8 ± 2.1 ns	128.0 ± 1.2 ns	122.2 ± 1.6 ns	122.1 ± 1.0 ns
	a*/b*	−0.57 ± 0.02 ab	−0.54 ± 0.01 b	−0.60 ± 0.01 a	−0.60 ± 0.01 a

Average values marked with the same letters within the same row are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

Application of eustressor in the form of high EC increased dry matter of fruits in the MW/high EC combination by nearly 17% and in the L/high EC by 10%. In contrast, the high EC of nutrient solution and type of substrate had no effect on dry matter content (TSS) in cucumber fruits (Table 5). The highest content of bioactive compounds such as β-carotene, lutein, chlorophyll a, b, total of chlorophyll a + b was found in fruits from the L/high EC combination. These values were significantly higher in comparison to fruits from MW/high EC combination by respectively 33.3% (β-carotene), 40% (lutein), 28.6% (chlorophyll a), 26.3% (chlorophyll b) and 26.7% (chlorophyll a + b). Similar relationships were found in fruit from the L/control EC versus MW/control EC combination (Table 5). At the same time, when eustressor was applied to the test media, nitrate accumulation was found to be 50% higher in fruit from the MW/high EC combination compared to fruit from the L/high EC combination, from which it follows that fruit from the L/high EC combination had in nearly 45 mg NO_3 kg^{-1} FW less nitrate (Table 5).

Table 5. Contents of dry matter, TSS and bioactive compounds in cucumber fruits (average from two years).

Parameter	Unit	Combination			
		MW/ Control EC	L/ Control EC	MW/ High EC	L/ High EC
Dry matter	%	3.8 ± 0.1 c	4.0 ± 0.1 bc	4.6 ± 0.2 a	4.4 ± 0.1 ab
TSS		3.8 ± 0.1 ns	4.0 ± 0.2 ns	4.3 ± 0.1 ns	4.3 ± 0.2 ns
β-carotene	$mg\ 100\ g^{-1}$ FW	0.2 ± 0.01 b	0.3 ± 0.01 a	0.2 ± 0.01 b	0.3 ± 0.01 a
Lutein		0.4 ± 0.01 b	0.5 ± 0.03 a	0.3 ± 0.01 b	0.5 ± 0.01 a
Chlorophyll a		3.7 ± 0.1 b	4.6 ± 0.2 a	3.0 ± 0.2 c	4.2 ± 0.09 a
Chlorophyll b		1.7 ± 0.07 bc	2.2 ± 0.02 a	1.4 ± 0.07 c	1.9 ± 0.04 ab
Total chlorophyll a + b		5.4 ± 0.2 b	6.7 ± 0.3 a	4.4 ± 0.2 c	6.0 ± 0.1 a
Nitrates	$mg\ NO_3\ kg^{-1}$ FW	28.2 ± 1.6 c	15.5 ± 0.6 d	89.9 ± 0.4 a	45.0 ± 1.3 b

Average values marked with the same letters within the same row are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

4. Discussion

4.1. Morphological Characteristics of Cucumber Plants Grown on Organic and Mineral Substrates at High EC

Excessive salinity modifies plant growth and development parameters, negatively affecting the entire plant organism [13]. However, using appropriate salt concentrations and a suitable cultivation strategy, salinity stress can improve the intrinsic quality of vegetables or fruits [25]. Combining controlled salinity stress with organic (biodegradable) substrates that can improve plant growth will achieve the desired effects with environmental benefits. The application of eustressor in the form of high EC at a level of 7.0 $dS \cdot m^{-1}$ of the nutrient solution did not affect the inhibition of shoot growth in the case of combination with lignite, while it significantly reduced the shoot length in plants growing in mineral wool. Despite the introduction of excessive salinity stress, which strongly shortens shoot growth [2], the lignite substrate reduced its negative effects. Salinity stress caused a significant reduction width 10th leaf. in the L/high EC, which probably resulted in a reduction of their area. Reduced leaf area leads to limitations in a light interception and interferes with its proper distribution within the canopy [2,35], which directly reduces plant productivity [36]. High EC simultaneously resulted in a significant reduction of the total leaf and shoot weight gained by the plants, especially in lignite substrate. The results are in agreement with many studies, where it has been proved that plant biomass or leaf area decreases with increasing salt stress intensity [13,37,38].

4.2. Variation in Photosynthetic Efficiency and Chlorophyll Fluorescence of Cucumber Grown on Organic and Mineral Substrates at High EC

The net photosynthetic rate (P_N) followed a similar pattern, where no sensitivity of cucumber plants to the high EC of the nutrient solution was observed (Figure 3a), while at the end of the experiment a strong reduction of stomatal conductance (g_s) in the MW/high EC combination (Figure 3b). A reduction in transpiration rate (*E*) was also observed in both combinations with eustressor. Perhaps by the end of the experiment, the ion accumulation in the substrate was at a level that led to changes in the parameters discussed. In a study of tomatoes under high salinity conditions, Schwarz and Kuchenbuch [39] found that transpiration rates decreased for the total dry weight as the EC of the nutrient solution increased. Ding et al. [40] reported no change in P_N in leaves of pakchoi plants (*Brassica campestris* L. ssp. *Chinensis*) at a nutrient solution EC of 4.8, while an EC of 9.6 strongly reduced P_N in leaves. For g_s and E, parameters decreased significantly with increasing nutrient solution EC (4.8–9.6). Perhaps the use of an intermediate EC nutrient solution in cucumber cultivation in combination with a lignite substrate would not result in changes in the parameters discussed. Changes in g_s under salt stress can occur rapidly, reducing CO_2 availability, which directly translates into a reduction in P_N [14]. Different results were obtained by treating cucumber plants with NaCl, where P_N and g_s were reduced after only 1 day of the experiment [15], which may indicate that the high EC stress used in the experiment does not have as strong an effect as NaCl. However, changes in P_N, g_s, and E can be caused by both high EC treatment of the nutrient solution as well as nutrient deficiencies and also different nutrients management [40–42].

The iWUE index is a frequently used parameter to assess gas exchange in plants. It has been found to be closely related to the CO_2 concentration [43]. In the environment, CO_2 levels in the plant can be regulated precisely by stress conditions. As indicated by studies conducted on the bean *Phaseolus vulgaris* L. iWUE clearly increases under mild stress conditions [44]. In cucumber stress studies where plants were treated with NaCl, iWUE decreased significantly [45,46], and *Chenopodium quinoa* Willd. plants responded similarly in a pot experiment that simulated salt stress in the groundwater [47]. In the results obtained, WUE and iWUE index did not change significantly in the combinations with high EC compared to the plants with standard EC nutrient solution. This indicates that the iWUE of plants is sensitive to salt stress, but if the salt stress level is moderate, plants tolerate its presence without changes in WUE or iWUE. This may indicate that plants are experiencing mild stress, or that some mechanisms are activated to tolerate this level of stress.

With numerous links to the processes of conversion of absorbed light to a stable chemical form, chlorophyll fluorescence analysis has become the most widely used tool for monitoring the state of the plant [15,48]. The current study showed no significant effect on Fv/Fm and Fm' in cucumber leaves, regardless of the EC of the nutrient solution and the substrate used. Similar results were obtained in a study on the effect of NaCl on Fv/Fm in cucumber leaves where no effect of salinity on this parameter was recorded [15], but other results show a strong reduction of Fv/Fm and ΦPSII in cucumber and strawberry leaves after the application of NaCl as a stress factor [49,50]. In the results presented here, ΦPSII did not decrease until day 28 DAEC (Figure 4c). Stationary fluorescence (Fs) did not change under the influence of the applied eustressor and nutrient solution for most of the experiment duration, except for the 14th and 28th DAEC, where lignite with standard EC and lignite with high EC obtained a significantly higher Fs index, respectively (Figure 4d). As reported by other authors, in the case of NaCl-induced salt stress, the chlorophyll fluorescence and gas exchange parameters in question are reduced, which is evident even after several hours of stress incorporation [2,9,51].

4.3. Dry Matter and Photosynthetic Pigment Content of Cucumber Leaves Grown on Organic and Mineral Substrates at High EC

The highest content of all discussed compounds was found in the leaves of plants grown in lignite in the fifth leaf of the combination with standard EC and in the tenth leaf of the combination with increased EC. In general, the content of the discussed compounds was higher in the combinations with lignite (Table 2). The presented results are in agreement with the results of chlorophyll a and b content in cucumber and tomato leaves, where the content of the compounds in question increased with increasing salinity [3]. Different results were obtained by studying bean (*Vicia faba* L.) leaves, where with the increase in salinity, the content of carotenes, chlorophyll a and b and total of chlorophyll a + b decreased [8]. Other researchers also confirmed, where the increase in salinity decreases significantly the content of chlorophyll a, b and total (a + b), in *Centaurium erythraea* (L.) *Paspalum vaginatum* (L.) plants [52,53].

4.4. Yield, Quality, and Bioactive Compound Content of Cucumber Fruit Grown on Organic and Mineral Substrates at High EC

Many vegetable species show different responses to the salinity [25]. Cucumber is considered a crop susceptible to high salinity [4]. The conducted studies show that the application of eustressor in the form of high EC of the nutrient solution at the level of 7 $dS{\cdot}m^{-1}$ strongly reduced the amount and weight of marketable yield in plants growing on mineral wool (Table 3). Dorai et al., 2001 confirmed in their study that high EC of the nutrient solution can lead to lower yield. In their study, Schwarz and Kuchenbuch [39] also obtained a 50% decrease in tomato yield in the combination where nutrient solution with EC 6 $dS \cdot m^{-1}$ was applied compared to plants fertilized with nutrient solution with 1 $dS \cdot m^{-1}$ EC. Similar results were obtained by Albornoz and Lieth [54] who reported that a high concentration of nutrients in the root zone leads to reduced yield. The application of lignite reduced the effect of stress and increased the number and weight of marketable yield compared to mineral wool (Table 3). At the same time, the number of unmarketable fruits was not significantly different between the combinations with high EC (Table 3). The total number and weight of fruits were significantly higher in plants grown in lignite compared to mineral wool (Table 3). The results indicate a significant effect of lignite on stress reduction and yield increase. Sources report that salinity affected both the reduction in the number and average weight of fruits [55]. Analyzing the results obtained, it can be concluded that the plants set a similar number of fruits in the combination of high EC and standard EC, but at the same time, the former dropped the excess fruit set. This translated into a reduced total yield (Table 3), while the unmarketable yield increased in stressed plants. Other researchers have also reported that high EC of nutrient solution leads to a decrease in yield and deterioration of yield quality [56,57]. Available research results prove that high EC reduced the total yield of lettuce grown in hydroponic systems [58,59]. For average fruit weight (total fruit number/total fruit weight quotient, eustressor in the form of high EC of nutrient solution affected its reduction compared to plants fertilized with a nutrient solution of standard EC, which is consistent with other results of stressed plants [60].

Cucumber fruits contain high amounts of water, a characteristic that contributes to the firmness and fresh appearance of the product on the store shelf. Considering the preferences of the final consumer, it is the physical quality and appearance of the product that determines the purchase [25,61]. The vegetable texture is a very complex trait, and the main compounds contributing to the firmness and overall texture are pectins, celluloses and hemicelluloses. In general, firmness is an important sensory trait in vegetable cultivation that is subject to high variability [25,62]. In the present study, the effect of eustressor of high EC of the nutrient solution on the firmness of cucumber fruit was not confirmed, regardless of the medium used. This is in agreement with the results of other researchers, where no effect of salinity stress on fruit firmness of cucumber and bell pepper was proved [28,63]. The high EC of the nutrient solution decreased the color index and the b* component parameter. This is consistent with other results of salinity effects on the L* component of CIE Lab and a*/b* ratio in greenhouse cucumber fruit, where no significant differences were found [64]. In contrast to vegetables, where the usable part is the fruit, in leafy vegetables salinity can have a more significant effect on color [25]. Perhaps salinity induced by a high concentration of minerals in the nutrient solution (high EC) does not affect fruit and/or leaf color as significantly as the application of NaCl. Appropriate fruit skin color also determines the final consumer choice [25]. Studies conducted show that salinity may have no effect on peel color, given the right intensity of the stress factor or when a suitable substrate is used.

The high EC of the nutrient solution led to an increase in fruit dry weight in MW/high EC combination, intermediate values were recorded for fruit from the L/high EC combination. Similar results were obtained by Schwarz and Kuchenbuch [39], where high EC of nutrient solution led to an increase in dry matter in tomato fruit. Dry matter content also increased after treating lettuce plants with high EC of nutrient solution, where the highest content of the trait in question was recorded at a concentration of 4.0 $dS \cdot m^{-1}$ [65]. Similar results were obtained in the cultivation of pakchoi (*Brassica campestris* L. ssp. *Chinensis*) in hydroponic systems, where the dry matter content also increased with increasing EC of the nutrient solution 4.8–9.6 $dS \cdot m^{-1}$ [40]. The presented results do not support the effect of eustressor and substrate type on TSS (Table 5). Rubio et al. [60] also found no effect of NaCl-induced salinity on TSS, while other researchers reported a decrease in TSS in bell pepper fruits after application of sodium sulphate and sodium chloride [63]. On the other hand, Rosadi et al. [57] found the highest concentration of TSS in tomato fruits when the nutrient solution with EC 5 dS·m^{-1}. If the application of a eustressor in the form of a high EC activates signaling pathways leading to the production of a higher content of biologically active compounds in the fruit, this may not lead to a reduction in yield. [25,26]. For the bioactive compounds studied in fruit, the combination of eustressor and lignite substrate significantly increased lutein, β-carotene, chlorophyll a, b and total chlorophyll (a + b) compared to mineral wool (Table 5). Similar results were obtained by studying the effect of reused lignite mats on the content of chosen bioactive compounds in cucumber fruit [20]. Low salinity intensity in romaine lettuce increased lutein and β-carotene [66]. An increase in carotenoids and anthocyanins in lettuce following a combination of higher salinity and CO_2 concentration was also noted by Pérez-López et al. [67]. Unfortunately, increased salinity may also influence the accumulation of more nitrate in the fruit or leaves, which is an undesirable characteristic. This is confirmed by the presented results of this study, where high nitrate content was demonstrated in fruits from plants grown in medium with elevated nutrient EC. However, it can be clearly seen that fruits from plants growing in lignite were characterized by lower nitrate content (Table 5). However, Scuderi et al. [58] report that high EC reduced nitrate content in the leaves. Different results were obtained by Ding et al. [40] where high EC of nutrient solution led to a significant increase in nitrate in pakchoi leaves. The results of nitrate content in cucumber fruits shown in Table 5 are not high, while fruits obtained from plants grown on lignite accumulated less nitrate, which is more desirable for the consumer. The negative effects of nitrates on consumer health make it necessary to control their content in food, focusing at the same time on proper fertilization and agronomic treatments [25,68].

5. Conclusions

A high EC of nutrient solution along with a lignite-based organic substrate can improve the nutritional and functional value of cucumber fruit, and the use of lignite in cultivation can reduce the negative effects of salinity during plant growth. However, the proper intensity of the stress factor and the developmental stage of the plant at which it should be introduced should be determined. Reducing excessive solid waste production and the search for new biodegradable substrates are further challenges for researchers. At the same time, the study of prospective organic substrates for hydroponic vegetable production and strategies for yield and quality control should continue. The results obtained indicate that growing cucumber in a lignite substrate in hydroponic technology using a nutrient solution with an EC of 7 dS·m^{-1} increases cucumber fruit quality, and, compared to cultivation using rockwool, reduces negative environmental impacts.

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Effect of lignite substrate and supplementary lighting and packaging type on post-harvest storage quality of cucumber fruit

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ABSTRACT

Cucumber is an economically important vegetable grown all over the world. Consumers demand that high-quality cucumber fruit is available throughout the year. The aim of this study was to evaluate the effects of growing conditions such as lignite substrates and assimilation lighting in hydroponic cultivation and storage methods on the quality and post-harvest shelf life of greenhouse cucumber fruit. Cucumber fruit quality was analysed from harvest through cold storage and simulated trading conditions.

Plants were grown in lignite and mineral wool growing mats. Sunlight supplementation was carried out using sodium and LED lamps. Post-harvest fruit were packed in plastic crates, cardboard boxes or plastic bags and stored in a cold store (5 days) and under simulated trading conditions (10 days - 5 days in a cold store and another 5 days at 22 °C). The weight loss of cucumber fruit during storage was determined depending on the combination. After fruit harvest, after fruit storage in the cold store and after 10 days of storage under simulated trading conditions, fruit hardness, dry matter content, TSS, nitrate content of cucumber fruit were studied and sensory evaluation of fruit quality was carried out.

Fruit from plants grown in lignite substrate had lower weight loss during storage and significantly higher TSS (total soluble solids) and dry matter content. They also had a lower nitrate content compared to fruit harvested from plants grown in mineral wool substrate. Furthermore, the best sensory parameters were found in fruit from plants grown in lignite substrate under LED lighting. It was also found that PE film packaging reduced the weight loss of fruit during transport and storage, and that fruit removed from the film and placed in a cardboard box lost weight more slowly compared to the other packaging tested.

1. Introduction

Cucumber fruits (*Cucumis sativus* L.) are one of the most popular vegetables eaten raw. They contain many vitamins, minerals and are a rich source of antioxidants (Patel and Panigrahi, 2019). Cucumber is the most widely grown vegetable species after tomato. The demand for high-quality cucumber fruits does not diminish even during the winter season (Kowalczyk et al., 2018; Soleimani et al., 2009). The global cucumber production volume in 2021 was close to 119.2 million tonnes and increased compared to 2020 (close to 115,66 million tonnes were recorded that year) (Food and Agriculture Organization Corporate Statistical Database) (FAOSTAT 2022). Unfortunately, a proportion of the world's food is still wasted, from production and harvest stages, through transport and storage, to sale (Owoyemi et al., 2021; Valverde-Miranda et al., 2021). Demand for cucumber fruit depends, amongst other things, on quality characteristics such as fruit size and shape, skin colour, firmness and undesirable characteristics such as visible damage to the fruit skin caused by insects or disease, skin scars and bruises

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(Valverde-Miranda et al., 2021). In production and during transport, cucumber fruits are subject to deformation or mechanical damage and may also lose firmness, which in turn is caused by loss of water and changes in polysaccharide content (Nishizawa et al., 2018; Valverde-Miranda et al., 2021). Cucumber fruits are also susceptible to microbial decomposition caused by bacteria (e.g. *Erwinia* spp. and *Xanthomonas* spp.) or fungi (e.g. *Alternaria* spp., *Rhizopus* spp.) (Olawuyi and Lee, 2019; Reddy, 2016). To reduce quality loss, cucumber fruits are usually stored at 10–12.5 °C (Gutiérrez-Pacheco et al., 2020). Research on maintaining fruit quality for longer periods of time, and thus extending *shelf life*, has been conducted using, amongst other things, wax coatings with added plant extracts (Gutiérrez-Pacheco et al., 2020), edible coatings (Chlebowska-Śmigiel et al., 2008; Kokoszka and Lenart, 2007; Patel and Panigrahi, 2019), perforated biodegradable packaging (Owoyemi et al., 2021), active and intelligent packaging (Dobrucka and Cierpiszewski, 2014) and modified atmosphere packaging and storage (Glowacz et al., 2015; Manjunatha and Anurag, 2014). Post-harvest treatment of cucumber fruit with hot water, saccharide treatment and chitosan-g-salicylic acid has also been investigated in order to extend shelf life and reduce cold damage (Nasef, 2018).

The storage quality of fruit depends on the cultivar (Díaz-Pérez et al., 2019) and agrotechnical and climatic factors such as, for example, excessive fruit load on the plant, high temperature (Marcelis, 1993), irrigation and fertilisation method (Wang, 1997), as well as low levels of solar radiation (Marcelis et al., 1998). In order to ensure a year-round supply of fresh fruit, producers grow cucumber in hydroponic systems with LED (*Light-Emitting Diode*) or HPS (*High-Pressure Sodium*) light during periods of insufficient solar radiation (Kowalczyk et al., 2018). Cucumber fruit quality may also depend on the substrate in which the plants are grown (R. Łaźny et al., 2022a, 2021; Olle et al., 2012). In hydroponic cultivation, the solid substrate is usually mineral wool. However, organic, fully biodegradable substrates that do not put such a strain on the environment after production has ended are now being sought (Łaźny et al., 2021). Previous studies have shown that cucumber fruit grown in lignite substrate had higher firmness and higher contents of β-carotene, lutein and chlorophyll *a* and *b* compared to fruit obtained from plants grown in mineral wool (Łaźny et al., 2021). However, there is no information on the effect of the use of lignite substrate during production on the quality of cucumber fruit during storage and sale.

The aim of this study was to evaluate the effects of lignite substrate and assimilation lighting and storage method on the quality and storability of hydroponically grown cucumber fruit. After fruit harvest, cold storage and simulated commodity trading conditions were used in the study: storage, transport under cold storage conditions and sale of fruit on an unrefrigerated shop shelf.

2. Materials and methods

2.1. Experimental conditions

Plants from which fruit was taken for research were grown in the chambers of the WULS Greenhouse Experimental Centre. The cultivation chambers, with an area of 40 m^2 each, were equipped with 3 cultivation troughs, each trough being 9 m long. Six cultivation mats were placed on each trough. Half of the mats were Grodan's Grotop Master mineral wool substrate and half were Carbomat lignite substrate from Carbohort. Before cultivation, the growing mats were flooded for 48 h with a nutrient solution (8 dm^3), with an EC of 2.0 $dS \cdot m^{-1}$ and a pH of 5.5. The composition of the nutrient solution in drip irrigation was: N-NO_3 230, N-NH_4 10, P-PO_4 40, K 290, Ca 180, Mg 45, S-SO_4 60, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15, B 0.33 and Mo 0.05 ($mg \cdot dm^{-3}$). The fertilisers used for the concentrated 100-fold nutrient solution were in tank A: $Ca(NO_3)_2$, KNO_3, and in tank B such fertilisers as KNO_3, KH_2PO_4, K_2SO_4, $MgSO_4$ and Superba Mikromix (Yara company), while container C contained 55% nitric acid. After this time, two 5 cm vertical drainage holes were made in the mineral wool mats in each of the 2 longer sides of the mat and 2 holes in the shorter sides of the mat. In the case of lignite mats, two 5 cm vertical drainage holes were made in the longer sides of the mat, according to a previously developed method (Łaźny et al., 2021). A greenhouse cucumber of the 'Mewa' F1 variety from Rijk Zwaan was used in the study. This variety is characterised by fruit 20–24 cm long and weighing 200–240 g, with dark green, smooth skin and light ribbing. According to the producer, the variety is resistant to light deficiency and has an even yield. Cucumber plants were planted in the 42nd week of 2021 at 6 plants per mat, with a density of 2.7 plants per m^2. Plants were grown under 18 HPS lamps (top lighting- Gavita GAN 600 W) (control) and 24 LED lamps (top lighting- Philips Green Power LED (DR/W - LB, 195 W) + interlighting - 2 lines of LEDs with 18 pcs. of Philips Green Power LED, 2.5 m HO DR/B 100 W module). Cucumber plants were exposed to light for 16 h per day and light conditions in terms of PAR (*Photosynthetically Active Radiation*) were maintained in each chamber as close as possible to ~320 $\mu mol\ m^{-2}\ s^{-1}$ (PPFD - *photosynthetic photon flux density*). The PPFD was measured at the horizontal position and in the middle of plants canopy. The lamps were placed over the tops of the plants and were automatically switched off at a solar radiation level of 250 W/m^{-2}. Temperature and other microclimate parameters were set and maintained at 23/21 °C D/N, RH 70% and CO_2 800 ppm. The nutrient solution was prepared from one- and two-component mineral fertilisers (Yara company). The composition of the nutrient solution in drip irrigation was: N—NO_3 230, N—NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15, B 0.33 and Mo 0.05 ($mg \cdot dm^{-3}$). The nutrient solution was dosed using a FertiMiX-Go automatic fertiliser dosing system equipped with a Ridder HortiMaX-Go controller. The nutrient solution parameters were set at 3.2 dS m^{-1} EC, pH 5.5 and checked daily with a portable pH/EC metre. The nutrient solution was dosed in interval cycles at a rate of 0.8 to 2.5 dm^3 per plant, depending on the developmental stage of the plant. Irrigation was started at 6 a.m. and finished at 8 p.m. After planting the seedlings, the first five buds of each plant were removed. The plants were managed on strings using the guide method, in which all lateral shoots and clinging tendrils were removed. Once the plants were rooted, every second bud on the guide shoot was removed. When the plants were fully fruiting, the lower oldest leaves were removed every three days (maximum three at a time). For the study, 6 growing mats (36 plants) were randomly selected from each combination, i.e. 3 replications, 2 growing mats each (12 plants per replication - $n = 12$).

2.2. Plant material

Cucumber was grown hydroponically in a solid lignite substrate and a mineral wool substrate. The plants were grown under HPS and LED lamps. Cucumber fruits weighing 200–240 g were harvested every 2 days and divided into marketable yield and non-marketable (malformed and crooked fruits) yield. Random fruit samples were taken from such harvested fruits for testing. A single sample was 4 fruits, i.e. approximately 1 kg +/- 0.1 kg (commercial yield only). Fruits were uniformly green in colour, with no signs of damage or disease. Fruits for storage were sampled twice: on date I - week 47 of 2021 and on date II - week 2 of 2022. A diagram of the trials is shown in Fig. 1. The total number of fruit taken for storage at each date was 192 fruit, with 4 fruit in 4 replicates for each combination.

2.3. Packaging treatments and storage conditions

Fruit destined for storage, at each of the two dates, was packaged appropriately and their storage started. The storability of fruit from 4 growing combinations was studied: fruit growing in mineral wool substrate under HPS light (HPS+MW), fruit growing in lignite substrate under HPS light (HPS+*L*), fruit growing in mineral wool substrate under LED light (LED+MW) and fruit growing in lignite substrate under LED light (LED+*L*). The study included 3 ways of packaging the cucumber fruit: 1 - a 16 cm x 40 cm x 30 cm HDPE (High Density Polyethylen)

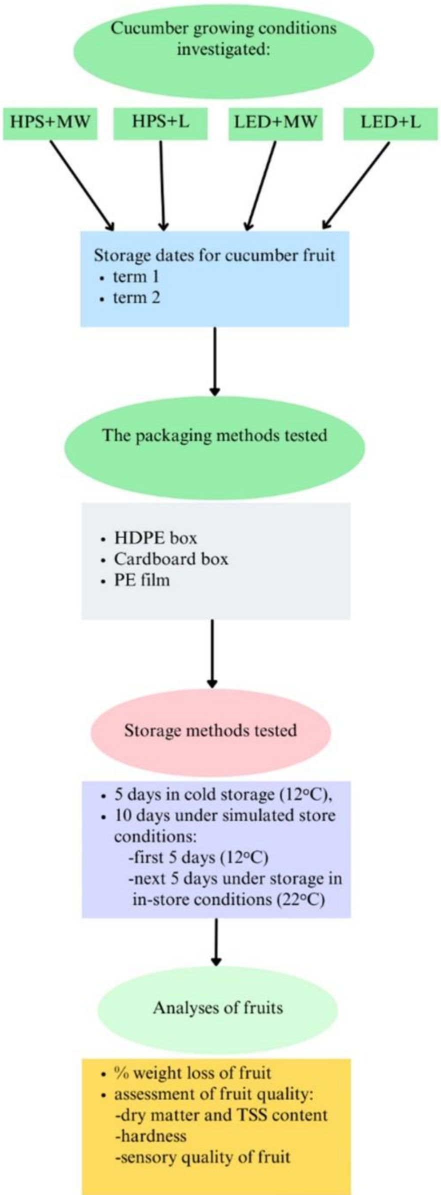

Fig. 1. Research scheme and experimental factors: 1) Cultivation method (light + substrate): HPS + mineral wool (HPS+MW), HPS + lignite (HPS+*L*), LED + mineral wool (LED+MW), LED + lignite (LED+*L*), 2) Post-harvest fruit packaging: HDPE box, PE film, Cardboard box, 3) Storage conditions: 5 days in cold storage (12 °C) and 10 days under simulated store conditions (22 °C): 5 days in cold storage and next 5 days under shop conditions.

plastic box, 2 - a 19.7 cm x 39.5 cm x 29.7 cm vegetable cardboard box (Cardboard box), 3 - a 59 cm x 21.5 cm PE (Polyethylene) film bag for food storage. All packaging was certified to meet the requirements of EU standards. The sampled fruits were placed 4 at a time (1 +/- 0.1 kg) in an HDPE box, a Cardboard box and a PE film bag in four equal replicates. Six perforation holes were made in the PE film bag with a G22 × 1.5 (0.70 × 40 mm) hypodermic needle (Pikdare S.p.A. a company of MTD Medical Technology and Devices S.A.).

The fruit was stored for 5 days in a cold storage (12 °C), and 10 days under simulated store conditions: first 5 days in a cold storage (12 °C) and the next 5 days under in-store conditions (22 °C). Fruits were initially placed in a cold store with a temperature of 12 °C and relative humidity (HR) of 85–90%, in the dark, for 5 days, which resembles typical transport and storage conditions. The fruit was then placed at 22 °C for 5 days, simulating sale on an unrefrigerated shop shelf (HR ~60%). The tests were carried out on two dates, in 4 replicates for each combination (Fig. 1).

2.4. Quality assessment

Percentage weight loss was calculated by weighing the fruit from each combination and repetition, recording the initial weight. For 5 consecutive days of cold storage (12 °C), the fruit and its packaging were weighed daily on a laboratory scale accurate to two decimal places. The weight of the packaging was taken into account when compiling the results. After 5 days of storage, the fruit was removed from the cold store and placed at 22 °C for a further 5 days, where the weight loss of the fruit in each combination was weighed and recorded daily in the same manner. Percentage weight loss was calculated as follows (Rab et al., 2013):

Water loss in stored cucumber fruit was calculated from the results of the fresh weight of the samples and the dry matter content of the fruit. From the water content of the cucumber fruit directly after harvest, the water content of the stored fruit was subtracted. The water loss was expressed as% relative to the water content of the fruit directly after harvesting. The results of water loss from stored fruit are included in the supplementary materials under the names Table S1 and Table S2. After removing the fruit from the cold room, 1 replicate from each combination was randomly selected and destined for analysis The remaining 3 replicates were left for 5 days at 22 °C. After 5 days in the cold store, fruits from the PE film combination were removed from the plastic bags and placed in cardboard boxes, as is practised at the point of sale, and then stored for another 5 days at 22 °C, like the other fruits. After such a simulated sale on an unrefrigerated shelf, the fruit was also destined for analysis.

Fruit analysis included determination of fruit firmness, dry matter, TSS and nitrate content. On all fruit from each combination, firmness was measured using an HPE hardness tester with a shank diameter of 5 mm (Bareiss, USA). Measurements were taken at 3 points on the fruit (at the peduncle, in the middle and in the bract area) at a 90° angle to the fruit, giving results on the HPE scale from 0 to 100 units. After homogenisation of 4 fruits (including the peel) from each combination, the dry matter content of the fruits was determined using the dryer-weight method at 105 °C (SUP-65 W laboratory dryer, Poland). Total Soluble Solids (TSS) content in the sample was determined using a digital refractometer (Hanna Instruments HI-96,800), giving the results in percentages (%). TSS was determined by taking approximately 5 g of homogenised fruit with a plastic spoon and applying it to the digital refractometer. After each measurement, the refractometer was rinsed with distilled water and wiped dry. The nitrate content was determined in a 10 g sample, which was weighed on a laboratory scale accurate to two decimal places and transferred quantitatively to plastic bottles. Then 0.5 g of activated carbon and 100 ml of 2% acetic acid ($C_2H_4O_2$) were added and the samples were shaken for 30 min on a laboratory stirrer. After this time, the resulting solution was filtered through a fluted filter. In the clear solution, the nitrate content was determined spectrophotometrically at 540 nm using a FIAstar 5000 analyzer FOSS instrument and the results are given in mg/kg^{-1} fresh weight; FW.

Sensory analysis of the fruit was carried out in the Sensory Analysis Laboratory of the Department of Vegetable and Medicinal Plants, which complies with PN-EN ISO 8589:2010/A1:2014–07 ("Polish Standards. PN-EN ISO 8589:2010/A1:2014–07 - English version - Sensory analysis - General guidelines for the design of sensory analysis laboratories. Polish Standards; PKN: Warsaw, Poland," 2014). Fruit evaluation was performed just after fruit harvest and after cold storage (5 days) and after 5 days under simulated trading conditions (10 days after harvest). Six fruits from each combination were randomly selected, then washed and peeled with a fruit and vegetable peeler (Tescoma Presto Expert). Four 5-mm-thick slices were then cut from the central part of the fruit (cross-section) and sticks representing approximately one-quarter of the cucumber fruit (longitudinal section) were cut from the rest of the fruit. Each sample consisted of 2 longitudinal sticks of cucumber fruit and 1 slice 5 mm thick. The fruit samples prepared in this way were placed in appropriately coded plastic containers with lids, intended for food. The fruit samples were evaluated by a trained team of 10 people for the distinguishing characteristics of aroma, colour, texture and flavour. The overall quality of the fruit was also assessed. A quantitative descriptive analysis (QDA) method - sensory profiling - was used to assess the cucumber fruit. Distinguishing characteristics were assessed on a continuous graphical scale from 0 to 10 contract units, labelled with appropriate terms. Each of the 10 people in the evaluation team was given an individual number and a set of 6 samples in a random order (according to the numbering codes). Between each sample, a piece of wheat bread roll had to be consumed and washed down with water to neutralise the taste. The assessors took 120-minute breaks before the next assessment.

The following cucumber fruit quality characteristics were assessed in the overall evaluation:

(a) smell
- fresh cucumber - characteristic smell of freshly sliced cucumber, scale: undetectable - very intense
- "foreign" - unusual for a fresh cucumber, if foreign smells were perceptible they had to be specified, scale: not perceptible - very intense

(b) the colour of the flesh, ranging from light cream to light green

(c) texture
- size of the seed cavity, scale: small - very large (3/4 of the diameter of the fruit)
- firmness of the flesh - the resistance of the flesh when biting into a piece of peeled cucumber, scale: soft, flabby - firm, hard
- juiciness of the fruit - sensation perceived when the piece of fruit is assessed orally, scale: not very juicy - very juicy

(d) taste
- fresh cucumber - taste characteristic of fresh cucumber fruit
- sweet - sensation of sweetness associated with the presence of carbohydrates in the sample, occurring with some delay after tasting
- sour - basic flavour
- bitter - basic flavour
- unfamiliar - taste unusual for a fresh cucumber, if felt, it had to be determined what the taste was

(d) overall evaluation - the overall sensory impression perceived when evaluating the sample, which included the texture and flavour attributes evaluated, scale: bad - very good

2.5. Statistical analysis

Statistical analysis was performed with Statistica software system [Dell Inc. Dell Statistica. Version 13. 2016. Available online: software.dell.com (accessed on 20 April 2022)]. Data were subjected to multifactorial analysis of variance (ANOVA) and Tukey's HSD test for evaluating the differences amongst means at $p \leq 0.05$. The biplot display of principal component analysis (PCA) was used to determine the relationship between sensory evaluation scores and multivariate differences of substrate and lighting combinations.

3. Results and discussion

3.1. Weight loss, firmness and dry matter of fruit

Weight, firmness, colour and flavour are key indicators of vegetable quality that are influenced by post-harvest handling (Nishizawa et al., 2018; Valverde-Miranda et al., 2021). The results show that the lowest fruit weight loss was recorded in the PE film combination and the highest in the control (HDPE box) (Table 1). The lowest weight loss during cold storage, as well as during simulated shelf sale, was observed in fruit from the PE film combination grown under LED light and in lignite substrate (Table 1). This was probably due to the use of PE film, while a significant effect of lignite substrate on cucumber fruit shelf life and reduction of weight loss during both cold storage and shelf storage was demonstrated (Table 1). Fruit grown in lignite also had significantly lower water loss during storage compared to fruit grown on rockwool (Table S1). A similar trend was noted for fruit stored at 22 °C (Table S2). Lignite substrate has stable physical properties during plant growth and development and contains a number of chemicals that can directly affect cucumber plants (Łaźny et al., 2021, 2022b). In a study comparing coconut fibre substrate and mineral wool Xing et al. (2019) indicate the induction of complex proteome changes in tomato roots related to mineral ion binding and transport in coconut fibre substrate. Similar changes may occur in lignite substrate and may indirectly affect

Table 1
Effect of packaging, supplementary lighting and growing medium on cucumber fruit weight loss [%] (average of two terms).

Packaging	Supplementary lighting	Growing medium: Mineral wool	Growing medium: Lignite	Mean	
after 5 days in cold storage					
HDPE box	HPS	4.04 ±0.10	4.27 ±0.31	4.11 ±0.22 b	4.31 ±0.49 c
	LED	4.82 ±0.77	4.21 ±0.26	4.51 ±0.61 c	
Cardboard box	HPS	4.40 ±0.39	3.75 ±0.19	4.08 ±0.45 b	3.96 ±0.37 b
	LED	3.99 ±0.29	3.71 ±0.09	3.85 ±0.25 b	
PE film	HPS	0.20 ±0.01	0.22 ±0.01	0.21 ±0.01 a	0.21 ±0.01 a
	LED	0.20 ±0.01	0.21 ±0.02	0.20 ±0.01 a	
	Mean	2.94 ±2.04	2.71 ±1.84 *		
after simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C					
HDPE box	HPS	12.54 ±1.18	12.39 ±1.51	12.19 ±1.27 b	13.18 ±2.06 c
	LED	15.49 ±2.84	12.85 ±0.28	14.17 ±2.31 c	
Cardboard box	HPS	13.26 ±1.36	11.14 ±1.36	12.20 ±1.52 b	11.89 ±1.18 b
	LED	12.14 ±0.35	11.02 ±0.35	11.58 ±0.72 b	
PE film	HPS	9.11 ±1.41	9.23 ±0.32	9.17 ±0.92 a	8.97 ±0.86 a
	LED	8.64 ±0.19	8.92 ±1.28	8.78 ±0.83 a	
	Mean	11.86 ±2.74	10.83 ±1.61 *		

Means marked with the same small letters are not significantly different at $\alpha = 0.05$ (Tukey test).
Means marked with an asterisk are significantly different ($p < 0.05$).

cucumber fruit quality, which is confirmed in previous studies conducted on lignite substrate (Łaźny et al., 2021, 2022b). Lignin and cellulose are also present in the lignite substrate, which can cause immobilisation of soluble N (Atzori et al., 2021). The presence of a range of nutrients that lignite substrate has and the ability to immobilise N can translate into fruit quality. As shown in Table 1, after 5 days of storing cucumber fruit in cold storage, the fruit had less weight loss than fruit stored for a further 5 days at room temperature (22 °C) (Table 1). In both cases, the best preserved, i.e. with the lowest weight loss compared to fruit immediately after harvest, were fruit packed with PE film, followed by fruit stored in a cardboard box, and the highest weight loss was shown by fruit stored in an HDPE box. (Tables 1). The results of the dynamics of weight loss during storage of cucumber fruit clearly show the best effects in reducing the rate of fruit weight loss when PE film was used both under cold storage conditions and after removal of the fruit from the film and further storage for 5 days at 22 °C (Fig. 2). The fastest weight loss was experienced by fruit stored in HDPE box plastic harvested from the crop grown in mineral wool substrate (Fig. 2).

Research findings by Abisoet al. (2015) demonstrate that storing tomato fruit at ambient temperature accelerates weight loss through transpiration, which is consistent with the results obtained for cucumber fruit (Table 1). According to Owoyemi et al. (2021) cucumber fruit without individual packaging or foil loses weight faster compared to fruit with packaging, which also confirms the results obtained in their study (Table 1). The study did not show any significant interactions between the compared combinations for weight loss for the two modes of cucumber fruit storage analysed.

The climatic parameters occurring at the time of cultivation, as well as the fruit load, the variety and a number of other factors directly affect the quality of the fruit (Marcelis, 1992). The hardness/firmness of cucumber fruit is considered to be one of the most important quality traits (Gómez-López et al., 2006). The marked decrease in firmness of stored fruit at ambient temperature is due to the rapid loss of water and respiration of the fruit. This parameter is also influenced by packaging, which is clearly noticeable in the case of fruit removed from the plastic bag (PF film) and placed in a cardboard box, as used by most supermarkets (Table 3). When analysing the hardness of cucumber fruit measured at harvest, there were no significant relationships between fruit hardness and the way the plants were grown: substrate and supplementary lighting (Table 2).

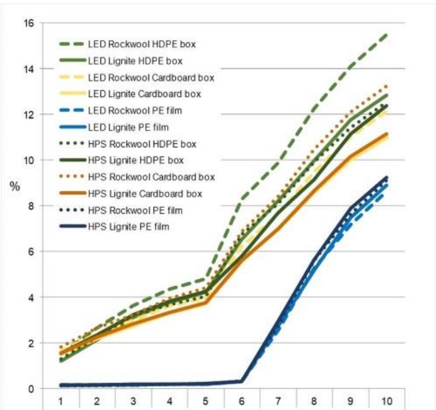

Fig. 2. Effect of packaging on dynamics of cucumber fruit weight loss during storage in simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C (average of two terms).

Table 2
Effect of supplementary lighting and growing medium on cucumber fruit hardness at harvest [HPE] (average of two terms).

Lamp	Growing medium Mineral wool	Lignite	Mean
HPS	62.93±0.62	63.20±0.84	63.06±0.70 ns
LED	64.80±0.65	64.28±0.75	64.71±0.66 ns
Mean	63.86±1.16 ns	63.91±1.06 ns	

ns - not significant ($p < 0.05$).

In contrast, there was a significantly higher hardness of stored cucumber fruit from plants grown in lignite substrate compared to those from plants grown in mineral wool (Table 3). Fruits stored under simulated trading conditions (5 days in cold storage and a further 5 days at room temperature) harvested from plants grown under LED light also showed higher firmness than those from the crop grown under HPS light (Table 3). In a study by Freitas et al. (2021) and Hovi-Pekkanen & Tahvonen (2008) there was no effect found of LED light on cucumber fruit quality and extension of post-harvest shelf life. The results obtained after storage under simulated trading conditions (Table 3) indicate a significant effect of the lignite substrate and LED light on cucumber fruit firmness, with this parameter being also influenced by the packaging method. Fruit packed in a cardboard box had significantly the lowest firmness, while loss of firmness was reduced by PE film packaging, which is particularly evident after simulated trading (Table 3). This confirms previous reports that adequate packaging reduces weight loss and firmness loss in cucumber fruit (Mahajan et al., 2016; Owoyemi et al., 2021).

Table 3
Effect of packaging, supplementary lighting and growing medium on cucumber fruit hardness [HPE] (average of two terms).

Packaging	Supplementary lighting	Growing medium Mineral wool	Lignite	Mean	
after 5 days in cold storage					
HDPE box	HPS	61.03 ±0.74	62.15 ±0.34	61.59 ±0.80 a	61.41 ±1.73 a
	LED	59.05 ±0.53	63.43 ±0.46	61.24 ±2.38 a	
Cardboard box	HPS	53.15 ±0.74	54.90 ±0.74	54.03 ±1.16 b	57.47 ±3.91 b
	LED	59.00 ±0.32	62.83 ±0.46	60.91 ±2.08 a	
PE film	HPS	60.80 ±0.73	60.93 ±1.09	60.86 ±0.87 a	61.94 ±1.47 a
	LED	62.20 ±0.59	63.83 ±0.82	63.01 ±1.09 a	
	Mean	59.20 ±3.05	61.34 ±3.16 *		
after simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C					
HDPE box	HPS	52.80 ±0.36	53.36 ±1.35	53.09 ±0.96 d	56.94 ±4.46 b
	LED	58.25 ±0.74	63.35 ±0.26	60.80 ±2.77 ab	
Cardboard box	HPS	50.95 ±0.44	50.65 ±0.97	50.80 ±0.71 cd	53.86 ±4.90 c
	LED	51.98 ±1.71	61.86 ±0.68	56.93 ±5.43 bc	
PE film	HPS	57.00 ±1.23	54.06 ±0.54	55.54 ±1.79 d	58.65 ±3.52 a
	LED	60.98 ±0.92	62.55 ±0.39	61.76 ±1.06 a	
	Mean	55.33 ±3.84	57.65 ±5.23 *		

Means marked with the same small letters are not significantly different at α = 0.05 (Tukey test).
Means marked with an asterisk are significantly different ($p < 0.05$).

3.2. TSS and nitrate content of cucumber fruit

Cucumber fruits harvested from plants grown on lignite substrate and under LED lamps had significantly higher TSS content than those from plants grown in mineral wool, under HPS light (Table 4). For TSS content in cucumber fruit, there was no interaction between the substrate used and supplementary lighting. Published studies show that the TSS and dry matter content of cucumber fruit can vary depending on the date of fruit harvest, the month of cultivation and the method of storage (Valverde-Miranda et al., 2021). According to Łaźny et al. (2022b) the TSS content of the fruit also depends on the type of substrate in which the plants are grown.

After cold storage of cucumber fruit, and after 10 days of simulated trading, higher concentrations of cell sap soluble components (TSS) were found in fruit from plants grown in lignite substrate compared to plants grown in mineral wool substrate (Table 5). A similar trend was also observed for plants grown under LED light. The type of packaging also had an effect on the TSS content of cucumber fruit. Fruit stored for 5 days in the cold storage in HDPE boxes contained more than 4% more TSS than fruit stored in other packaging (Table 5).

However, after 10 days of storage, the HDPE box and PE film combinations had the highest TSS content (by more than 4%) compared to fruit stored in a Cardboard box (Table 5). Ahmad et al. (2011) found no effect of organic substrates (date-palm peat, cocopeat) on increasing TSS content in cucumber fruit compared to mineral substrate (perlite). Fruit stored for 5 days in cold storage had lower TSS concentrations than fruit stored for another 5 days at 22 °C (Tables 5). Similar results were obtained by Bahnasawy & Khater (2014) where the concentration of TSS in cucumber fruit increased as the storage temperature increased from 5 °C to 25 °C. On the other hand, researchers in Spain found that the TSS content in cucumber fruit decreased with the storage length (Valverde-Miranda et al., 2021). Results of the study by Kahramanoğlu & Usanmaz (2019) also confirm a decrease in TSS content in fruit with the storage length.

Similarly to the TSS content of cucumber fruit, the dry matter content was also significantly higher in fruit obtained from plants grown in lignite substrate and under LED lamps (Table 6). Researchers Kahramanoğlu and Usanmaz (2019) showed a linear relationship between TSS and fruit dry matter content until ageing. In the study it was found that as the TSS content of the fruit increases, the dry matter content increases and vice versa. In the results presented, for fruit stored for 5 days in cold storage, the average dry matter content of the fruit was 3.59%, and for fruit stored a further 5 days at 22 °C it was 3.84% (Tables 7).

After storing cucumber fruit under simulated trading conditions (5 days of cold storage and another 5 days at 22 °C), there was a significantly higher dry matter content in fruit from plants grown in lignite substrate than in plants grown in mineral wool (Table 7). It is likely that the increase in dry matter in the fruit correlated with water loss through the fruit. There was no effect of the supplementary lighting on the cucumber plants, whether with HPS or LED lamps or the packaging used in the study on the dry matter content of the fruit, either after 5 days of cold storage or after a further 5 days at 22 °C (Table 7).

Valverde-Miranda et al. (2021) showed that the concentration of dry matter in cucumber fruit decreases with the increasing storage length. Previous findings by Łaźny et al. (2021) also showed the effect of lignite substrate on the dry matter content of cucumber fruit. In addition, it was found that despite the significantly higher dry matter content of fruits grown in lignite, these fruits also lost water more slowly. Despite storing fruit at 22 °C, fruit obtained from plants grown on brown coal also lost water to a lesser extent compared to fruit grown on mineral wool as presented in table S1 and S2. Thus, lignite substrate can influence the dry matter content, increasing the post-harvest shelf life of cucumber fruit.

The results also show that the fruit obtained from plants grown in lignite substrate and under LED lamps had a significantly lower nitrate content (Table 8.). By controlling the growing conditions, it is possible to influence the content of desirable components in cucumber fruit, i.e. quality. A reduction in nitrate content can be achieved, amongst other things, by controlling the concentration and composition of the nutrient solution by inducing eustress, as well as by using appropriate lighting (Łaźny et al., 2022b; Rouphael et al., 2018). Also, studies by Długosz--Grochowska et al. (2016) showed that light control during the

Table 4
Effect of supplementary lighting and growing medium on cucumber fruit TSS at harvest [°Brix] (average of two terms).

Lamp	Growing medium Mineral wool	Lignite	Mean
HPS	3.55±0.06	3.38±0.05	3.46±0.11
LED	3.68±0.05	3.93±0.06	3.86±0.21 *
Mean	3.61±0.08	3.71±0.36 *	

Means marked with an asterisk are significantly different ($p < 0.05$).

Table 5
Effect of packaging, supplementary lighting and growing medium on cucumber fruit TSS content [°Brix] (average of two terms).

Packaging	Supplementary lighting	Growing medium Mineral wool	Lignite	Mean	
after 5 days in cold storage					
HDPE box	HPS	3.58 ±0.05	3.98 ±0.05	3.78 ±0.22 b	3.95 ±0.30 a
	LED	3.88 ±0.05	4.38 ±0.05	4.13 ±0.27 a	
Cardboard box	HPS	3.68 ±0.05	3.68 ±0.05	3.68 ±0.05 b	3.79 ±0.18 b
	LED	3.73 ±0.05	4.08 ±0.05	3.90 ±0.19 ab	
PE film	HPS	3.55 ±0.06	3.78 ±0.05	3.66 ±0.13 b	3.79 ±0.20 b
	LED	3.78 ±0.05	4.08 ±0.05	3.93 ±0.17 ab	
	Mean	3.70 ±0.12	3.99 ±0.24 *		
after simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C					
HDPE box	HPS	4.23 ±0.05	4.25 ±0.06	4.24 ±0.05 a	4.25 ±0.11 a
	LED	4.15 ±0.06	4.38 ±0.13	4.26 ±0.15 a	
Cardboard box	HPS	3.85 ±0.10	4.03 ±0.05	3.94 ±0.12 b	3.99 ±0.15 b
	LED	3.93 ±0.10	4.18 ±0.10	4.05 ±0.16 ab	
PE film	HPS	3.78 ±0.05	4.38 ±0.05	4.08 ±0.32 ab	4.05 ±0.27 a
	LED	3.85 ±0.06	4.20 ±0.14	4.03 ±0.21 ab	
	Mean	4.09 ±0.18	4.23 ±0.15 *		

Means marked with the same small letters are not significantly different at α = 0.05 (Tukey test).
Means marked with an asterisk are significantly different ($p < 0.05$).

Table 6
Effect of supplementary lighting and growing medium on cucumber fruit dry matter content at harvest [%] (average of two terms).

Lamp	Growing medium Mineral wool	Lignite	Mean
HPS	3.20±0.04	3.35±0.06	3.28±0.09
LED	3.20±0.11	3.73±0.04	3.47±0.30 *
Mean	3.20±0.07	3.54±0.21 *	

Means marked with an asterisk are significantly different ($p < 0.05$).

Table 7
Effect of packaging, supplementary lighting and growing medium on cucumber fruit dry matter content [%] (average of two terms).

Packaging	Supplementary lighting	Growing medium Mineral wool	Lignite	Mean	
after 5 days in cold storage					
HDPE box	HPS	3.45 ±0.22	3.65 ±0.04	3.55 ±0.18 ab	3.69 ±0.21 ns
	LED	3.74 ±0.10	3.92 ±0.06	3.83 ±0.13 b	
Cardboard box	HPS	3.39 ±0.21	3.54 ±0.26	3.46 ±0.23 ab	3.54 ±0.29 ns
	LED	3.32 ±0.21	3.90 ±0.12	3.61 ±0.35 ab	
PE film	HPS	3.50 ±0.02	3.31 ±0.10	3.41 ±0.12 a	3.55 ±0.24
	LED	3.64 ±0.40	3.74 ±0.03	3.69 ±0.26	ns
	Mean	3.51 ±0.24 ns	3.68 ±0.24 ns	ab	
after simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C					
HDPE box	HPS	3.90 ±0.10	3.90 ±0.01	3.90 ±0.06 ns	3.87 ±0.08 ns
	LED	3.78 ±0.07	3.91 ±0.04	3.85 ±0.09 ns	
Cardboard box	HPS	3.74 ±0.16	3.87 ±0.10	3.78 ±0.14 ns	3.83 ±0.14 sn
	LED	3.74 ±0.14	3.98 ±0.03	3.86 ±0.16 ns	
PE film	HPS	3.77 ±0.10	4.14 ±0.16	3.95 ±0.24 ns	3.83 ±0.21 ns
	LED	3.65 ±0.02	3.76 ±0.03	3.70 ±0.06	
	Mean	3.76 ±0.12	3.93 ±0.14 *	ns	

Means marked with the same small letters are not significantly different at α = 0.05 (Tukey test).
Means marked with an asterisk are significantly different ($p < 0.05$).

Table 8
Effect of supplementary lighting and growing medium on cucumber fruit nitrates content at harvest [mg/kg^{-1} FW] (average of two terms).

Lamp	Growing medium Mineral wool	Lignite	Mean
HPS	214.5 ± 2.00	198.9 ± 0.95	230.6 ± 3.75 b
LED	118.7 ± 0.67	71.7 ± 0.05	95.2 ± 2.61 a *
Mean	190.5 ± 7.98	135.3 ± 7.00 *	

Means marked with an asterisk are significantly different ($p < 0.05$).

cultivation of leafy vegetables allows a reduction in nitrate and an increase in the content of ascorbic acid, folic acid, polyphenols and chlorophyll in leaves (Rouphael et al., 2018).

Stored cucumber fruits from plants grown in lignite substrate and under LED light were also found to have significantly lower nitrate content than those from plants grown in mineral wool and under sodium lamps (Table 9). There was more than 50% reduction in nitrate content in fruit stored for 5 days in cold storage for fruit from combinations with LED lamps, compared to fruit from plants grown under HPS lamps (Table 9). A similar trend was observed for fruit after simulated trading, where the nitrate content was lowest in the combination grown in lignite substrate and under LED lamps (Table 9). The content of these

Table 9
Effect of packaging, supplementary lighting and growing medium on cucumber fruit nitrates content [mg/kg^{-1} FW] (average of two terms).

Packaging	Supplementary lighting	Growing medium Mineral wool	Lignite	Mean	
After 5 days in cold storage					
HDPE box	HPS	198.7 ± 1.28	160.8 ± 0.11	179.7 ± 2.23 b	135.8 ± 5.17 a
	LED	116.8 ± 0.76	67.1 ± 0.12	91.9 ± 2.76 a	
Cardboard box	HPS	221.5 ± 0.48	197.6 ± 0.06	209.5 ± 1.34 b	150.8 ± 6.41 b
	LED	112.6 ± 1.09	71.4 ± 0.51	92.0 ± 2.38 a	
PE film	HPS	217.5 ± 0.85	181.9 ± 1.47	199.7 ± 2.23 b	133.7 ± 7.07 a
	LED	71.8 ± 0.64	63.6 ± 0.41	67.7 ± 0.66 a	
	Mean	156.5 ± 6.05	123.7 ± 5.93 *		
after simulated trading 10 days - 5 days in cold storage and 5 days at 22 °C					
HDPE box	HPS	126.4 ± 0.53	149.2 ± 0.36	137.8 ± 1.31 b	111.5 ± 3.48 b
	LED	111.3 ± 0.57	59.3 ± 0.59	85.3 ± 2.90 a	
Cardboard box	HPS	200.5 ± 1.19	75.9 ± 0.16	114.3 ± 6.87 b	100.8 ± 6.12 a
	LED	74.3 ± 0.46	52.4 ± 0.05	63.3 ± 1.23 a	
PE film	HPS	197.7 ± 1.74	85.1 ± 0.43	141.4 ± 6.27 b	102.4 ± 6.58 ab
	LED	72.0 ± 0.07	54.9 ± 0.39	63.4 ± 0.97 a	
	Mean	130.3 ± 5.44	79.5 ± 3.44 *		

Means marked with the same small letters are not significantly different at α = 0.05 (Tukey test).
Means marked with an asterisk are significantly different ($p < 0.05$).

compounds was also influenced by the method of packaging, where fruit stored in a Cardboard box had a significantly higher nitrate content after 5 days of cold storage (Table 9). After a further 5 days of storage at room temperature, the nitrate content of the cucumber fruits decreased and the fruits in the Cardboard box had a lower nitrate content than those stored in the HDPE box (Table 9).

The nitrate concentration in cucumber fruit was found to decrease with the length of storage (Table 9). The results obtained are consistent with the results of Wieczorek and Traczyk(1995), where it was proven that the nitrate content of white cabbage decreases during cold storage. Different results were obtained by studying lettuce (*Lactuca sativa* L.), where it was shown that the nitrate content increases with the length of storage (Silalahi et al., 2016).

Not only the type of light, composition and temperature of the medium, but also the type of substrate influences the content of nutrients and substances harmful to human health. However, knowledge on this subject is still limited. Available studies on tomatoes only show a beneficial effect of nutrient solution temperature at 20 °C on the rate of nutrient uptake and increased fruit quality (Rouphael et al., 2018). On the other hand, the results of previous experiments in cucumber cultivation clearly indicate that the type of substrate significantly affects the fruit quality of greenhouse cucumber (Łaźny et al., 2021, 2022b).

3.3. Sensory assessment

In the assessment of sensory quality of fruit at harvest, PCA principal component analysis was applied to the QDA data, and the first two principal components explained 87.46% of variance (PC1 63.23% and PC2 24.13%). PCA was used for dimensionality reduction and exploratory data analysis. A dataset that includes sensory evaluations of cucumbers depending on the packaging (when fruits were stored), supplementary lighting and growing medium was used. PCA identifies the principal components (PCs), which are linear combinations of the original sensory parameters that explain the maximum variance in the data. Objects that are close to each other in the PCA plot are more similar in terms of their sensory parameters. Parameters that have similar values on the same PCs are positively correlated, indicating that they tend to vary together. Conversely, sensory parameters with values of opposite signs on the same component are negatively correlated, indicating an inverse relationship. The projection of samples on the plane defined by PC1 and PC2 is shown in Fig. 3. Applying principal component analysis showed significant sensory variation in cucumbers harvested from plants grown in the substrate and supplementary lighting combinations tested. The most homogeneous group were the fruit samples from the lignite substrate cultivation grown under LED lamps, which were also characterised by the best sensory parameters: fresh cucumber smell (A1), fruit firmness (A5) and sweet taste (A8). Sour taste (A9) and bitter taste (A10) were very poorly or not perceptible at all. Some assessors also indicated the foreign smell (A2) and foreign taste of the fruit (A11), which were described positively as being similar to melon and watermelon. In fruit grown under LED light but in mineral wool, the most noticeable was the taste of fresh cucumber fruit (A7) and fairly high juiciness (A6) (Fig. 3).

Fruits from cultivation under HPS lamps were characterised by different sensory quality - samples from cultivation in lignite substrate were dominated by sour taste (A9) and bitter taste (A10), while fruits grown in mineral wool were characterised by low fresh cucumber flavour intensity and green flesh (A3), with large seed nest size (A4). As reported by Kowalczyk et al. (2018), fruit grown under HPS and LED lamps did not differ significantly in terms of sensory evaluation parameters. However, the presented study indicates higher ratings of sensory parameters of fruit obtained in cultivation under LED lamps, but the substrate used in the cultivation may also play a role here. According to a study by Luoto (1984), tomato fruits grown in peat substrate were tastier in the assessors' perception compared to fruits from plants grown in mineral substrate.

In the analysis of fruit after simulated trading, PCA principal component analysis was applied to the QDA data, and the first two principal components explained 67.68% of variance (PC1 54.79% and PC2 12.89%). The results of the PCA after storage under different conditions made it possible to distinguish groups correlated with combinations of substrate, light type and packaging for the fruit after storage. Two opposite groups were clearly distinguished, suggesting a relationship between their location and descriptor vectors. The first group consisted of fruit obtained from the cultivation grown in lignite substrate, while the second one consisted of cucumbers from plants grown in mineral wool. Within these groups, varied sensory scores were recorded for fruit stored in different packages under the light combinations tested. The most homogeneous group consisted of fruit samples originating from cultivation in lignite substrate under LED light, regardless of the type of packaging. They were characterised by an intense sweet taste (A8) and high firmness (A5), similar to the analysis of fruit at harvest, indicating that these characteristics were retained after storage. Cucumbers stored in a foil bag (PE film) received the highest ratings within these samples, similar to cucumbers grown in lignite substrate under HPS light, although this group was more diverse. Fruit stored in the PE film bag was characterised by the most intense fresh cucumber smell (A1) and flavour (A7), while cucumbers stored in the cardboard and HDPE box were characterised by high juiciness (A6) and intense green flesh colour (A3).

Stored fruit from the cultivation in mineral wool also varied depending on the light used in cultivation and post-harvest packaging. In samples of cucumbers grown under HPS light and later stored in a cardboard box and plastic bag, the most noticeable foreign smell (A2) was described by the assessors as musty. The fruit stored in the cardboard box was further characterised by a sour taste (A9). Samples from plants grown in mineral wool under LED lighting, regardless of the packaging used during storage, were characterised by a strong bitter taste (A10) and a foreign taste (A11), described as musty, while low scores for parameters such as fresh cucumber smell (A1), sweet taste (A8) and firmness (A5) (Fig. 4).

As reported by Owoyemi et al. (2021), the flavour of cucumber fruit changes with storage length, and the flavour ratings of fruit stored in sealed packages were significantly lower. During simulated cucumber fruit trading, taste ratings of unpackaged fruit (stored in bulk) decreased and were significantly lower compared to fruit packed in micro-perforated packaging (Owoyemi et al., 2021). In a study where shrink-wrapped cucumbers were stored at 12 ± 1 °C with 90–95%

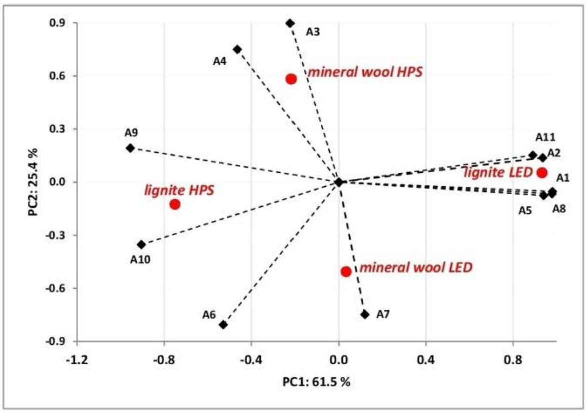

Fig. 3. Results of PCA presenting the relationships between sensory evaluation scores and multivariate differences of substrate and lighting combinations of the fruits at harvest (red point in the biplot): A1 - smell of fresh cucumber fruit, A2 - foreign smell, A3 - colour of the flesh, A4 - size of the nest, A5 - hardness, A6 - juiciness, A7 - fresh cucumber fruit flavour, A8 - sweet, A9 - sour, A10 - bitter, A11 - foreign flavour (black vectors).

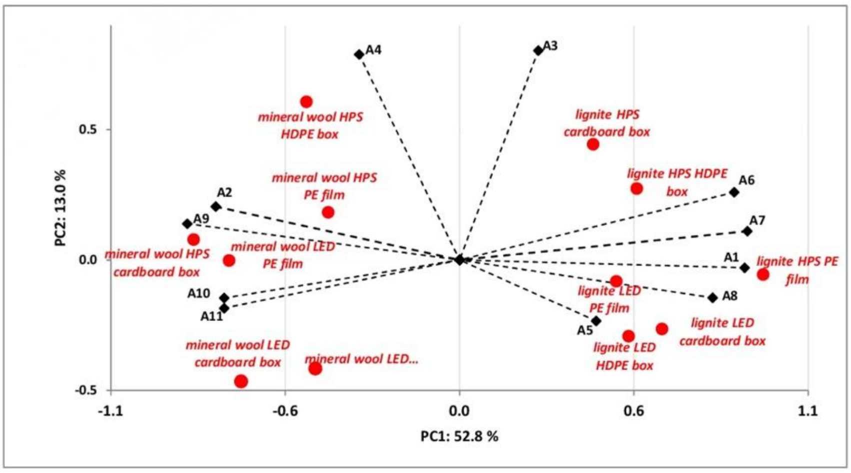

Fig. 4. Results of PCA presenting the relationships between sensory evaluation scores and multivariate differences of substrate, packaging and lighting combinations of the fruits after storage (red point in the biplot): A1 - smell of fresh cucumber fruit, A2 - foreign smell, A3 - colour of the flesh, A4 - size of the nest, A5 - hardness, A6 - juiciness, A7 - fresh cucumber fruit flavour, A8 - sweet, A9 - sour, A10 - bitter, A11 - foreign flavour (black vectors).

relative humidity, sensory scores of 7.02 were recorded after 15 days of storage, after which flavour deteriorated (Dhall et al., 2012). The results presented in this study show that fruit from combinations grown in lignite substrate and under LED light received higher sensory scores. There was no significant effect of packaging apart from the indication of a foreign taste, defined as musty, in the case of fruit stored in PE film and cardboard from combinations grown in mineral wool and under HPS lamps. These results indicate that the growing medium can have a greater influence on the taste and overall desirability of cucumber fruit than the method of storage, provided that the fruit is stored at the right temperature and in packaging dedicated to this type of vegetable.

4. Conclusions

One way to prolong the post-harvest quality of vegetables is through proper packaging, transport and storage. However, if certain solutions during production are applied, higher quality cucumber fruit with increased post-harvest quality can be obtained. Organic lignite substrate and LED supplementary lighting have a positive effect on the quality and post-harvest shelf life of greenhouse cucumber fruit. Packing cucumber fruit in foil extends the shelf life and post-harvest quality of these fruits compared to storing fruit in plastic crates or cardboard boxes.

CRediT authorship contribution statement

Radosław Łaźny: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Project administration. **Jarosław L. Przybył:** Methodology, Software, Validation, Data curation, Writing – review & editing, Visualization. **Elżbieta Wójcik-Gront:** Software, Data curation. **Małgorzata Mirgos:** Methodology, Software, Resources, Data curation, Writing – review & editing, Visualization. **Stanisław Kalisz:** Writing – review & editing. **Sebastian Bella:** Formal analysis, Data curation. **Janina Gajc-Wolska:** Software, Resources, Writing – review & editing, Supervision. **Waldemar Kowalczyk:** Software, Formal analysis. **Jacek S. Nowak:** Formal analysis. **Małgorzata Kunka:** Software, Formal analysis, Formal analysis. **Katarzyna Kowalczyk:** Validation, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2023.112350.

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Research Paper

Effect of lignite substrate compared to mineral wool and supplementary lighting with HPS and LED on growth, plant photosynthetic activity, yield and fruit quality of greenhouse cucumber

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ABSTRACT

The substrate in hydroponic cultivation is one of the basic factors for proper plant growth, and current environmental trends suggest replacing the previously used mineral wool with organic substrates. Light is also essential for proper plant growth, which is why LEDs (*Light Emitting Diode*) are increasingly used to provide plants with supplementary light, allowing, among other things, to control the spectral composition. The aim of this study was to determine the effect of lignite substrate and LED supplementary lighting on morphological and physiological parameters as well as quality and yield of *cucumber* (*Cucumis sativus* L.) in hydroponic cultivation compared to the cultivation in mineral wool substrate. Lignite mats applied in cultivation with LED supplementary lighting had a beneficial effect on cucumber plant growth and development and plant nutrition in Fe, K, P, Ca, Mg and Zn compared to cultivation in mineral substrate and HPS supplementary lighting. The combination of LED lighting and lignite mats also improved the physiological parameters of the cucumber plants, as well as fruit hardness. Fruits harvested from plants grown in lignite substrate and supplemented with LEDs had the lowest nitrate content and increased TSS value, as well as increased fruit firmness.

1. Introduction

Increasing human activities in the second half of the 20th century and the ever-increasing demands of many economic sectors, mainly agriculture and forestry, have led to soil degradation across Europe and beyond (Virto et al., 2014). Therefore, for these reasons, as well as the need to increase the efficiency of vegetable crops, still largely traditionally grown in monoculture, soilless cultivation is being introduced (Hossain et al., 2020). Hydroponic cultivation using inert substrates is becoming increasingly important and technologically feasible. There are an estimated 135 000 ha of glass-covered greenhouse crops in Europe (Paris et al., 2022) and it is predicted that, due to the ever-increasing global population, the area of these crops will show an increasing trend (Khan, 2018). In intensive production under covers, a hydroponic growing system using solid substrates (organic or mineral) is usually used. The main advantage of growing in a soilless system is the isolation of the plant's root system from the soil and the possibility to optimise the physical and chemical characteristics for the root environment (Savvas and Gruda, 2018). Often the soil is highly degraded, saline or becomes a habitat for pathogenic organisms, eliminating it as a potential environment for crop root development (Barrett et al., 2016; Kamran et al., 2019). Substrate is one of the key factors for adequate plant development, and the most commonly used substrate in cover cultivation is mineral wool, which provides good air and water conditions, has a high water-holding capacity, moderate porosity and a stable structure (Kleiber et al., 2012; Xiong et al., 2017). Mineral wool is mainly obtained from diabase and limestone, which are melted at 1600 °C. Mineral wool substrates are a non-organic material that is not biodegradable (Xiong et al., 2017). A 1 ha production greenhouse leaves 150 m^3 of used rockwool after one year. Problems with the management of used

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substrate are forcing the search for greener, but equally efficient substitutes (Łaźny et al., 2021). A widely used substrate in greenhouse cultivation is coconut fibre and dust from the outer shell or mesocarp of coconut fruits. These have good physical properties for plant growth, but depending on the country of origin they can vary (Tuckeldoe et al., 2023; Xiong et al., 2017). Dried wood bark, which is a by-product of wood production, can also be a good substrate, characterised by its high water-holding capacity, neutral pH in the range 5–7 and long durability. The high variability of the material and the increasing costs caused by the use of wood bark as an alternative fuel and landscaping application reduce the attractiveness of this product as a substrate (Yang et al., 2023). In recent years, biocarbon has also gained interest due to its nutrient retention capacity and energy neutrality, but its variable physicochemical parameters and high production costs pose a problem (Savvas and Gruda, 2018). Miscanthus (*Miscanthus* x *gigantus*) substrate has become a promising alternative to mineral wool in recent years (Kraska et al., 2018), the production of which is possible locally, without much financial input (Nguyen et al., 2022). As indicated by studies, composted miscanthus has high porosity and high oxygen diffusion (Kraska et al., 2018).

A substrate with suitable physical properties for plants is lignite substrate (Łaźny et al., 2022a, 2021b). Lower CO_2 emissions by 40 % during production of lignite growing mats (Łaźny et al., 2022a) compared to mineral wool and the possibility to use the spent substrate as organic fertiliser in conventional cultivation, reduces the negative environmental impact. Fresh lignite is characterised by a high content of fatty acids, humic acids, hymatomelan and fulvic acids, in addition to being a rich source of cellulose and lignin (Łaźny et al., 2022b). As noted, the substrate can also influence the health-promoting properties of food. Many researchers indicate that the production of nutrient-rich foods should be a priority, as should the protection of the environment (García-Mier et al., 2013; Lisiewska et al., 2008; Tuckeldoe et al., 2023). Previous studies confirm the effect of lignite substrate in hydroponic cultivation on the content of bioactive compounds in cucumber fruit (Łaźny et al., 2022a, 2021).

A very important factor in the proper development of plants is light, which, as the primary source of energy, determines proper plant growth. Light scarcity in autumn and winter in the countries of the European continent necessitates the use of artificial lighting for plants. For this purpose, lamps with a broad emission spectrum in the PAR range are used (Gajc-Wolska et al., 2021). At present, the most commonly used light sources are HPS (*High Pressure Sodium*) lamps. They are characterised by a high proportion of photosynthetically active radiation (*PAR-Photosynthetically Active Radiation*), but a low proportion of blue light (5 %). Blue light affects the efficiency of photosynthesis and thus plant growth. For comparison, sunlight contains 18 % blue light (Gajc-Wolska et al., 2021; Islam et al., 2012). The light spectrum of HPS lamps is strictly defined by their design, so changing it is not possible. In addition, this light source emits very high amounts of heat and can cause thermal damage to plants (Islam et al., 2012). In recent years, LEDs (*Light Emitting Diode*) have become a replacement for traditional HPS lamps. Technological developments of LEDs have made it possible, among other things, to control the spectral composition (Wojciechowska et al., 2015). The introduction of higher amounts of blue light in LEDs contributes to increased photosynthetic intensity and increased chlorophyll and dry matter content in plants such as cucumber and lettuce, among others (Gajc-wolska et al., 2021). The high efficiency of LED lamps and the lack of excessive heat production allows them to be placed in the inter-rows (Särkkä et al., 2017; Wojciechowska et al., 2015). LED lamps have a high life expectancy, currently around 50 000 h and expected to reach up to 200 000 h in the future (Cole and Driscoll, 2012; Olle and Viršile, 2013). In addition, LED lamps are low in energy consumption, which translates into cost savings. There are no data in the literature on the effect of lignite substrate and LED supplementary lighting on the growth and development and yield of greenhouse cucumber in autumn-winter cultivation.

The aim of this study was to investigate the effects of lignite substrate and sunlight supplementation with LED lamps on growth, plant development, leaf photosynthetic activity and yield quantity and quality of greenhouse cucumber in autumn-winter cultivation compared to mineral cultivation in mineral wool substrate with HPS supplementary lighting.

2. Materials and methods

2.1. Plant material and experimental conditions

The research was conducted at the Greenhouse Experimental Centre of the Warsaw University of Life Sciences (SGGW) in Warsaw in two terms, term 1. winter year 2020/2021, term 2. winter year 2021/2022. The cucumber used for the research was the greenhouse cucumber cultivar 'Mewa' F1 by Rijk Zwaan with fruit length of 20–24 cm and weight of 200–240 g. The plants were grown in two identical experimental chambers. One chamber was equipped with HPS lamps (HPS combination) and chamber two was equipped with LED lamps (LED combination). The microclimate parameters in the chambers were controlled using a Ridder HortiMaX-Go climate computer. Cucumber seedlings on the first and second test dates were prepared by sowing cucumber seeds into mineral wool seedling cubes, which were soaked in nutrient solution with pH 5.4 and EC 1.8 $mS\cdot cm^{-1}$. At each date, seedlings were supplemented with HPS lamps (Gavita GAN 600 W) at light levels averaging 170 $\mu mol\ m^{-2}\cdot s^{-1}$ PPFD (*Photosynthetic Photon Flux Density*) for 16 h per day. The average temperature was D/N 22/21 °C, the average daily relative humidity (RH) was about 60–70 %.

Two experimental chambers, each with 40 m^2 of usable area, were equipped with 9 m long cultivation troughs. Six cultivation mats were placed on each trough; half were Grodan's Grotop Matser mineral wool mats measuring 100 cm × 20 cm × 7.5 cm and half were Carbomat lignite mats from Carbohort measuring 100 cm × 20 cm × 8 cm. The cultivation mats were flooded 48 h before planting the seedlings with nutrient solution (in the amount of 8 $dm^3\cdot mat^{-1}$) with an EC of 2.0 $dS\cdot m^{-1}$ and pH of 5.5. After this time, drainage holes were made in the mineral wool mats according to the methodology described in previous reports (Łaźny et al., 2022a, 2021). The ready cucumber seedlings 35 days after sowing (DAS) were placed in the holes in the growing mats. On the first experimental date, plants were planted on 14 October 2020 (42nd week of the year), on the second date on 21 October 2021 (42nd week of the year), at a rate of six plants per growing mat, while cucumber cultivation was completed in the 10th week of the year in term 1 and in the 11th week of the year in term 2. The 35 DAS transplants had three to four proper leaves and a well-developed root system, the plants had no signs of diseases and pests. The plants were illuminated in the HPS combination with 18 HPS lamps, (Gavita GAN 600 W) in the cultivation camera. In the LED combination, the plants were supplemented with LED lamps: the top lighting was provided by 24 Philips Green Power LED lamps (DR/W - LB, 195 W) and the inter-row lighting consisted of 2 lines of 18 LED lamps, in the Philips Green Power LED interlight chamber (2.5 m HO DR/B 100 W module). Light conditions in terms of PAR were maintained at approximately ~320 $\mu mol\ m^{-2}\cdot s^{-1}$ PPFD in both cultivation chambers. The lamps placed over the tops of the plants switched off automatically at a solar radiation level of 250 W/m^{-2}. The temperature was maintained at D/N 23/20° C on the first and second test dates, and the air RH and CO_2 concentration were maintained at 70 % and 800 ppm, respectively. At term 1, daily solar radiation averaged 475.8 J/cm^2, and at term 2 it averaged 533.4 J/cm^2 (Figure S1 and S2).

Fertilisation of the cucumber was carried out using a HortiMaX-Go fertilisation computer. The nutrient solution was composed based on single and multi-nutrient fertilisers. The contents of the individual nutrients in the working medium were ($mg\cdot dm^{-3}$): N—NO_3 230, N—NH_4 10, P-PO_4 50, K 330, Ca 180, Mg 55, S-SO_4 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15, Mo 0.05 and B 0.33. Nitric acid 55 % was used to adjust the pH of the nutrient solution. The nutrient solution with pH 5.5 and EC 3.1 - 3.3 mS·cm^{-1} was dosed to the plants by capillary in interval cycles. Depending on the development stage of the plant and the cultivation parameters, between 0.5 and 3.5 litres of the nutrient solution were used per plant per day. At the beginning of cultivation, after planting the seedlings on the growing mats, the first 5 fruit buds were removed from each cucumber plant. At full fruiting of the cucumber, the number of buds per plant was regulated by removing every second bud from the main shoot to prevent fruit drop. The plants were string-trained, removing side shoots and tendrils. The number of leaves per plant was regulated by removing every three days a maximum of three leaves each of the oldest leaves, the lowest leaves on the plant shoot and damaged leaves.

2.2. Morphological measurements

For morphological studies, six test plants were selected in each combination, on which the weekly cucumber shoot increment in length, shoot diameter, petiole length, and the length and width of the 5th and 10th leaves, counting from the plant apex, were measured. Weekly shoot increment was obtained by measuring the shoot segment from where the shoot apex was a week earlier to the current position of the shoot apex. Shoot diameter was measured with an electronic calliper at two locations, between the 4th and 5th and 9th and 10th fully developed leaves counting from the top of the plant. The total number of leaves on the plant and the number of buds dropped during the cultivation period were also determined.

2.3. Gas exchange and chlorophyll fluorescence

The relative chlorophyll content of the leaves was measured with the SPAD (Soul Plant Analysis Systems) test using a Minolta SPAD-502 Plus portable meter.

Chlorophyll content was measured on the 5th and 10th fully developed leaf of the test plants. Net photosynthetic activity (PN), stomatal conductance (gs) and transpiration rate (E) were measured using a LI-6400 photosynthesis system (LI-COR, Inc., Lincoln, NE, USA) equipped with a 6400–40 Leaf Chamber Fluorometer and CO_2 mixer 6400–01. Measurements were made on 6 randomly selected plants on both the 5th and 10th fully developed leaf, counting from the top of the plant. Measurements were taken between 10:00 am and 12:00 am. Measurements were made at a reference CO_2 concentration (500 μmol s^{-1}), constant flow rate (400 μmol s^{-1}), relative humidity between 30 % and 50 %, and photosynthetic photon flux density (PPFD, 1000 mmol m^{-2} s^{-1}). The measuring device was brought into the greenhouse and the required parameters were set. After a time of about 20 min for stabilisation of the device parameters, measurements were taken. Leaves were cut from the shoot with a pruning shear immediately before the measurements, so as to limit the effect of leaf ontogeny on the net assimilation rate and stomatal conductance. Leaves were not removed from the cultivation chamber and, after cutting, were directly transferred to the analyser chamber. The procedure was repeated for each combination.

Chlorophyll fluorescence was measured on each of 6 plants in all combinations using the FMS-2 Field Portable Pulse Modulated Chlorophyll Fluorescence Monitoring System (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK), measuring parameters such as maximum quantum efficiency of PS II (ΦPSII) and maximum efficiency of PS II photosystem in the dark-(Fv/Fm). Maximum efficiency of PS II photosystem in the dark was obtained after 30-min adaptation of leaves to the dark. A pocket PEA fluorescence meter (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK) was used to measure direct fluorescence. Measurements were taken three times during the experiment.

2.4. Macro- and micronutrient content of cucumber leaves

The macro- and micronutrient content of cucumber leaves was examined twice during the experiment at 50 and 90 days after planting (DAP). Three leaves were sampled each time: younger leaves at 4.−5th leaf height and older leaves at 9.−10th fully expanded leaf height from the top of the plant. Petiole-free leaf blades were dried at 60 °C in a laboratory air dryer and then ground in a Bosch TSM6A013B grinder. The ground plant material was incinerated in HNO_3. Elements (P, K Mg, Na, Ca, Fe, Mn, Cu, Zn, B) were determined using an inductively coupled plasma spectrometer (ICP Model OPTIMA 2000DV, Perkin Elmer, Waltham, MA, USA), giving results in mg-kg^{-1} DW. Nitrogen content was determined using a Kijeldahl apparatus (Vapodest, Gerhardt, Königswinter, Germany). After distillation of nitrogen as NH_3, the N content was determined by titration (Official Methods of Analysis of AOAC International. 19th Edition, 2012), ("Official Methods of Analysis of AOAC International. 19-th Edition," 2012) giving the results in% DW. For its determination, the powdered plant material was digested in concentrated sulphuric acid in the presence of a copper catalyst.

2.5. Fruit yield and quality

2.5.1. Yield assessment

The first fruits were harvested from the plant after 15 DAP on date 1 and 18 DAP on date 2. Fruits were harvested from each plant every 2 days, determining their number and weight. Total yield, marketable yield and non-marketable yield were determined. Non-commercial yield consisted of fruit that was undeveloped, crooked or had damage caused during plant care.

2.5.2. Analysis of fruit firmness

The material used for fruit quality analyses was commercial fruit only. Fruit quality analyses were carried out 3 times during the course of the experiments at both experimental date 1 and experimental date 2. Fruit hardness was determined using an HPE hardness meter with a 5 mm shank diameter. Measurements were taken at 3 points on the fruit, at an angle of 90° from the plane of the fruit. The results were given on the HPE hardness scale (0–100 units).

2.5.3. Dry matter, TSS and nitrate content

The dry weight of the fruit was carried out using the dryer-weight method. Cucumber fruits selected at random from each combination and replicate weighing approximately 1 kg, which corresponded to 4–5 cucumber fruits, were homogenised together with the peel. Total soluble solids (TSS) were determined in freshly pressed cucumber fruit juice of 200 ml. The results were obtained using a digital refractometer (Hanna Instruments HI96801) and given in%. Nitrate content was determined by taking 10 g of homogeneous plant material, adding 0.5 g of activated carbon and 100 ml each of 2 % acetic acid ($C_2H_4O_2$), and then the samples were shaken in specially designated containers. After 30 min, the samples were filtered through a fluted filter. Nitrate content in mg kg^{-1} FW of fruit was determined using a Fiastar 5000 Analyzer by reducing nitrate (V) to nitrate (III) by passing the sample solution through a cadmium column. The resulting coloured solution was measured spectrophotometrically at 540 nm.

2.5.4. Analysis of carotenoids and chlorophyll content

The content of β-carotene, lutein and chlorophyll *a* and *b* in the fruit was determined by high-performance liquid chromatography HPLC (Shimadzu Scientific Instruments). The sample preparation methodology was described in an earlier publication (Łaźny et al., 2022a).

2.6. Statistical analysis

The multifactorial analysis of variance (ANOVA) was used to analyse the influence of the substrate and lighting on variables describing plants, leaves and fruits. The homogeneous groups for a combination of factors were obtained using Tukey's procedure at a significance level of 0.05. Statistical analyses were performed using Statistica 13.3. Prior to analyses, we tested whether the assumptions of an ANOVA, homogeneity of variances were achieved. The homogeneity of variances for all the studied parameters was evaluated by Levene's test.

3. Results

3.1. Morphological parameters

The results obtained from the two cucumber cultivation dates showed no significant differences in the weekly growth of the plant shoot to length depending on the HPS and LED supplementary lighting used and the mineral and organic substrate (Table 1). Weekly cucumber shoot growth to length averaged about 60 cm, and the plants reached a height of about 12.5 m during the growing period (Table 1). Cucumbers growing in lignite substrate and supplemented with LED lamps (LED/L) were characterised by a larger shoot diameter compared to plants grown under sodium lamps and in mineral wool substrate (HPS/MW). At the height of the 5th leaf, counting from the shoot apex, and at the height of the 10th leaf, this difference in shoot diameter, on average from the two cultivation dates, was about 5 % and more than 7 %, respectively (Table 1). Especially at the first cultivation date, the difference in plant shoot diameter was greater in LED-supplemented plants than in HPS-supplemented plants (Tab. S1). The number of leaves in HPS- and LED-supplemented plants and in plants grown in mineral wool and lignite substrate was similar (Table 1). Only on the first cultivation date, the HPS/MW combination had a higher number of leaves than the LED-supplemented combination (Table S1). No significant differences were found for most of the tested cucumber leaf size parameters depending on the applied light supplementation and substrate. However, it was found that the 5th younger leaves counting from the top of the cucumber shoot, higher up on the plant, were wider when supplemented with LED lamps than those supplemented with HPS and when grown simultaneously in lignite substrate (Table 1).

3.2. Gas exchange and chlorophyll fluorescence

The leaf chlorophyll content in both 5th and 10th cucumber leaves did not differ significantly among the tested combinations (Table 2, Tab. S2). Analysing the results obtained from the two years of the study, a higher photosynthesis intensity score (PN) was found in the 5th and 10th leaves supplemented with LED than in those supplemented with HPS (Table 2). Higher PN and stomatal conductance (gs) values of more than 29 % and 28 %, respectively, were recorded for plants supplemented with LED lamps (10th leaf). In plants grown under HPS lamps, higher values for the PSII maximum photochemical yield index (Fv/Fm) were recorded for the 5th leaf compared to the LED-lamp-supplemented combination (Table 2, Table S2). In contrast, in leaves lower on the plant (10th), no such difference was found. For the 10th leaf, indices such as PN, gs and E were lower in the HPS/MW combination, by more than 34 %, 31 % and 23 %, respectively, compared to the other combinations (Table 2). Cucumber supplemented with LED lamps and grow in mineral wool substrate (LED/MW) had 22 % higher PN activity compared to plants supplemented conventionally with sodium lamps and grown in mineral wool (HPS/ MW). In term 2, plants were characterised by a higher photosynthetic rate (PN) by more than 26 % compared to term 1 (Table S2). The gas exchange parameters of the 10th leaf were found to be highest for plants supplemented with LED lamps and grown in lignite substrate (LED/L). Leaves of plants grown in the LED-lamp-supplemented combination in both substrates had more than 40 % higher photosynthetic rate (PN) compared to plants grown in the HPS-lamp-supplemented combination at term 1 (Table S2).

Table 1
Selected morphological parameters of cucumber plant according to supplementary lighting: HPS, LED and substrate: MW - mineral wool, L- lignite (average of two terms).

Parameter	Unit	Combination HPS/MW	HPS/L	LED/MW	LED/L
		Shoot			
Weekly increase in length	Cm	60.61 ± 7.87 ns	60.44 ± 7.66 ns	60.7 ± 10.21 ns	59.42 ± 11.01 ns
Total length		1272.92 ± 55.54 ns	1262.94 ± 36.95 ns	1274.40 ± 118.75 ns	1247.72 ± 142.43 ns
Diameter under 5th leaf	mm	6.66 ± 0.45 a	6.95 ± 0.5 ab	6.95 ± 0.65 ab	6.99 ± 0.46 b
Diameter under 10th leaf		7.07 ± 0.46 a	7.38 ± 0.54 ab	7.56 ± 0.62 ab	7.97 ± 2.1 b
		Leaf			
Total number of leaves per plant	No./plant	67.25 ± 10.16 ns	66.17 ± 10.2 ns	67.00 ± 11.43 ns	67.50 ± 12.07 ns
		5th leaf			
Length	cm	22.19 ± 3.17 ns	21.19 ± 1.94 ns	22.91 ± 2.82 ns	22.64 ± 2.8 ns
Width		26.15 ± 4.84 ab	24.12 ± 2.55 a	26.86 ± 4.86 b	27.01 ± 4.99 b
Petiole length		13.5 ± 1.25 ns	14.41 ± 1.55 ns	13.88 ± 2.57 ns	13.54 ± 1.99 ns
		10th leaf			
Length		25.84 ± 3.26 ns	25.82 ± 2.59 ns	26.49 ± 3.14 ns	26.09 ± 3.15 ns
Width		30.57 ± 4.86 ns	28.59 ± 2.64 ns	31.5 ± 5.64 ns	31.49 ± 5.53 ns
Petiole length		16.15 ± 1.6 ns	16.61 ± 1.67 ns	16.7 ± 2.22 ns	16.06 ± 1.88 ns

Average values marked with the same letters within the same row are not significantly different within the analysed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

Table 2
Chlorophyll content and photosynthetic rate (PN), stomatal conductance (gs) and transpiration rate (E) and chlorophyll fluorescence parameters: ΦPSII and Fv/Fm for the 5th and 10th leaf according to supplementary lighting: HPS, LED and substrate: MW - mineral wool, L- lignite (average of two terms).

Parameter	Unit	Combination HPS/MW	HPS/L	LED/MW	LED/L
		5th leaf			
Chlorophyll content	SPAD unit	41.75 ± 7.06 ns	43.08 ± 9.25 ns	40.48 ± 3.80 ns	41.33 ± 3.74 ns
PN	µmol CO_2 $m^{-2} s^{-1}$	8.75 ± 3.75 a	9.71 ± 4.48 ab	11.22 ± 2.95 b	11.44 ± 2.60 b
gs	mmol H_2O $m^{-2} s^{-1}$	0.45 ± 0.14 ns	0.45 ± 0.16 ns	0.50 ± 0.16 ns	0.54 ± 0.12 ns
E		7.25 ± 1.76 ns	7.36 ± 1.78 ns	7.25 ± 1.91 ns	7.95 ± 1.32 ns
ΦPSII	Relative unit	0.75 ± 0.07 ns	0.75 ± 0.03 ns	0.72 ± 0.06 ns	0.74 ± 0.03 ns
Fv/Fm		0.81 ± 0.01 b	0.81 ± 0.02 b	0.79 ± 0.03 a	0.79 ± 0.02 a
		10th leaf			
Chlorophyll content	SPAD unit	40.24 ± 7.59 ns	42.55 ± 8.41 ns	41.43 ± 3.82 ns	41.20 ± 4.68 ns
PN	µmol CO_2 $m^{-2} s^{-1}$	6.64 ± 4.01 a	8.90 ± 5.12 ab	10.16 ± 3.67 b	11.82 ± 4.34 b
gs	mmol H_2O $m^{-2} s^{-1}$	0.24 ± 0.14 a	0.29 ± 0.15 ab	0.36 ± 0.15 b	0.40 ± 0.14 b
E		4.55 ± 2.21 a	5.26 ± 2.18 ab	5.85 ± 2.07 ab	6.64 ± 2.03 b
ΦPSII	Relative unit	0.78 ± 0.02 ns	0.77 ± 0.03 ns	0.77 ± 0.04 ns	0.77 ± 0.03 ns
Fv/Fm		0.82 ± 0.01 ab	0.82 ± 0.01 ab	0.82 ± 0.01 ab	0.81 ± 0.02 a

Average values marked with the same letters within the same row are not significantly different within the analysed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

3.3. Macro- and micro element content in leaves

PCA was performed for young (5th) and old (10th) leaves for the following variables (average of two terms content of macro and micro-elements in cucumber leaves) as N, P, K, Ca, Mg, Na, S-SO_4, Fe, Mn, Cu, Zn and B (Fig. 1). The first two components provide 71.77 % total variability of the data set. PC1 determines the most important differences i.e. between young and old leaves. Young leaves (red dots in Figure) were strongly positively correlated and had high values of N. Young leaves had low values of P, K, Ca, Mg, Na, S-SO_4, Fe, Mn, Cu, Zn and B. Old leaves (blue dots in Figure) except of LED lignite were strongly positively correlated and had high values of P, K, Ca, Mg, Na, Fe, Mn, Cu, Zn and B. LED lignite had high value of S-SO_4 and was negatively correlated with Cu.

In the case of first date, the first two components provide 66 % total variability of the data set (Fig. 2). PC1 determines the most important differences i.e. between young and old leaves. Young leaves (red dots in Figure) were grouped together and had high values of N and Cu. Young leaves had low values of P, Ca, Mg, Na, S-SO_4, Fe, Mn, Zn and B. Old leaves (blue dots in Figure) were grouped together and had high values of P, Ca, Mg, Na, Fe, Mn, Zn and B. The highest content of Na, Fe and K were observed for old leaves in HPS lignite treatment. The highest content of P, S-SO_4, Mg, Zn and Ca was observed for old leaves in both treatments with LED (LED lignite and LED mineral wool).

Most of the elements are correlated positively with each other. The exceptions are Cu and N which are negatively correlated with all other elements, the strongest negative correlations were observed between these two elements (Cu and N) with B, Mn, Ca, Zn and Mg.

In the case of second date, the first two components provide 77 % of the total variability of the data set (Fig. 3). PC1 determines the most important differences i.e. between young and old leaves. Young leaves (red dots in Figure) were grouped together and had high values of N and low values of Ca, K, Mg, Fe and B. Old leaves (blue dots in Figure) were grouped together and had high values of P, Ca, Mg, Na, Fe, Mn, Zn, Cu and B. The most similar treatments of old leaves are both treatments with mineral wool (HPS mineral wool and LED mineral wool). These two treatments are characterised by the highest content of Cu, Mn, P, Zn, B, Mg and Fe. Old leaves from both treatments with lignite (HPS lignite and LED lignite) are characterised by medium content of most elements and the highest content of Na. Most of the studied elements were strongly positively correlated, the exceptions were S-SO_4 and N which were negatively correlated with all other elements.

3.4. Fruit yield and quality

Analysing the average results from the two dates, there were no significant differences in the total, marketable and non-marketable yield of cucumber plants in the combinations tested (Table 3). The share of marketable yield in total yield in the combinations HPS/MW; HPS/L; LED/MW; LED/L was 98.3 %; 98.9 %; 99.7 % and 99.7 %, respectively. In contrast, the number of fruits in total yield was higher for HPS-supplemented plants than for LED-supplemented plants, especially when plants were grown in mineral wool. The proportion of the number of marketable fruit in the total yield, on average from the two dates, was 97.9 %; 98.56 %; 99.65 %; 99.6 % for the combinations tested, respectively (Table 3). On the other hand, the percentage of fruit dropped during the growing season in relation to the total number of fruit on the plant was 2.07 %; 1.39 %; 0.38 %; 0.36 % for the combinations, respectively (Table 3).

Fruits harvested from LED-supplemented and mineral wool-grown plants had the lowest dry matter and cell sap soluble component content, relative to the other combinations (Tab 4). Fruit from this combination also had the highest nitrate concentration and the lowest HPE hardness (Tab 4). There were no significant differences in the content of B-carotene, chlorophyll *a* and *b* and lutein in cucumber fruit depending on the light (HPS and LED) and substrate (MW and L) used in the study. Instead, fruit from plants grown in lignite had a higher hardness compared to fruit harvested from plants grown in mineral wool. The increase in fruit hardness was recorded at 10.7 % in the HPS/L combination compared to HPS/MW and by 11.5 % in the LED/L combination compared to LED/MW (Table 4).

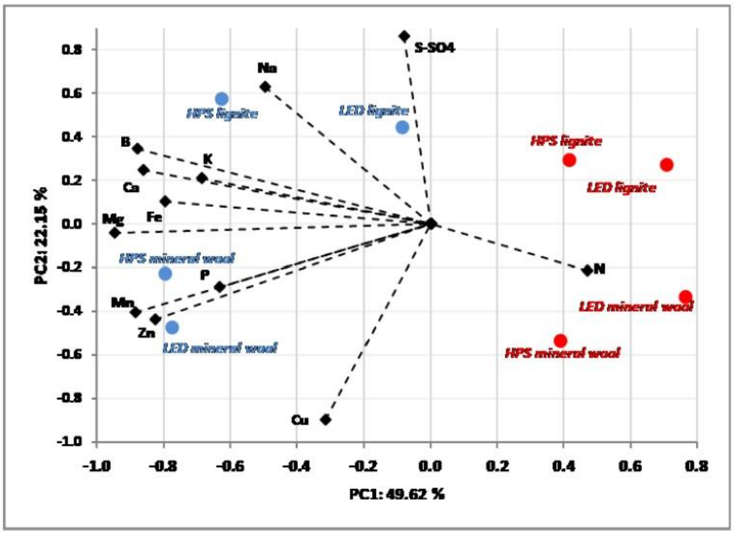

Fig. 1. Results of PCA presenting the relationships between macro and micro elements in young 5th (red) and old 10th (blue) leaves and multivariate differences of lighting and substrate combinations (average of two terms).

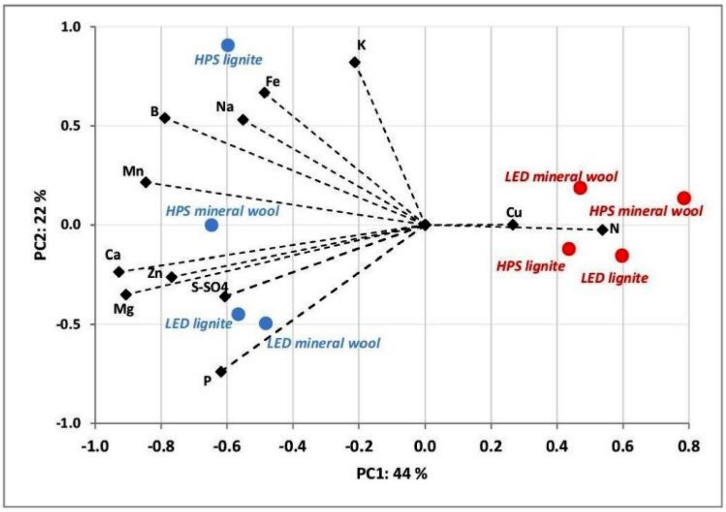

Fig. 2. Results of PCA presenting the relationships between macro and micro elements in young 5th (red) and old 10th (blue) leaves and multivariate differences of lighting and substrate combinations in the first date of harvesting.

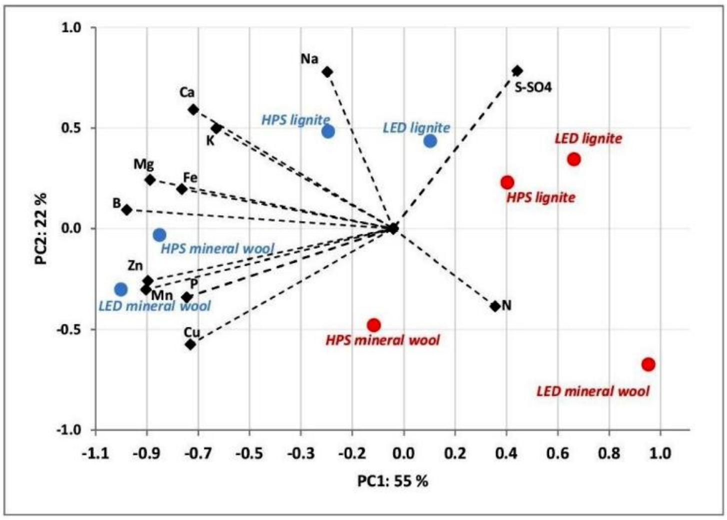

Fig. 3. Results of PCA presenting the relationships between macro and micro elements in young 5th (red) and old 10th (blue) leaves and multivariate differences of lighting and substrate combinations in the second date of harvesting.

4. Discussion

Light is one of the most important factors necessary for photosynthesis. Particularly important from the point of view of horticultural production is the fact that its quantity and quality can be optimised in the cultivation of plants under cover. This is very important especially in months with low solar radiation intensity (Alloggia et al., 2023; Zou et al., 2020). The growing medium, its physical and chemical properties are also an important factor in plant growth (Łaźny et al., 2022b). Based on the results obtained, it is not possible to conclude unequivocally that the growth of cucumber plants was most favourably affected by lignite as a substrate or by the type of light used to supplement the plants. The results obtained confirm previous observations, where also no effect of substrate on morphological parameters of cucumber plants was found (Łaźny et al., 2021). Analysing the available literature, it was proven that monochromatic red light from LED lamps influences the shortening

Table 3
Cucumber fruit yield according to supplementary lighting: HPS, LED and substrate: MW - mineral wool, L- lignite (average of two terms).

Yield of fruit	Unit	Combination HPS/MW	HPS/L	LED/MW	LED/L
		Weight of fruits			
Total	g $plant^{-1}$	10,280.96 ± 1014.33 ns	10464.77 ± 706.79 ns	9615.5 ± 1029.9 ns	9981.8 ± 1357.11 ns
Marketable		10103.88 ±918.99 ns	10353.11 ± 630.51 ns	9587.58 ± 1010.93 ns	9952.63 ± 1308.91 ns
Unmarketable		177.08 ± 199.78 ns	111.67 ± 180.95 ns	27.92 ± 66.66 ns	29.17 ± 68.95 ns
		Number of fruits			
Total	pcs $plant^{-1}$	48.25 ± 3.08 b	48.33 ± 1.83 b	44.75 ± 4.20 a	46.17 ± 4.91 ab
Marketable		47.25 ± 2.67 ns	47.67 ± 1.72 ns	44.58 ± 4.01 ns	46.00 ± 4.71 ns
Unmarketable		1 ± 1.13 ns	0.67 ± 0.98 ns	0.17 ± 0.39 ns	0.17 ± 0.39 ns
Aborded		1 ± 1.04 b	0.67 ± 0.89 ab	0.08 ± 0.29 a	0.08 ± 0.29 a

Average values marked with the same letters within the same row are not significantly different within the analysed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

Table 4
Contents of dry matter, TSS and bioactive compounds in cucumber fruits according to supplementary lighting: HPS, LED and substrate: MW - mineral wool, L- lignite (average of two terms).

Parameter	Unit	Combination HPS/MW	HPS/L	LED/MW	LED/L
Dry matter	%	3.69 ± 0.61 b	3.65 ± 0.49 b	3.00 ± 0.18 a	3.28 ± 0.29 ab
TSS		3.50 ± 0.19 cb	3.55 ± 0.35 c	3.08 ± 0.28 a	3.32 ± 0.50 b
B-carotene	mg 100 g^{-1} FW	0.19 ± 0.12 ns	0.19 ± 0.10 ns	0.17 ± 0.10 ns	0.2 ± 0.12 ns
Chlorophyll *a*		2.58 ± 1.91 ns	2.54 ± 1.67 ns	2.44 ± 1.58 ns	2.82 ± 1.92 ns
Chlorophyll *b*		1.18 ± 0.65 ns	1.25 ± 0.62 ns	1.19 ± 0.53 ns	1.38 ± 0.67 ns
Lutein		0.40 ± 0.15 ns	0.42 ± 0.11 ns	0.42 ± 0.08 ns	0.48 ± 0.14 ns
Nitrates	mg kg^{-1} FW	48.9 ± 0.14 a	46.5 ± 0.34 a	101.0 ± 1.22 b	60.5 ± 2.09 a
Firmness	HPE	61.91 ± 4.85 ab	64.87 ± 0.36 b	60.85 ± 3.56 a	65.40 ± 1.11 b

Average values marked with the same letters within the same row are not significantly different within the analysed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation. Abbreviations: ns, not significant.

of the hypocotyl of cucumber seedlings (Hernández and Kubota, 2014). Another study found that red light and a combination of red and green light affected stem elongation in tomato, while blue light inhibited stem elongation (Liu et al., 2011). In the first term of the experiment, the use of LED lights affected stem diameter, but in the second term, the effect of light type on this parameter was not confirmed (Table S1). The type of substrate can affect the shoot diameter of cucumber, as confirmed in a study by Alifar et al. (2010). Climatic conditions, plant morphological structure and physiological processes also affect photosynthesis. The position of the leaf itself in the canopy also affects the photosynthetic process. The deeper the leaf is positioned in the canopy, the photosynthetic efficiency decreases (Trouwborst et al., 2010). This is relevant when using a top light source such as HPS or LED lamps, where the vertical irradiance profile has an exponential decrease with canopy depth (Monsi and Saeki, 2004; Trouwborst et al., 2010). The use of LED lamps in the inter-row significantly improves the light conditions of the whole canopy, which can affect the photosynthetic properties of plants (Trouwborst et al., 2010). In the results obtained, an increase in the intensity of the PN photosynthetic process was confirmed in combinations where the plants were supplemented with LED lamps. In addition, gas exchange parameters such as stomatal conductance gs and transpiration intensity E were significantly higher in combinations where LED light was used compared to the combinations grown under HPS. It is likely that inter-row LED supplementation may have influenced the results obtained, which supports the thesis of Trouwborst et al. (2010). The blue light from LEDs can affect the length, width and degree of stomatal opening, as well as their number per leaf area (Liu et al., 2018). As early as 1981, the positive effect of blue light on stomatal conductance was confirmed (Sharkey and Raschke, 1981). As reported by Gajc-Wolska et al. (2021), plants supplemented with LED lamps had a higher PN ratio in winter cucumber cultivation compared to plants grown under HPS lamps. The authors also proved that cucumber plants in combinations where LED or HPS supplementation was used with simultaneous inter-row LED lamp plant supplementation had higher PN, gs and E values. Also, numerous research results confirm the effect of light spectrum on photosynthesis and gas exchange in plants (Elvidge et al., 2010; Santos et al., 2009; Talebnejad and Sepaskhah, 2016). The results obtained by Lanoue et al. (2017) do not confirm the effect of light spectrum on the rate of photosynthesis. Light is not the only factor affecting photosynthesis. The lignite substrate may also have influenced gas exchange parameters in cucumber leaves. In leaf 10th of cucumber plants, higher PN, gs and E scores were recorded when the plants were grown on this substrate (Table 2). A general upward trend in most of the photosynthetic activity parameters of cucumber was observed when the lignite substrate was applied, irrespective of the combination and timing of the experiment (Table 2 and S2). In an earlier study, where the effect of the combination of eustress and lignite substrate on gas exchange parameters in PN, gs and E cucumber was analysed, it was found that substrate significantly reduced the negative effect of eustress on these parameters (Łaźny et al., 2022a). In the combination where lignite gs was applied, gs did not start to decrease until seven days after the stress application of the high EC nutrient solution. The lignite substrate also reduced the decrease in E in the plants tested compared to the combination where mineral wool substrate was applied (Łaźny et al., 2022a). A study by Yang et al. (Yang et al., 2023) also confirmed the differential effects of pine bark and wood fibre substrates on PN, gs and E in cucumber leaves. It is well known that the macronutrient and micronutrient content of leaves can be influenced by a number of factors, ranging from the amount and proportion of individual elements to the pH of the solution and the right conditions for growth and crop care (Łaźny et al., 2022a; Machado and Serralheiro, 2017; Nurzyński, 2013). In studies on tomato plants Nurzyński (2013) found that changes of elements in the nutrient solution occur frequently, but changes in the leaves are slow and minimal. In the results presented in this study, high N content was found in young leaves, while older leaves were characterised by higher values of the other elements at the first and second cultivation dates (Fig. 1-3). As reported by Lizhong et al. (2022) the higher C/N ratio in coconut fibre may be due to the high lignin and cellulose content, which should influence the adjustment of the nutrient solution composition. The type of substrate used may also affect the nutritional status of the plants and thus the macro- and micronutrient content of the leaves (Łaźny et al., 2022b; Yılmaz et al., 2014). In the results obtained, high S-SO_4 content was found in cucumber leaves of the LED/L combination (Fig. 3). Similar results were obtained in the study of Yılmaz et al. (2014), where cucumber leaves grown on coconut fibre had a higher S content compared to the combination where mineral wool was used. As reported by Jankauskienė et al. (2019), the Ca content in young cucumber leaves varied with the type of substrate used. Similar results were obtained by studying cucumber plants, where the highest P and K contents were recorded in the leaves of plants grown on peat substrate, while the highest N content was recorded in the leaves of plants grown on zeolite substrate (Yılmaz et al., 2014). Similar results were obtained for Mg content in cucumber leaves, where the highest concentration of this element was obtained in plants grown in peat (Francke et al., 2021). In an earlier study conducted on cucumber plants, the lignite substrate and its physical properties influenced the Fe and Zn content of cucumber leaves (Łaźny et al., 2022b). The spectrum of light can also affect the elemental content of leaves (Verma et al., 2018). This is confirmed by studies on the effects of blue light, red light and their combinations affecting the macro- and micronutrient content of basil, beetroot, mustard, broccoli and parsley (Gerovac et al., 2016; Zhang et al., 2020). The effect of light type also plays an important role in the yield and its quality. However, yield did not significantly depend on the combinations used in the studies conducted. In the analysed results, a higher proportion of marketable yield in the total yield and a lower tendency to drop fruit buds were found for LED-supplemented plants compared to HPS-supplemented plants. The higher yields caused by light supplementation, also inter-row, are based on the assumptions of maintaining optimal photosynthetic capacity of leaves located deep in the canopy, increased light absorption and higher light use efficiency due to uniform vertical light distribution (Trouwborst et al., 2011). It is likely that the HPS lamps may have influenced the achieved cucumber yields by converting part of the energy into infrared radiation, which reaches the deeper leaves in the canopy (Särkkä et al., 2017). In their study Marcelis (1993) proved that temperature significantly affects fruit growth rate and yield of cucumber in hydroponic cultivation. Särkkä et al. (2017) obtained results where the use of LED lamps in the top and inter-row lighting system reduced the yield of cucumber plants compared to plants grown under HPS lamps. The authors of the cited study concluded that the lower infrared radiation may have had the effect of reducing cell growth rates. Different results were obtained by investigating the effect of LED lamp supplementation in winter cucumber cultivation, where combinations with LED top supplementation and LED top supplementation together with inter-row lighting obtained the highest yield compared to HPS top supplementation (Gajc-Wolska et al., 2021). In earlier experiments where the effect of substrate on cucumber fruit yield and quality was investigated, it was found that plants planted on reused lignite substrate achieved higher yield compared to plants grown in reused mineral wool (Łaźny et al., 2021). The use of lignite substrate also increased yield and reduced the number of non-marketable fruits in an experiment where eustress was applied in the form of a high EC nutrient solution (Łaźny et al., 2022a). Higher cucumber fruit yield was obtained in combinations where bark (2 fractions), coconut fibre and wood fibre substrate were used compared to perlite (Yang et al., 2023). In contrast, no significant differences were obtained when analysing the effect of sheep wool as a substrate in hydroponic cucumber cultivation compared to mineral wool (Komorowska et al., 2023).

The high nutrient content of vegetables provides consumers with a positive impact on body well-being (Łaźny et al., 2022a; Yang et al., 2023). In the results presented in this study, the effect of the type of lighting or substrate used on the content of bioactive compounds was not proven, but the effect of lighting and substrate on the content of TSS in the first term of the experiment (average of two years) was noted. A similar trend was noted in fruit from plants supplemented with HPS lighting on the first experimental date. For cucumber fruit hardness, the lignite substrate had a positive effect on this parameter. In the case of fruit dry matter, an increase in this parameter was recorded in fruit from plants grown in lignite substrate. Similar results were obtained in cucumber fruit obtained from plants grown on organic substrates, where the dry matter content of the fruit was higher compared to fruit obtained from plants growing in mineral wool (Lizhong et al., 2022). Previous studies have shown that lignite substrate influenced higher dry matter content in fruit compared to mineral wool. Similarly for TSS content, where fruit obtained from plants grown in lignite obtained higher values for the trait in question compared to fruit from combinations where mineral wool was used. (Łaźny et al., 2023, 2022b, 2022a). In their study Nurzyński (2013) confirmed the effect of straw substrate on tomato fruit dry matter content. Comparing the effects of mineral wool, sheep wool, peat and hemp fibre, the lowest dry matter content was found in tomato fruit grown in hemp fibre, while the dry matter content of tomato fruit in the other combinations was similar. In contrast, the researchers reported no significant differences for fruit firmness in the studies cited (Dannehl et al., 2015). As reported by Valverde-Miranda et al. (2021) the dry matter content and TSS of the fruit may also depend on the harvest date, but also on climatic and agrotechnical conditions (Marcelis, 1992). Both light and substrate can also influence the increased nitrate content of the food produced (Zhang et al., 2020), which can be harmful to the human body. Studies indicate that 80 % of the nitrate consumed by humans comes specifically from vegetables (Amr and Hadidi, 2001; Zhang et al., 2020). In the results obtained, the nitrate content of the fruit is not high, but the highest concentration was found in the LED/MW combination compared to the other test combinations. Other authors report that red light increases nitrate reductase activity and thus lowers nitrate content (Lillo and Appenroth, 2001; Zhang et al., 2020) compared to blue light, which has no such effect on nitrate reduction (Maevskaya and Bukhov, 2005). The combination of LED light and organic lignite substrate affected the hardness of cucumber fruit. This is an important parameter from the point of view of storage quality (Gómez-López et al., 2006). Previous studies have confirmed the positive effect of lignite substrate and LED light supplementation on fruit hardness and storability. Furthermore, it was found that fruit obtained from plants grown in lignite substrate and supplemented with LED light had lower weight loss during storage and higher sensory parameters (Łaźny et al., 2023).

5. Conclusions

In conclusion, the research presented here showed that lignite mats used in cultivation with LED light supplementation had a beneficial effect on cucumber plant growth and development and plant nutrition in Fe, K, P, Ca, Mg and Zn compared to mineral substrate and HPS light supplementation. Fruits harvested from plants grown in lignite substrate and supplemented with LED light had the lowest nitrate content and increased TSS value. The use of organic substrates in hydroponic cultivation will undoubtedly contribute to reducing the negative impact on the environment and may improve the quality of the food produced.

CRediT authorship contribution statement

Radosław Łaźny: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Małgorzata Mirgos:** Data curation, Methodology, Resources, Software, Visualization, Writing – review & editing. **Jarosław L. Przybył:** Data curation, Methodology, Software, Validation, Visualization. **Elżbieta Wójcik-Gront:** Data curation, Software, Validation. **Sebastian Bella:** Formal analysis. **Janina Gajc-Wolska:** Resources, Software, Supervision, Writing – review & editing. **Waldemar Kowalczyk:** Data curation, Formal analysis, Methodology, Software, Validation. **Jacek S. Nowak:** Data curation, Formal analysis, Methodology, Software, Validation. **Małgorzata Kunka:** Formal analysis. **Katarzyna Kowalczyk:** Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2023.112839.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy autorstwa Łaźny R., Mirgos M., Przybył J.L., Wójcik-Gront E., Bella S., Gajc-Wolska J., Kowalczyk W., Nowak J.S., Kunka M., Kowalczyk K. 2024. **Effect of lignite substrate compared to mineral wool and supplementary lighting with HPS and LED on growth, plant photosynthetic activity, yield and fruit quality of greenhouse cucumber. Scientia Horticulturae (Amsterdam) 327: 112839**, mój udział w jej powstaniu polegał na:

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Udział procentowy współautorów w powstaniu **publikacji 5.**

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8. ANEKS

8.1. Materiał roślinny

Fotografie przedstawiają ogórka odmiany ‘Mewa’ w uprawie doświetlanej lampami HPS (fot. S1 i S2) i w uprawie z doświetlaniem lampami LED (fot. S3 i S4).

Fotografia S1. Rośliny ogórka w uprawie doświetlanej lampami HPS

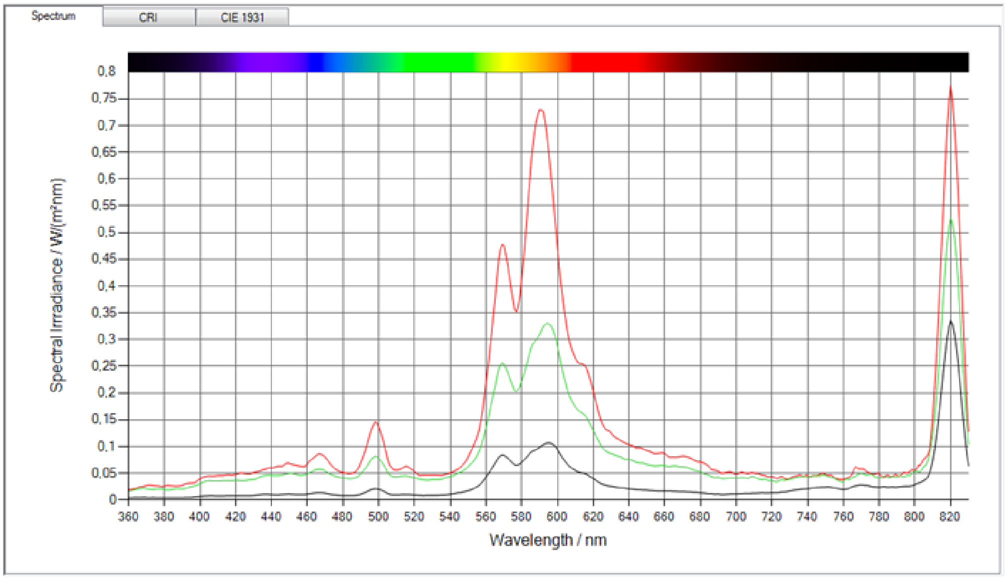
Fotografia S2. Owoc ogórka w uprawie doświetlanej lampami HPS

Fotografia S3. Rośliny ogórka w uprawie doświetlanej lampami LED

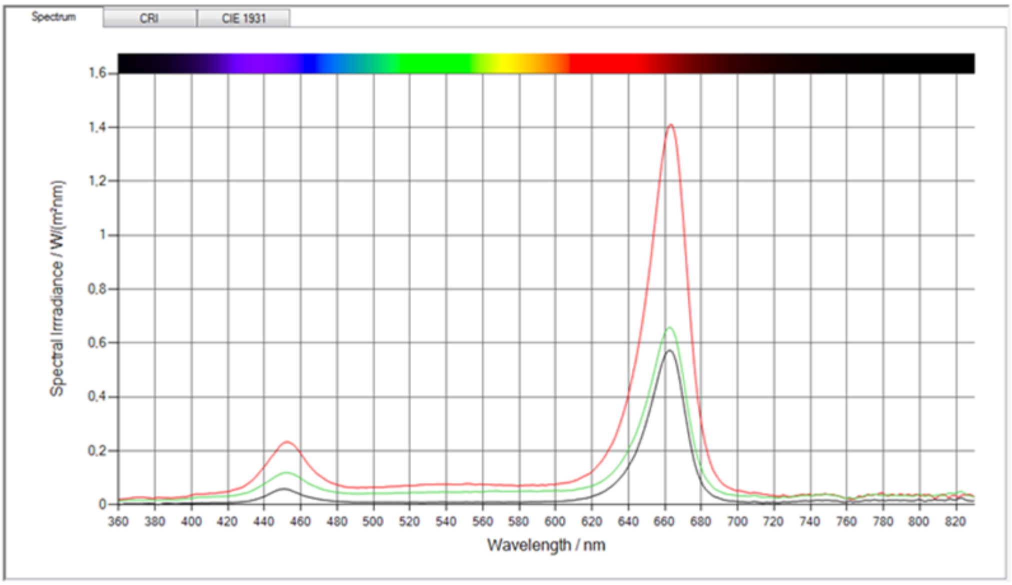
Fotografia S4. Owoc ogórka w uprawie doświetlanej lampami LED

8.2. Charakterystyka widma światła lamp HPS i LED

Wykresy S1 i S2 przedstawiają charakterystykę światła w kamerach uprawowych z doświetlaniem HPS i LED na różnych wysokościach roślin ogórka.



Wykres S1. Charakterystyka światła mierzonego na wysokości wierzchołków roślin oraz piątego i dziesiątego liścia w kamerze z lampami HPS (pomiar 17.02.2021 r.)



Wykres S2. Charakterystyka światła mierzonego na wysokości wierzchołków roślin oraz piątego i dziesiątego liścia w kamerze z lampami LED (pomiar 17.02.2021 r.)