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Evaluation of genotype × environment interaction for grain crop quality

Ocena interakcji genotyp × środowisko cech jakości zbóż

Doctoral thesis

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Abstract

This doctoral study examines multi-trait stability and genotype-by-environment (G×E) interactions in temperate cereals, focusing on spring wheat, winter wheat, and winter rye under varying crop management systems. By applying advanced multivariate tools, including the Multi-Trait Stability Index (MTSI), Classification and Regression Tree (CART), and Canonical Correspondence Analysis (CCA), this work identifies stable cultivars and the key traits influencing yield and quality stability in temperate conditions.

In spring wheat, seven cultivars were assessed across four locations and two seasons under moderate and high-input systems. MTSI and CART revealed that stability profiles differed across management intensities. Bombona and Izera were identified as the most stable cultivars under moderate and high input, respectively. Stability rankings were driven by spike fertility traits such as grain yield, thousand-grain weight, and loaf volume. Genotypic effects were particularly significant for traits like gluten index and falling number, indicating the importance of cultivar choice in preserving end-use quality. The findings underscore that multi-trait stability is specific to management regime and highlight the utility of combining MTSI with CART for evaluating complex genotype × environment × management interactions.

Winter wheat performance was assessed using 55 cultivars evaluated across 60 environments over five years. Five traits, grain yield, thousand-grain weight, protein content, sedimentation value, and falling number, were analyzed for stability using Shukla's variance, MTSI, and CCA. While Shukla's variance identified cultivars like SY Yukon as stable, MTSI highlighted Medalistka and KWS Spencer for their superior multi-trait performance. CCA linked yield stability with resistance to powdery mildew, brown rust, and chaff septoria, while quality trait stability was associated with winter hardiness and lodging resistance. Soil nutrient availability, clay content, and water capacity also emerged as environmental moderators, reinforcing the role of genotype and site-specific factors in shaping stability.

In winter rye, 16 cultivars (11 populations and 5 hybrids) were evaluated across three locations over two seasons under moderate (MIM) and high-input (HIM) management. Hybrids yielded ~24% more but had significantly lower grain protein content and trait stability compared to population cultivars. Path analysis indicated spikes per square meter as the main yield determinant. MTSI and Shukla's variance confirmed population cultivars as more stable, especially under MIM. CART analysis revealed septoria resistance and aluminum tolerance as top stability predictors under MIM and HIM, respectively.

Collectively, this research confirms the robustness of MTSI and complementary multivariate methods in characterizing G×E responses. These findings support the development of climate-resilient breeding strategies and trait-based cultivar selection tailored to temperate environments.

Keywords: Genotype × environment interaction; multi-trait stability index (MTSI); Shukla stability variance; classification and regression tree (CART); canonical correspondence analysis (CCA); farinograph analysis; grain yield; grain protein content; dough and bread-making quality; cultivar adaptation; climate change; crop management intensity; hybrid vs. population cultivars; food security; cereal stability; rye; wheat.

Abbreviations: Crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), high-input management (HIM), loaf volume (LV), moderate-input management (MIM), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV); CART, classification and regression trees; MTSI, multi-trait stability index.

Streszczenie

Niniejsza rozprawa doktorska koncentruje się na analizie stabilności wielocechowej i interakcji genotyp–środowisko (G×E) u zbóż uprawianych w klimacie umiarkowanym, ze szczególnym uwzględnieniem pszenicy jarej, pszenicy ozimej i żyta ozimego w zróżnicowanych poziomach agrotechniki. W badaniach zastosowano zaawansowane narzędzia statystyki wielowymiarowej, takie jak Indeks Stabilności Wielocechowej (MTSI), Drzewa Klasyfikacyjne i Regresyjne (CART) oraz Kanoniczną Analizę Korespondencji (CCA), aby wskazać stabilne odmiany i zidentyfikować cechy kluczowe dla utrzymania stabilności plonu i wysokiej jakości.

Dla pszenicy jarej przebadano siedem odmian w czterech lokalizacjach i dwóch sezonach wegetacyjnych na przeciętnym i wysokim poziomem intensywności agrotechniki. Wyniki wykazały, że odmiany Bombona i Izera były najbardziej stabilne zarówno w przeciętnym i wysokiego poziomu agrotechniki. Cechy płodności kłosa, takie jak plon ziarna, masa tysiąca ziaren i objętość bochenka, były głównymi determinantami wielocechowej stabilności. Zaobserwowano istotny wpływ genotypu na cechy jakościowe, takie jak indeks glutenu i liczba opadania. Analiza CART podkreśliła znaczenie cech strukturalnych kłosa w stabilności wielocechowej.

Dla pszenicy ozimej przeanalizowano 55 odmian w 60 środowiskach w ciągu pięciu lat, oceniając pięć kluczowych cech jakości i plonu. Wariancja Shukli wskazała na stabilność odmian takie jak SY Yukon i Bataja, natomiast MTSI wyłonił Medalistkę i KWS Spencera jako liderów stabilności wielocechowej. Analiza CCA powiązała stabilność plonowania z odpornością na mączniaka prawdziwego i rdzę brunatną, a stabilność jakości ziarna – z mrozoodpornością i odpornością na wyleganie. Cechy środowiskowe, takie jak pojemność wodna gleby i zawartość gliny, miały istotny wpływ na poziom stabilności.

W przypadku żyta ozimego przebadano 16 odmian w trzech lokalizacjach i dwóch sezonach, na przeciętnym i wysokim poziomem intensywności agrotechniki. Odmiany mieszańcowe wykazywały wyższy plon (średnio +24%), lecz niższą zawartość białka i mniejszą stabilność. Analiza CART wskazała odporność na septoriozę i tolerancję na glin jako kluczowe czynniki determinujące stabilności.

Podsumowując, zastosowane metody MTSI, CART i CCA skutecznie wspomagają ocenę stabilności odmian i stanowią cenne narzędzie w projektowaniu strategii hodowlanych dla zbóż odpornych na zmienność klimatyczną.

Słowa kluczowe: Interakcja genotyp × środowisko; wskaźnik stabilności wielocechowej (MTSI); wariancja stabilności Shukli; drzewo klasyfikacyjne i regresyjne (CART); kanoniczna analiza korespondencji (CCA); analiza farinograficzna; plon ziarna; zawartość białka w ziarnie; jakość ciasta i pieczywa; adaptacja odmian; zmiany klimatyczne; intensywność zarządzania uprawą; odmiany mieszańcowe vs. populacyjne; bezpieczeństwo żywnościowe; stabilność zbóż; żyto; pszenica.

Skróty i akronimy: Twardość miękiszu (CH), rozwój ciasta (DD), zmiękczenie ciasta (DSF), stabilność ciasta (DS), wydajność mąki (FY), indeks glutenu (GI), zawartość popiołu w ziarnie (AC), zawartość białka w ziarnie (PC), plon ziarna (GY), liczba opadania (FN), intensywne zarządzanie uprawą (HIM), objętość bochenka (LV), umiarkowane zarządzanie uprawą (MIM), masa 1000 ziaren (TGW), liczba jakościowa (QN), wchłanianie wody (WA), zawartość glutenu mokrego (WG), wartość sedymentacyjna Zeleny'ego (SV); CART – drzewa klasyfikacyjne i regresyjne; MTSI – wskaźnik stabilności wielocechowej

List of Publications Included in Doctoral Thesis

1. Abu Zar Ghafoor, Alicja Ceglińska, Hassan Karim, Magdalena Wijata, Grzegorz Sobczyński, Adriana Derejko, Marcin Studnicki, Jan Rozbicki, and Grażyna Cacak-Pietrzak. Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars. Agriculture, 2024, 14(12), 2131. https://doi.org/10.3390/agriculture14122131 (IF=3.3, pkt=100)

2. Abu Zar Ghafoor, Adriana Derejko, and Marcin Studnicki. (2024). Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates. Agronomy, 14(4), 779. https://doi.org/10.3390/agronomy14040779 (IF=3.3, pkt=100)

3. Abu Zar Ghafoor, Magdalena Wijata, Jan Rozbicki, Robert Krzysztofik, Kazimierz Banasik, Hassan Karim, Adriana Derejko, & Studnicki, M. (2024). Influence of crop management on stability rye yield and some grain quality traits. Agronomy Journal, 1–12. https://doi.org/10.1002/agj2.21647 (IF=2.0, pkt=100)

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CHAPTER I INTRODUCTION

1.1 Background

Cereal crops such as rye (*Secale cereale L.*) and wheat (*Triticum aestivum L.*) have long been essential to global food security, owing to their adaptability, nutritional value, and widespread cultivation across diverse agroecological zones. Their success lies in their capacity to withstand various environmental stresses and deliver stable yields under varied soil and climate conditions. However, escalating climate change presents serious challenges to the sustainability and resilience of these crops. Increased global temperatures, erratic rainfall patterns, prolonged droughts, and more frequent extreme weather events are disrupting the phenological development, yield formation, and grain quality of cereals, particularly in temperate and boreal regions (A. Ghafoor et al., 2024; Lan, Chawade, Kuktaite, & Johansson, 2022). In wheat, drought and heat stress during critical reproductive stages lead to substantial reductions in grain number and weight, while in rye, fluctuating winter conditions and excessive autumn rainfall exacerbate overwintering damage and disease susceptibility (Peltonen-Sainio, Hakala, & Jauhiainen, 2011). These stressors not only threaten yield stability but also alter pest dynamics, reduce nutrient uptake efficiency, and challenge existing management practices. As such, the adaptation of rye and wheat to climate change is an urgent scientific and breeding priority, demanding integrated strategies that combine genetic resilience, agronomic optimization, and advanced modeling of genotype-environment interactions (Bajwa et al., 2020; Johansson et al., 2024). Rye, in particular, exhibits distinct advantages over other cereals due to its tolerance to poor soils, aluminum toxicity, and abiotic stresses such as low temperatures and low nitrogen availability. These characteristics have historically facilitated its expansion in marginal environments, particularly across Central and Eastern Europe. The crop's current ecological role spans from food production and animal feed to ecosystem services, such as soil stabilization and nitrate scavenging via cover cropping (Sellami, Pulvento, & Lavini, 2021). Despite its inherent resilience, rye remains vulnerable to yield instability due to strong genotype-by-environment interactions (GEI) and the variable effectiveness of its yield components under intensified agricultural regimes (Kottmann, Wilde, & Schittenhelm, 2016).

In addition to their agricultural versatility, rye and wheat have played a pivotal role in shaping regional food systems, particularly in temperate Europe and Central Asia. Wheat has long been the backbone of global caloric intake, whereas rye, often regarded as a "secondary cereal," offers unique agronomic and environmental benefits. As a cross-pollinating species, rye possesses a highly diverse gene pool, which contributes to its notable adaptability across marginal lands and stress-prone environments (Hackauf, Siekmann, & Fromme, 2022). This genetic plasticity is also a challenge; strong genotype-by-environment interactions complicate breeding for stability, especially when managing trade-offs between yield potential and resilience traits.

The advent of hybrid rye breeding has improved yield, yet these gains are often accompanied by lower stability under variable environmental conditions, particularly under low-input or stressed systems (Haffke et al., 2015). Meanwhile, wheat breeding has focused extensively on increasing grain number and harvest index, but modern varieties remain vulnerable to heat and water stress at flowering and grain-filling stages, leading to steep yield penalties in regions with fluctuating precipitation or poor water management (Ishaque et al., 2023).

Importantly, the structural and functional traits of rye, such as deeper rooting systems, superior nitrogen use efficiency, and tolerance to low pH soils, position it as a valuable model for climate-resilient cropping. However, utilization of this potential has been limited by underinvestment in genomics and precision phenotyping compared to major crops like wheat and maize. The recent assembly of a chromosome-scale rye genome has enabled deeper exploration into its evolutionary traits, revealing novel resistance genes, fertility control systems, and stress-responsive loci with potential for breeding applications (Rabanus-Wallace et al., 2021). Rye's environmental value extends beyond grain production. As a cover crop, rye contributes significantly to soil structure improvement, nitrate scavenging, and erosion control. Its rapid biomass accumulation and allelopathic effects on weeds make it a strategic option in sustainable crop rotations, further supporting agroecological resilience (A. Z. Ghafoor, H. Karim, et al., 2024).

1.2 Climate change and cereal adaptability

Climate change is accelerating the frequency and severity of environmental stresses that affect cereal crops, particularly in temperate and boreal regions where rye and wheat are dominantly cultivated. Increased global temperatures, shifts in rainfall patterns, and more frequent extreme weather events such as droughts, floods, and unseasonal frosts significantly impact plant development, physiological processes, and yield formation. In wheat, reproductive stages, notably flowering and grain filling, are susceptible to heat and water stress. These stresses cause considerable reductions in grain number and weight, affecting both the quantity and quality of yield (Lan, Kuktaite, Chawade, & Johansson, 2024). While better adapted to cold and poor soils, Rye faces its own challenges. Changing winter conditions, such as freeze-thaw cycles and increased autumn precipitation, result in overwintering damage, enhanced susceptibility to fungal diseases, and stand instability (Poggi et al., 2022).

Furthermore, altered seasonal cues and erratic temperature profiles influence flowering time and development synchrony, which can disrupt pollination in cross-pollinating cereals like rye. These phenological mismatches reduce seed set and grain uniformity, critical in commercial and subsistence agriculture. In wheat, simulation studies project grain yield declines of up to 30% by mid-century under high-emission scenarios, especially in rainfed systems (Ishtiaq et al., 2022).

Climate change also exacerbates existing agronomic challenges, such as nutrient leaching, weed pressure, and shifts in pest and disease complexes. The resilience of rye to drought, low pH, and nitrogen stress makes it a promising cereal for sustainable systems, but these advantages are not immune to breakdown under extreme or erratic conditions. Therefore, breeding for climate adaptation requires not only enhancing trait resilience but also improving stability across multiple environments and input regimes (Johansson et al., 2024).

These developments highlight the urgency of integrated climate-resilient strategies that combine stress-tolerant genetics, precision agronomy, and predictive climate modeling. Both rye and wheat will need to be managed as dynamic systems, where adaptability and stability must be evaluated in tandem, particularly in regions where weather volatility is projected to intensify.

1.3: Importance of Multi-Trait Analysis

Conventional agronomic evaluations have traditionally emphasized single-trait assessments, most commonly grain yield or protein content, thereby overlooking the complex, integrated nature of crop responses to environmental stress and agronomic management. Recent studies increasingly demonstrate that yield and quality are not independent outcomes; instead, they arise from interactions among multiple, interdependent traits, including spike number, grain weight, protein composition, and disease resistance. These interconnections, particularly among yield components (e.g., number of spikes, grains per spike, thousand-grain weight), physiological processes, and biochemical quality indicators, highlight the inadequacy of single-trait approaches. Consequently, multi-trait analytical frameworks have gained prominence as more comprehensive tools for evaluating genotype performance. By incorporating trait interdependencies and accounting for environmental variability, multi-trait genomic prediction and stability indices enable breeders to more effectively select genotypes that meet both productivity and end-use requirements under variable climatic conditions (Hackauf et al., 2017; Michel et al., 2019; Montesinos-López et al., 2021).

The Multi-Trait Stability Index (MTSI) has emerged as a powerful and statistically rigorous tool for evaluating the joint stability of multiple phenotypic traits across diverse environmental conditions. Its utility lies in enabling breeders to identify genotypes that are not only high-yielding but also resilient to environmental variability. In contrast to traditional single-trait approaches, MTSI integrates both mean performance and stability across multiple traits while effectively addressing multicollinearity, an issue common in multi-dimensional datasets. The index has been widely adopted in breeding programs for cereals and other crops to manage trade-offs between key traits, such as grain yield and protein content, or between growth vigor and disease resistance (Abdelghany et al., 2021; Benakanahalli et al., 2021; Mohammadi & Geravandi, 2024). In wheat and other cereals, MTSI has demonstrated strong predictive capacity for identifying genotypes with consistent performance under both rainfed and irrigated conditions, thus improving the accuracy of cultivar recommendations for stress-prone and marginal environments.

Moreover, recent research in winter and durum wheat has highlighted the capacity of the Multi-Trait Stability Index (MTSI) to consistently identify genotypes that combine high yield potential with resilience to abiotic stress, particularly drought. These multi-environment evaluations, conducted under both rainfed and irrigated conditions, demonstrate that MTSI effectively integrates trait performance and stability over time, enabling the identification of cultivars with superior adaptability across fluctuating agroecosystems (Mohammadi & Geravandi, 2024; Taria, Arora, Kumar, & Arunachalam, 2025). These insights reinforce MTSI's relevance not only as a practical selection tool but also as a comprehensive framework for assessing cultivar stability amid climate-induced stress and agronomic intensification.

In addition to its theoretical rigor, the practical utility of the MTSI has been increasingly recognized in modern breeding programs due to its ability to manage high-dimensional trait data and support environment-specific selection. For instance, in multi-location wheat trials across India, MTSI demonstrated superior effectiveness compared to traditional models like AMMI and WAASB in identifying drought-tolerant genotypes, with indicators such as the Normalized Difference Vegetation Index (NDVI) enhancing predictive accuracy (Reddy et al., 2024). Furthermore, combining MTSI with complementary indices such as the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) has shown promise in identifying genotypes with synergistic traits like stay-green capacity and stem reserve mobilization, critical features for resilience under complex stress environments (Taria et al., 2025).

In temperate agroecosystems, both edaphic and climatic factors, such as soil pH, texture, organic matter content, rainfall distribution, and accumulated thermal time, have been shown to strongly influence trait expression and genotype stability rankings when evaluated using MTSI (Ghafoor, Derejko, & Studnicki, 2024). These findings emphasize the necessity of incorporating environmental metadata into trait evaluation pipelines to improve selection accuracy. While MTSI has been predominantly applied in wheat, its methodological versatility makes it equally suited for other cereals such as rye, where genotype-by-environment interactions are particularly pronounced. Applying MTSI to rye breeding programs could yield critical insights into the stability of traits conferring tolerance to abiotic and biotic stresses, including aluminum toxicity, lodging, and overwintering challenges, that are increasingly relevant under shifting management regimes and climate variability.

Despite its methodological robustness, the application of MTSI in rye breeding remains limited. This gap is particularly important given the agronomic divergence between hybrid and population rye cultivars, which differ not only in their yield potential but also in physiological responses to nutrient inputs and environmental stresses. Recent evidence suggests that while hybrid cultivars often outperform in terms of yield, they tend to exhibit lower stability under fluctuating management and environmental conditions, especially when challenged by disease pressure or soil acidity (A. Ghafoor et al., 2024). These observations highlight the critical need to incorporate both abiotic (e.g., acid soil tolerance, lodging resistance) and biotic (e.g., fungal disease resistance) stress-related traits into multi-trait stability frameworks. However, few studies have examined how these trait–environment interactions shape overall cultivar adaptability in rye, particularly under diverse cropping systems. Additionally, structural and biochemical factors, such as enhanced lignin accumulation and reinforced stem vascular tissues, have recently been recognized as key heritable components of lodging resistance in both rye and wheat (Muszynska et al., 2021). This further underscores the need for integrative, multi-trait approaches that capture trait co-expression, environmental responsiveness, and management interaction. In response, this dissertation leverages multi-environment trials in rye and spring wheat, employing the Multi-Trait Stability Index (MTSI) and Classification and Regression Tree (CART) modeling to identify the key plant and environmental drivers of cultivar stability.

1.4 Main purpose of the study

The primary purpose of this study is to evaluate the multi-trait phenotypic stability of rye (*Secale cereale L.)* and spring wheat (*Triticum aestivum L.*) cultivars across diverse environmental conditions and crop management systems, using the MTSI as a core analytical framework. By integrating field performance data with trait-based modeling approaches, such as Classification and Regression Tree (CART) analysis, the study aims to identify key plant characteristics and environmental factors that influence cultivar stability. The research ultimately seeks to systematize multi-environment trial results to inform the selection and recommendation of resilient, high-performing genotypes for sustainable cereal production in temperate agroecosystems

1.5 Objectives

1. To evaluate the multi-trait performance and stability of spring wheat, winter wheat, and winter rye cultivars under temperate environments and contrasting crop management systems.
2. To identify key morphological, physiological, and biochemical traits influencing yield and quality stability across cereal crops using multivariate tools such as MTSI, CCA, and CART.
3. To integrate multi-environment trial data from three species to develop trait-based selection criteria and breeding recommendations for climate-resilient, high-performing cultivars.

1.6 Hypothesis

1. H1: The stability and performance of cereal cultivars differ significantly across environments and crop management systems, depending on their genotype and input response.

2. H2: The Multi-Trait Stability Index (MTSI) and associated multivariate tools provide a more robust assessment of cultivar adaptability and performance than traditional single-trait models.
3. H3: Traits such as spike fertility, aluminum tolerance, disease resistance, and phenological maturity are key predictors of multi-trait stability across diverse environments.

CHAPTER II LITERATURE REVIEW

2.1 Genotype × Environment Interactions and Stability

Crop productivity and resilience under diverse environmental conditions have long been influenced by the stability of cultivar performance, particularly in cereals like wheat and rye. Numerous multi-environment trials (METs) have revealed that genotype × environment interactions (GEI) significantly affect yield and associated traits, making stability assessment a cornerstone of breeding programs for temperate climates (Khan et al., 2023). Traditionally, univariate stability measures such as Eberhart and Russell's regression and Shukla's variance (Shukla, 1972) have been employed to evaluate cultivar adaptability; however, these approaches often overlook the multidimensional nature of crop traits. Recent studies underscore the advantage of incorporating multivariate models and phenotypic indices for assessing cultivar stability across yield, quality, and physiological traits (Al-Ashkar et al., 2022). In rye, where population and hybrid cultivars exhibit distinct genetic architectures and environmental responses, phenotypic stability remains an emerging but underrepresented research area. Genome-wide selection approaches are now being integrated with phenotypic data to enhance trait stability predictions across multi-site trials (Y. Wang, 2016), marking a paradigm shift in how breeders evaluate genotype resilience.

Genotype × environment interactions (G×E) are fundamental in shaping cultivar performance, especially in cereals like wheat and rye, which are grown under highly variable environmental conditions. These interactions occur because the expression of a genotype can vary significantly across different environments due to factors such as temperature, precipitation, soil quality, and agronomic practices (Khare, Shukla, Pandey, Singh, & Singh, 2024). G×E interactions are responsible for the fluctuations observed in yield and other agronomic traits, emphasizing the need for multi-environment trials (METs) to evaluate genotype stability across a wide range of conditions. In wheat, a globally significant crop, G×E interactions strongly influence yield stability, with temperature fluctuations and water stress being major contributors to this variability (Reddy et al., 2024).

In rye, which is often grown in marginal soils and harsh climates, G×E interactions also play a crucial role in determining cultivar performance. Rye cultivars are exposed to fluctuating winter temperatures, varying soil types, and unpredictable water availability, all of which contribute to variability in performance. While exhibiting higher yield potential, hybrid rye cultivars can show significant instability across different environments, especially under low-input conditions. This variability reinforces the need for a thorough evaluation of genotype × environment interactions in assessing rye's adaptability (A. Ghafoor et al., 2024).

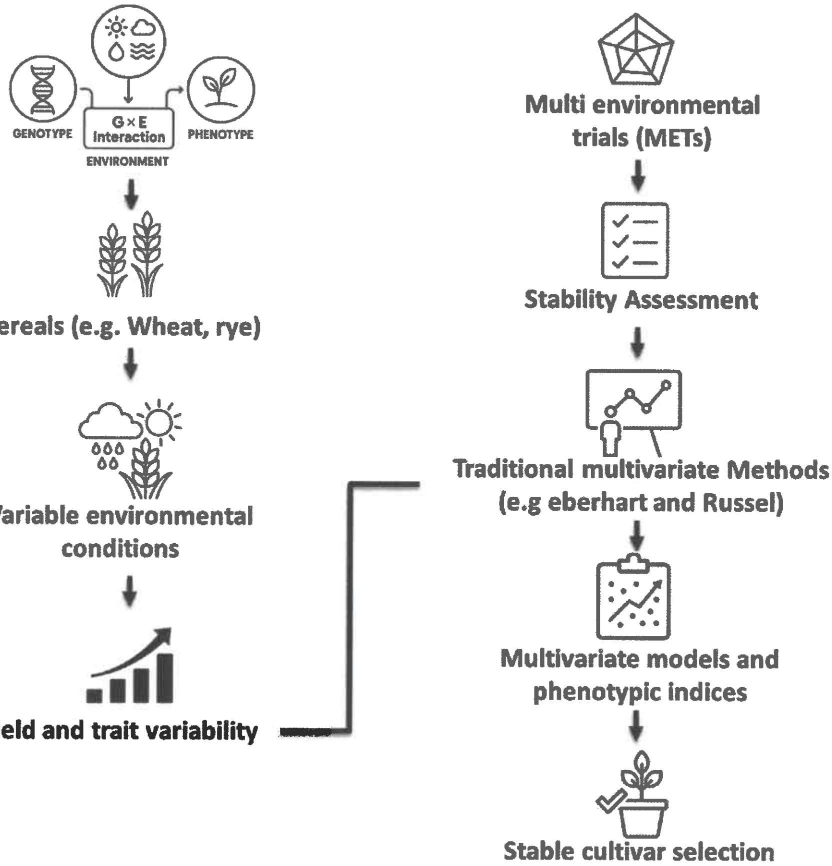

Figure 1. Conceptual flowchart of the genotype × environment interaction pathway in cereals, outlines environmental variability, trait expression, traditional and modern stability assessment tools, and the integration of phenotypic and genomic information to support stable cultivar selection.

Traditional and multivariate stability metrics (Figure 1) play distinct roles in interpreting G×E interactions across multi-environment trials, particularly when integrated with genomic selection strategies. Traditional methods for assessing cultivar stability, such as Eberhart and Russell's regression model, focus primarily on single traits such as yield. However, these models often fail to capture the complexity of multi-trait stability. Recent advancements in multivariate stability indices, such as the Multi-Trait Stability Index (MTSI), provide a more comprehensive approach by evaluating multiple traits simultaneously. This method allows breeders to assess not only yield but also disease resistance, lodging resistance, and stress tolerance (Joshi et al., 2024).

Integrating genomic selection (GS) with phenotypic data has emerged as a powerful tool to improve predictions of cultivar stability across diverse environments. Combining genomic data with phenotypic performance allows breeders to more accurately identify stable cultivars that can adapt to changing environmental conditions, which is crucial for crops like rye and wheat, which are sensitive to climate change (Arif et al., 2025). This integration facilitates the identification of genotypes with consistent performance under various climatic stresses and provides a pathway for breeding climate-resilient cultivars.

2.2 Importance of Multi-Trait Stability (MTSI)

The Multi-Trait Stability Index (MTSI) addresses a major shortcoming of classical stability models by enabling the concurrent evaluation of multiple phenotypic traits across diverse environments. By integrating both mean performance and trait stability into a unified framework, MTSI offers a comprehensive assessment of genotype adaptability under variable agroecological conditions (Abdelghany et al., 2021). Its application in major cereals such as wheat and maize has demonstrated strong discriminatory capacity for selecting genotypes that combine yield, quality, and stress-resilience traits even in the presence of complex genotype × environment (G×E) interactions(Yue et al., 2022). This multivariate approach is particularly useful in temperate regions, where moderate climatic fluctuations and soil heterogeneity necessitate evaluation strategies that go beyond yield-centric analyses. For example, a long-term study on durum wheat demonstrated the value of MTSI in identifying genotypes well-suited to Mediterranean-type climates characterized by episodic drought and heat (Sellami et al., 2024). While MTSI's utility has been established in several cereal crops, its adoption in rye breeding remains limited. However, emerging evidence suggests that MTSI holds considerable promise in capturing genotype stability across grain yield, end-use quality, and biotic stress tolerance in both hybrid and population rye cultivars (A. Ghafoor et al., 2024). Figure 2 conceptualizes MTSI's role as an integrative tool that combines phenotypic assessment with genomic and machine learning-based selection frameworks.

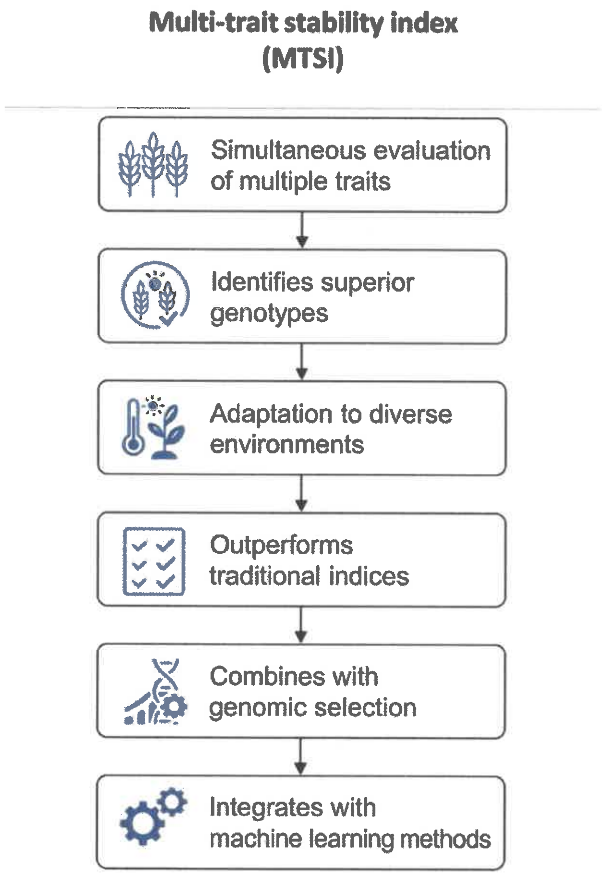

Figure 2. Schematic representation of the Multi-Trait Stability Index (MTSI) framework.

Recent studies have further reinforced the versatility of the Multi-Trait Stability Index (MTSI) across a wide range of crop species, underscoring its adaptability to diverse breeding objectives and agroecological conditions. In chickpea, for example, MTSI successfully identified genotypes with both high yield and stability for drought tolerance traits across six contrasting environments, thereby facilitating the development of cultivars suited for arid regions (Hussain, Akram, Shabbir, Manaf, & Ahmed, 2021). Similarly, in maize, MTSI enabled the selection of stable inbred lines capable of maintaining performance under drought stress, highlighting its dual applicability in both hybrid breeding and population improvement programs (Balbaa et al., 2022). In wheat, comparative evaluations have demonstrated MTSI's superiority over classical stability indices in capturing genotypes with consistent agronomic and physiological performance under drought conditions. Notably, the integration of Normalized Difference Vegetation Index (NDVI) as a phenotypic predictor has enhanced the screening efficiency in these studies (Reddy et al., 2024). Although its application in rye remains limited, the consistent success of MTSI across crop species affirms its broad utility in improving selection accuracy and accelerating genetic gain, particularly in breeding programs targeting stress-prone and variable environments.

Recent advancements in rice breeding further underscore the relevance of MTSI in multi-trait evaluation frameworks. When combined with AMMI and GGE biplot analyses, MTSI has facilitated the identification of genotypes not only with high yield potential but also with desirable secondary traits such as early maturity and plant vigor, thereby demonstrating its utility in comprehensive genotype assessment across heterogeneous environments (Ponsiva et al., 2024). Furthermore, the integration of MTSI with AMMI-derived stability metrics, including the Yield Stability Index (YSI) and Weighted Average of Absolute Scores from the BLUP (WAASB), has enhanced the robustness of genotype ranking. This combined approach allows breeders to assess both performance and consistency simultaneously, ultimately improving the precision of genotype selection in variable agro-climatic conditions (Verma & Singh, 2024).

In parallel, modern breeding programs are increasingly integrating multivariate statistical frameworks and machine learning tools to dissect trait–environment interactions with greater precision. Among these, the Multi-Trait Genotype Ideotype Distance Index (MGIDI) has gained attention for its ability to rank genotypes based on proximity to an ideal ideotype. Similarly, machine learning approaches such as Classification and Regression Trees (CART) and Canonical Correspondence Analysis (CCA) are being employed to model complex trait relationships and environmental influences. In a recent study, Al-Ashkar et al. (2023) demonstrated the power of pooled analyses combining AMMI, MGIDI, and WAASB to identify wheat ideotypes with superior multi-stress tolerance, highlighting the potential of integrated data analysis pipelines to enhance genotype selection accuracy in complex, multi-environment scenarios (Al-Ashkar et al., 2023).

Although the adoption of MTSI in rye breeding remains limited, emerging cytogenetic studies offer encouraging prospects for its application. Farshadfar et al. (2012) identified chromosome 5R as a key genomic region associated with yield and phenotypic stability in rye, suggesting that stability-related loci can be effectively targeted within multi-trait selection frameworks. These findings underscore the potential of integrating genomic tools with phenotypic assessments to improve selection accuracy and advance the development of climate-resilient rye cultivars (Farshadfar, Farshadfar, & Kiani, 2012).

Furthermore, recent research highlights the value of integrating genomic selection (GS) with the Multi-Trait Stability Index (MTSI) to enhance the prediction of genotype performance across diverse environments. While GS estimates the genetic potential of cultivars using molecular markers, MTSI accounts for the phenotypic expression and stability of multiple traits under variable environmental conditions. The synergy between these approaches offers a more robust framework for identifying cultivars that combine high yield potential with resilience to climate-induced stressors. For example, Bančič et al. (2023) demonstrated that integrating GS with MTSI improved the accuracy of predicting both yield stability and disease resistance in winter wheat, even under complex genotype × environment interactions. Such integrated frameworks are particularly relevant for rye, which is cultivated under diverse management regimes and environmental gradients, making stability prediction essential for breeding programs targeting climate resilience (Bančič, Ovenden, Gorjanc, & Tolhurst, 2023).

Achieving a comprehensive understanding of phenotypic stability requires more than the evaluation of individual trait performance; it necessitates unraveling the complex interactions between plant characteristics, environmental variables, and genotype adaptability. Recent studies emphasize that morphological (e.g., plant height, root structure), physiological (e.g., lodging resistance, chlorophyll retention), and biochemical traits (e.g., lignin content, disease resistance) interact synergistically to influence multi-trait stability, particularly under variable agronomic inputs and climatic fluctuations (Muszynska et al., 2021). Advanced analytical techniques, such as Classification and Regression Tree (CART) analysis and Canonical Correspondence Analysis (CCA), have emerged as powerful tools to dissect these intricate relationships. While classical G×E models partition phenotypic variance, CART enables hierarchical trait classification and identification of key predictors of stability. For example, high-throughput phenotyping and CART were used to reveal that NDVI, root density, and aboveground biomass are strong indicators of drought tolerance and yield consistency in wheat (Kumar et al., 2020). Similarly, multivariate analyses such as Principal Component Analysis (PCA) and AMMI have shown that physiological traits like canopy temperature and chlorophyll retention are reliable markers of performance stability under varying sowing conditions (Negash & Birr, 2022). Collectively, these integrative approaches enhance the resolution of trait-based selection strategies and complement stability indices like MTSI by providing a mechanistic understanding of genotype adaptability.

2.3 Trait-Based Modeling and Analytical Tools in Stability Assessment

Stability assessment in temperate cereal production systems is particularly relevant for crops like rye (*Secale cereale* L.) and spring wheat (*Triticum aestivum* L.), which are exposed to moderate but highly variable abiotic and biotic stressors. In these systems, yield stability is often influenced by unpredictable temperature shifts, soil acidity, water availability, and disease pressure during critical growth phases. Although spring wheat has been extensively evaluated for phenotypic stability using multivariate and biplot-based models, rye remains less explored despite its genetic potential for adaptation to poor soils and harsh environments. Recent multi-environment studies in spring wheat have identified genotypes with consistent performance across agroecological zones and linked this stability to traits such as chlorophyll content, grain weight, and disease resistance under varying input levels (Romena, Najaphy, Saeidi, & Khoramivafa, 2022). Meanwhile, the few available studies on rye suggest that hybrid cultivars offer higher yield potential but may lack stability across seasons, particularly under reduced input systems (A. Ghafoor et al., 2024). Furthermore, trait combinations such as lodging resistance, aluminum tolerance, and nitrogen uptake efficiency are proving to be critical determinants of performance in rye under temperate conditions (Muszynska et al., 2021). As breeding programs increasingly focus on climate-smart and input-efficient cultivars, the integration of multivariate stability tools like MTSI with trait-explaining models such as CART and AMMI becomes crucial for identifying resilient genotypes suited to variable temperate environments. The integration of trait-based modeling with analytical tools for stability assessment is summarized in Figure 3. This framework connects stress-responsive traits in temperate cereals with multivariate and machine-learning approaches, supporting high-throughput phenotyping and data-driven selection for climate-resilient genotypes.

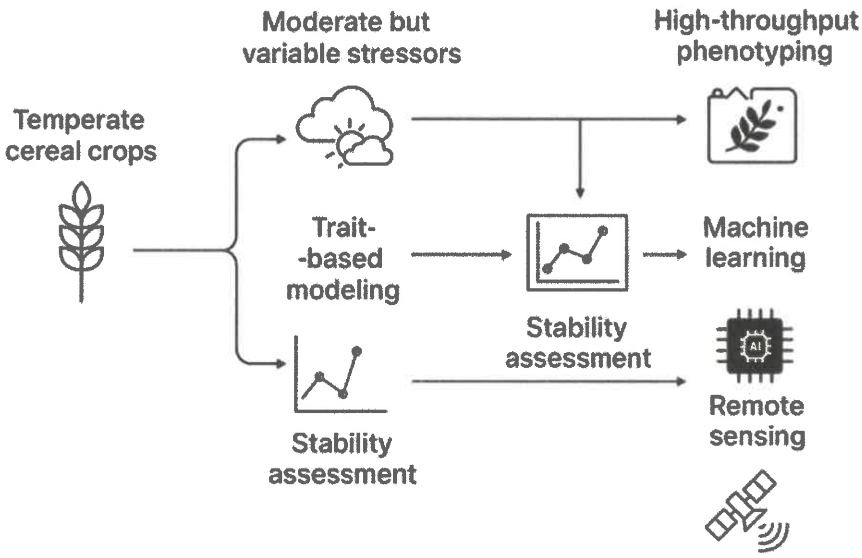

Figure 3. Conceptual pipeline illustrating trait-based stability assessment in temperate cereal crops.

Recent advances in high-throughput phenotyping and trait-based modeling further reinforce the relevance of CART and similar machine-learning methods in breeding programs. For instance, a study by Wang et al. (2022) integrated CART analysis with UAV-based multispectral imaging to evaluate chlorophyll content and leaf area index in spring wheat. The results demonstrated high prediction accuracy (R^2 up to 0.94) across different growth stages and water regimes, validating CART as a robust tool for mapping quantitative trait loci (QTL) related to physiological stability traits such as NDVI and chlorophyll content (W. Wang et al., 2022). Beyond CART, the integration of proximal sensing platforms has shown promise in phenotyping drought-adaptive traits under field conditions. Thompson et al. (2018) developed a low-cost proximal sensing cart equipped with sensors for canopy temperature, NDVI, and leaf area index to identify drought-tolerant upland cotton genotypes. Their protocol provided reliable trait estimates under variable water regimes, highlighting the feasibility of such tools in identifying resilient cultivars in temperate cereal systems as well (Thompson et al., 2018).

In durum wheat, high-throughput phenotyping platforms, including UAVs and ground-based systems, were compared for their ability to detect QTLs linked to NDVI, chlorophyll content, and biomass under drought stress. The study found that aerial platforms captured more QTLs with greater phenotypic variation explained, suggesting their superiority in trait-dissection for stability selection (Condorelli et al., 2018). These findings collectively illustrate the growing power of data-driven selection methods in understanding and improving phenotypic stability. As machine learning and remote sensing technologies become more accessible, their integration with multivariate indices like MTSI will be key to enabling precise, large-scale selection in breeding programs targeting climate resilience and multi-trait optimization.

The Multi-Trait Stability Index (MTSI) is a robust multivariate statistical tool designed to identify genotypes that simultaneously exhibit superior mean performance and stability across multiple traits and environments. Developed by (Olivoto, Lúcio, da Silva, Sari, & Diel, 2019) MTSI extends the classical selection index by integrating both phenotypic performance and stability estimates into a unified framework. This enables breeders to rank genotypes not only based on high mean values but also on their consistency across environments.

The MTSI builds upon the Weighted Average of Absolute Scores (WAASB) derived from the singular value decomposition (SVD) of the genotype-by-environment interaction (GEI) matrix obtained via the Additive Main Effects and Multiplicative Interaction (AMMI) model. It also incorporates genotype-by-trait biplots to evaluate performance across multiple traits simultaneously.

MTSI calculation involves the following steps:

1. **Model fitting**: AMMI or BLUP models are fitted to the multi-environment trial (MET) data to extract the mean and interaction components.
2. **Stability computation**: WAASB values are computed for each genotype to assess interaction-related stability.
3. **Ideotype planning**: A virtual "ideal genotype" is conceptualized, one that has the best performance and stability across all traits.
4. **Distance calculation**: The Euclidean distance between each genotype and the ideotype is calculated; the smaller the distance, the better the genotype in terms of simultaneous mean performance and stability.
5. **Genotype ranking**: Genotypes are ranked based on this distance, allowing a joint selection for performance and stability.

Mathematically, the MTSI is expressed as:

$$MTSI_i = \sqrt{\left(\sum_{j=1}^{t} (Z_{ij} - Z_j^{(ide)})^2\right)}$$

where:

Z_{ij} is the standardized score of genotype iii for trait jjj,

Z_j^{ide} is the standardized score of the ideotype for trait jjj,

t is the total number of traits.

The index is dimensionless and interpretable across a wide range of breeding contexts. A lower MTSI score indicates higher stability and performance, aligning well with breeders' objectives of selecting elite, climate-resilient cultivars.

2.4 Research Gap and Rationale for the Present Study

Despite notable advances in the application of multivariate stability indices such as the Multi-Trait Stability Index (MTSI) and analytical tools like Classification and Regression Tree (CART) analysis, the literature reveals a significant underrepresentation of these approaches in rye and spring wheat breeding under temperate production systems. Most existing studies have focused either on single stress factors, such as drought or nutrient deficiency or have been confined to high-input environments, failing to reflect the complexity and variability of real-world agroecosystems. As a result, our understanding of how multiple plant traits interact with environmental and management variables to influence phenotypic stability in these crops remains limited.

Rye, in particular, has received comparatively little attention in the context of modern stability analysis. Although it is recognized for its adaptability to low-input and marginal environments, especially in northern temperate regions, there is a lack of comprehensive multi-trait, multi-environment evaluations that incorporate stability indices and trait-environment models. Despite its increasing relevance in sustainable agriculture and climate-resilient cropping systems, the few available studies often treat rye as a secondary cereal. This research gap is especially concerning given the ongoing climate variability, which is expected to further intensify the frequency and unpredictability of abiotic and biotic stressors.

Spring wheat, while more extensively studied, also presents methodological limitations. Many stability studies in wheat rely solely on univariate models or focus predominantly on yield-related traits, overlooking physiological and morphological components contributing to broader agronomic resilience. Moreover, few studies have attempted to integrate multivariate stability indices like MTSI with machine learning-based trait analysis tools such as CART or Canonical Correspondence Analysis (CCA), especially under contrasting management systems that better reflect practical farming scenarios. Figure 4 summarizes the key research gaps identified in rye, spring, and winter wheat breeding and the rationale for the present study, which integrates multivariate stability indices, machine learning, and multi-environment trials to address current limitations.

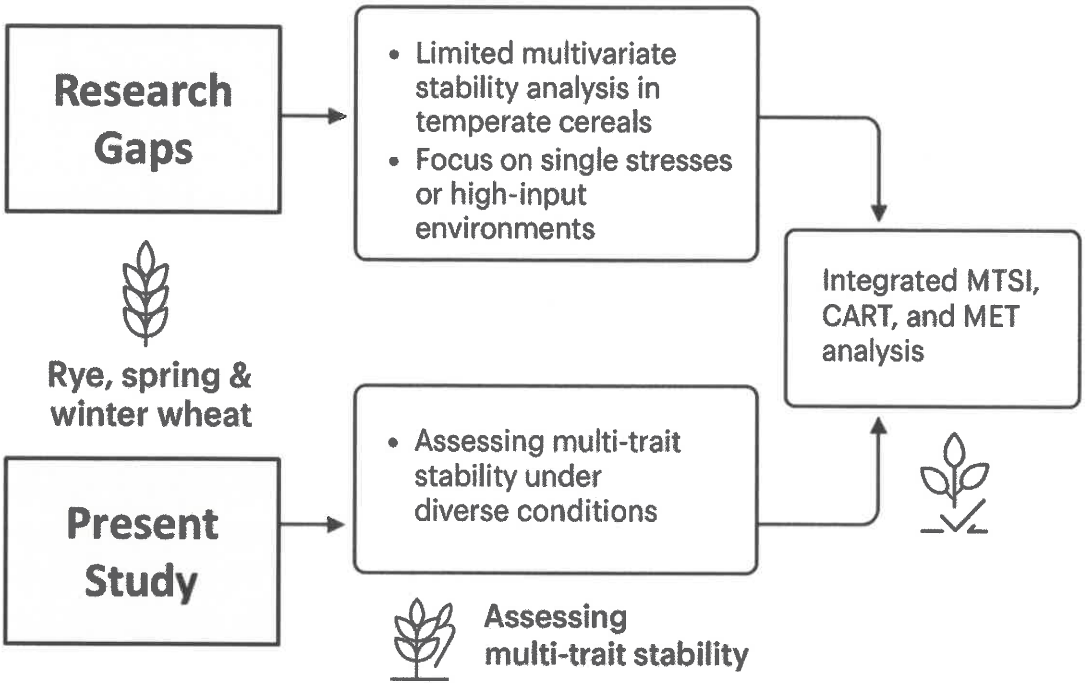

Figure 4. Conceptual framework outlining the research gaps in stability assessment of temperate cereals and the rationale for the present study.

In response to these gaps, the present study proposes an integrated framework that combines MTSI, CART, and multi-environment trial (MET) data to assess the phenotypic stability of rye and spring wheat cultivars. By conducting this analysis under conventional and low-input management systems, the research aims to identify genotype-by-environment patterns that influence trait stability, highlight key physiological and agronomic predictors of adaptation, and pinpoint genotypes with high multi-trait stability. This integrated approach not only enhances selection accuracy but also contributes to the development of more climate-resilient cultivars suited to diverse and fluctuating growing conditions in temperate zones.

CHAPTER III MATERIALS AND METHODS

3.1.1 Experimental Design and Study Locations

This study integrates data from multi-environment field experiments (METs) involving spring wheat (*Triticum aestivum L.*), winter wheat, and winter rye (*Secale cereale L.*) cultivars conducted under temperate climatic conditions in Poland. All experiments assessed genotype performance, trait stability, and management effects under real-world production systems, with particular emphasis on genotype × environment interactions (G×E).

The spring wheat experiment evaluated seven cultivars: Bombona, Izera, Torridon, Ostka Smolicka, Radocha, Trappe, and Tybalt, across four trial locations over two consecutive growing seasons (2019 and 2020). Table S1 presented descriptions of soil and weather in study trial locations and growing seasons for spring wheat. The descriptions of study cultivars are shown in Table S2. Trials followed a two-factorial strip-plot design with two replicates per site. Crop management intensity, designated as either moderate-input management (MIM) or high-input management (HIM), was applied as the main plot factor, while cultivars were nested within subplots. MIM involved standard nitrogen fertilization (~90 kg N ha^{-1}), herbicide use, and seed treatment fungicides. HIM included increased nitrogen levels (up to 130 kg N ha^{-1} total), foliar micronutrients, growth regulators, and two fungicide applications timed at GS 31–32 and GS 49–60. Each plot measured 15 m^2, with sowing densities of 450 seeds m^{-2}.

The winter wheat data were derived from an extensive multi-year cultivar evaluation system coordinated by the Polish Research Centre for Cultivar Testing (COBORU). Fifty-five cultivars were assessed in 12 locations over five growing seasons (2015/2016-2019/2020), resulting in 60 environment combinations. Trials followed an alpha design with two replicates and 15 m^2 plots. The soil characteristics of trial locations, including, among others, reference bulk density, soil organic carbon stock, and cation exchange capacity, are presented in Table S3. Crop management included two fungicide treatments (Zadoks GS 31-32 and 49-60), a growth regulator (trinexapac-ethyl), and nitrogen fertilization with an additional 40 kg N ha^{-1} above the optimal rate for the given environment. Due to their low interannual variability, soil characteristics such as bulk density, organic carbon stock, and cation exchange capacity were measured and treated as fixed location traits.

The winter rye trials were conducted over two growing seasons (2018/2019 and 2019/2020) at three core production sites: Choryń, Laski, and Sobiejuchy. The trials featured 11 population and 5 hybrid cultivars from European breeding programs. The characteristics of Experiments were conducted using a split-block design with two replicates per location. The management factor (MIM or HIM) was applied to main plots and cultivar type to subplots. The HIM treatment included elevated nitrogen doses (30-40 kg N ha^{-1} above MIM), a growth regulator, and two fungicide applications. Soils ranged from Retisols to Cambisols and Luvisols, all characterized by high macronutrient availability and neutral to alkaline pH. The details of the field conditions for the trial location, including planting date, seeding density, and fungicides used, are presented in Table S6. Climatic variation between seasons was documented, including an unusually long autumn growing period and fluctuating precipitation levels, important for assessing environmental stress responses.

Across all experiments, data were collected on grain yield (GY), thousand-grain weight (TGW), and a range of quality and physiological traits. For rye, this included test weight, starch content, and protein content, while for wheat, additional assessments included ash content, wet gluten (WG), gluten index (GI), sedimentation value (SV), falling number (FN), flour yield (FY), water absorption (WA), dough development and stability, and baking parameters such as loaf volume and crumb hardness.

3.1.2 Plant Materials and Trait Measurement

Across all field experiments, a standardized protocol was applied to assess agronomic, quality, and physiological traits in wheat and rye cultivars. These traits were chosen to capture essential aspects of crop productivity, processing value, and stress adaptability under temperate environmental conditions and contrasting management systems.

Agronomic traits were measured at physiological maturity using samples collected from the center of each plot (1 m^2), thereby avoiding edge effects. Grain yield (GY) was calculated by weighing the cleaned grain harvested from this sample area. Thousand-grain weight (TGW) was determined using calibrated grain counters and balances. In the rye trials, additional yield components, including the number of spikes per square meter and grains per spike were measured and used in path coefficient analysis to quantify their direct influence on yield performance under different cultivar types and management systems.

Grain quality traits were evaluated using internationally recognized standards. For both wheat and rye, test weight (TW) was measured according to AACC Method 55-10. Protein content (PC) was determined using the Kjeldahl method (AACC 46-11.02), and ash content (AC) was assessed via the incineration method (AACC 08-01.01). In wheat, wet gluten content (WG) and gluten index (GI) were measured using the Glutomatic 2200 system (AACC 38-12), while sedimentation value (SV) was obtained using the Zeleny test (AACC 56-61.02). The falling number (FN), indicating enzymatic activity and sprouting susceptibility, was assessed using the Hagberg-Perten method (AACC 56-81B). In rye, starch content and protein concentration were determined using near-infrared spectroscopy (NIR) with an Infratec™ 1241 analyzer, following calibration to AACC grain standards.

Spring wheat samples were additionally analyzed for end-use and baking quality. Flour yield (FY) was calculated after two-pass milling with a Quadrumat Senior laboratory mill. Dough properties, including water absorption (WA), dough development time (DD), stability (DS), softening (DSF), and overall quality number (QN), were measured using a Brabender Farinograph following AACC Method 54-21. Baking performance was evaluated through standardized test baking. Loaf volume (LV) was determined using a 3D scanner and normalized per 100 g of bread. Crumb hardness (CH) was measured using a TA-XT2i texture analyzer in a dual-compression test to simulate chewing resistance. Biotic and abiotic stress resistance traits were assessed through visual scoring and metadata from national cultivar databases. In winter wheat and rye, resistance to major fungal diseases such as powdery mildew (PM), brown rust (BR), septoria leaf blotch (SLB), chaff septoria (CS), stem base disease (DSB), and fusarium ear blight (FEB) was evaluated on a 9-point scale, where 1 represented maximum susceptibility and 9 maximum resistance. These data on disease resistance for winter wheat are presented in Table S4, and for Winter rye, they are presented in Table S5. Lodging resistance, winter hardiness, and resistance to sprouting in the spike were also recorded. Additionally, phenological traits such as plant height, days to heading, and maturity were included in trait analyses to investigate their association with yield and quality stability across environments.

3.2. Statistical Analysis

To quantify the performance, stability, and adaptability of cereal cultivars across diverse environments and crop management systems, a comprehensive statistical approach was adopted. Data analysis across all field experiments, spring wheat, winter wheat, and rye, involved a combination of linear mixed models (LMMs), stability indices, and multivariate analysis techniques. These methods were chosen to model the hierarchical and factorial structure of the experiments, assess genotype × environment (G×E) interactions, and explore trait interdependencies. Additionally, advanced modeling tools such as Canonical Correspondence Analysis (CCA) and Classification and Regression Trees (CART) were employed to identify environmental and cultivar characteristics associated with trait stability. The MTSI and Shukla's stability variance (Shukla, 1972), were used to quantify genotype performance across multiple environments and traits. All analyses were carried out using R software (versions 4.2.1 and 4.3.0), with dedicated packages including metan for stability analysis, vegan for multivariate statistics, and rpart for decision tree modelling (Team, 2024).

The general form of the linear mixed model (LMM) used across the studies can be represented as:

$$y = X\beta + Z\gamma + \epsilon$$

where:

y is the vector of observed values for a given trait,

X is the design matrix for fixed effects,

β is the vector of fixed effect parameters (e.g., cultivars, crop management),

Z is the design matrix for random effects (e.g., location, year, replications, blocks),

γ is the vector of random effects, and

ϵ is the residual error term.

However, the specific model structures were customized according to the design and objectives of each crop study. For instance, the spring wheat trials used a two-stage model typical of strip-plot designs, while the winter wheat and rye trials employed single-stage models reflecting their alpha and split-block layouts, respectively.

3.2.1 Model for Spring Wheat

The statistical analysis for the spring wheat experiment was conducted using a two-stage linear mixed model (LMM) approach, accounting for the strip-plot design used across four locations and two growing seasons (2019–2020). In the first stage, each individual trial was analyzed to estimate adjusted means using an LMM appropriate for strip-plot structure, where crop management levels were assigned to whole plots and cultivars to subplots. These adjusted means were then carried forward into the second stage, which utilized a combined LMM to evaluate the joint effects of genotypes, environments, and management practices.

The model applied in the second stage was as follows:

$$Xijkl = \mu + Yi + Lj + YLij + Gk + GYki + GLkj + GLYijk + Ml + MYli + MLjl + MLYijl + GMkl + GMYkli + GMLlkj + GMLYijkl + \epsilon ijkl$$

Where:

Xijkl: observed trait value

μ: overall mean,

Yi, Lj are the random effects of year and location,

Gk and MlM_lMl are the fixed effects of genotype and crop management,

All two-way to four-way interactions (e.g., GLYijk, GMLYijkl) are included as random effects,

ϵijkl is the residual error.

Descriptive statistics such as means, standard deviations (SD), coefficients of variation (CV), and trait ranges were calculated from the adjusted means derived from this model. These corrected means were then used for correlation analysis using the Pearson coefficient and for dimension reduction via principal component analysis (PCA), helping identify underlying relationships among traits. To evaluate cultivar performance across traits and environments, the MTSI was computed using the metan package in R (Olivoto & Lúcio, 2020). The MTSI methodology is based on factor analysis of standardized means, where genotype-environment interaction values serve to normalize trait performance. Stability analyses were conducted separately by crop management level (MIM and HIM), and combinations of year and location were treated as distinct environments.

3.2.2 Model for Winter Wheat

The statistical analysis of the winter wheat data was conducted using a single-stage linear mixed model (LMM) approach. This dataset comprised five growing seasons (2015/2016–2019/2020) and 12 locations, resulting in 60 unique environment combinations. The trials followed an alpha-lattice design with two replications per environment, and the model structure was designed to reflect the complexity of the multilocation, multiyear setup.

The LMM used for the analysis was specified as:

$$yijklhn = \mu + gk + lj + ai + gaki + glkj + laji + glakji + rjih + bjihn + \epsilon ijklhn$$

Where:

yijklhn is the observed value of the trait,

μ is the overall mean,

gk is the fixed effect of the kth genotype (cultivar),

lj, ai are the random effects of location and growing season,

gakiga, glkj and laji are their respective two-way interactions,

glakji is the three-way interaction among genotype, location, and year,

rjih is the random effect of replication nested within location-year,

bjihn is the random effect of the block nested within replication,

ϵijklhn is the residual error.

Adjusted means for each cultivar, location, and year combination were estimated and subsequently used for trait comparison and stability assessments. To quantify trait stability across environments, two indices were employed: Shukla's stability variance (Shukla, 1972), used for evaluating individual traits, and the MTSI for analysing stability across multiple traits simultaneously . The MTSI approach relies on exploratory factor analysis of the matrix of standardized adjusted means, where genotype-by-environment interaction effects are used to compute a comprehensive stability value. Lower values of both indices indicated higher phenotypic stability (Olivoto et al., 2019).

To further understand the sources of stability, Canonical Correspondence Analysis (CCA) was performed using the vegan package in R. CCA enabled exploration of the relationships between environmental characteristics (e.g., soil traits from Table S3) and mean trait values across locations. Additionally, the relationship between cultivar features (from Table S4) and trait stability (via Shukla's variance) was assessed to identify key plant attributes associated with robust performance. These analyses provided insight into the biological and ecological factors influencing genotype adaptability in diverse temperate wheat-growing conditions

3.2.3 Model for Rye

For the rye trials, a single-stage linear mixed model (LMM) was employed to assess genotype performance, yield stability, and the interaction effects of cultivar type, crop management level, and environment. The trials were conducted over two growing seasons and three locations, with each season-location combination treated as a unique environment. The experimental design followed a split-block structure with two replications, and the LMM accounted for the nested and factorial arrangement of the treatments.

The statistical model used was defined as:

$$yijknr = \mu+zi+mj+zmij+gk+gzki+gmkj+gmzkij+rjih+bihn+\epsilon ijknr$$

Where:

yijknr is the observed trait value,
μ is the overall mean,
zi is the random effect of the ith environment (year × location),
mjis the fixed effect of the jth crop management level (MIM or HIM),
zmij is the interaction between environment and crop management,
gk is the fixed effect of the kth cultivar,
gzki, gmki and gmzkij are the interactions between cultivar, environment, and management,
rjih is the random effect of replication within environment,
bihn is the random effect of block within replication,
ϵijknr is the residual error.

Following model estimation, cultivars were grouped into population and hybrid types to explore differences in trait expression and stability. The significance of mean differences in the investigated traits between these groups of cultivars was compared using a linear contrast with Sidak's procedure (Šidák, 1967). Adjusted means were derived for each cultivar × environment × management combination and used for trait comparison. Path coefficient analysis was performed to further dissect yield formation to determine the direct effects of key yield components (number of spikes, grains per spike, TGW) on grain yield. This analysis was carried out separately for each cultivar type (population, hybrid) and management level using the methodology of Welham (Welham, Gogel, Smith, Thompson, & Cullis, 2010)

Trait stability was quantified using Shukla's stability variance (Shukla, 1972), where lower values indicate greater phenotypic consistency across environments. Cultivars were ranked for each trait based on their stability variance, and the ranks were summed to identify the most stable genotypes overall. In addition, the MTSI was calculated using factor analysis of standardized adjusted means, enabling simultaneous assessment of cultivar stability across multiple traits. Both indices were evaluated separately for MIM and HIM systems.

To explain trait stability based on cultivar characteristics, the Classification and Regression Tree (CART) method was applied using the rpart package in R. This analysis utilized a dataset of varietal traits from COBORU, including resistance to fungal diseases, sprouting, and lodging (scored on a 9-point scale) (Table S5), as well as agronomic features such as plant height, heading date, flour yield, and starch viscosity. The CART model identified which of these features were most predictive of stability across grain yield, yield components, and grain quality traits, offering interpretable insight into trait drivers of cultivar adaptability in rye under temperate conditions

CHAPTER IV RESULTS

4.1 Overview

This chapter presents the key experimental results derived from multi-environment trials (METs) conducted on three cereal crops, spring wheat, winter wheat, and winter rye, evaluated under temperate climatic conditions in Poland. The trials were performed under varying levels of agricultural input management and spanned multiple years, locations, and genotypes. The findings in this chapter are organized crop-wise to reflect the distinct genetic structures, management responses, and analytical approaches applied in each study. Results for each species are structured around yield performance, grain quality attributes, trait interrelationships, and phenotypic stability using univariate and multivariate models. Across all experiments, substantial phenotypic variability was observed for agronomic and quality traits.

In spring wheat, cultivar performance varied considerably under moderate-input (MIM) and high-input (HIM) systems, with notable differences in baking quality traits such as gluten content, loaf volume, and flour yield. The application of MTSI enabled the identification of genotypes that combined high yield with desirable end-use quality and adaptability under different management levels.

In winter wheat, which was tested across five growing seasons and twelve locations, significant genotype × environment (G×E) interactions were detected. The stability of grain yield and grain quality traits was assessed using Shukla's stability variance (Shukla, 1972) and MTSI. Canonical Correspondence Analysis (CCA) further elucidated the influence of cultivar and environmental characteristics on trait expression and stability, highlighting the potential of certain genotypes for wide adaptation.

For winter rye, the experimental focus was on distinguishing performance between population and hybrid cultivars under MIM and HIM conditions. Results indicated that hybrid cultivars generally outperformed population types in yield but showed greater sensitivity to environmental fluctuations. Stability was analyzed using Shukla's variance and MTSI, while path analysis quantified the contribution of yield components to the final yield. Additionally, the Classification and Regression Tree (CART) method was employed to identify varietal traits most predictive of phenotypic stability.

4.2 Results for Spring Wheat

The variability of the studied traits was assessed separately for genotype and environmental effects and is presented in Table 1. The GY for the genotypes ranged from 5.66 to 6.40 t ha^{-1}; for the environments, it ranged from 5.50 to 6.63 t ha^{-1}. For yield, variability was greater for environmental effects (CV 7.92%) than for genotypic effects (CV 4.20%). The AC for genotypes means ranged from 1.67 to 1.82% d.m.; for the environment, it ranged from 1.70 to 1.82% d.m.

For this trait, we observe a similar level of variability for genotypes and environments (CV 2.67 and 2.63%, respectively). PC for genotypes ranged from 11.82 to 14.00% d.m. We observed a range of 11.58 to 13.78% d.m. for environmental effects. As for PC, we observed greater variability for environments (CV 7.93%) than for genotypes (CV 5.23%). For WG, genotypes ranged from 19.49 to 27.23%, and for environments ranged from 20.72 to 24.96%. For this trait, greater variability was observed for genotypes (CV 12.95%) than for environments (9.57%). For the FN, the values for genotypes ranged from 281.96 to 375.15 s, while for environments, ranging from 300.40 to 377.18 s. And the variability was greater for environments (CV 10.47%) than for genotypes (CV 9.49%). The FY for the genotypes ranged from 77.24 to 79.15%; for the environments, it ranged from 77.29 to 78.69%. For FY, we observe a similar level of variability for genotypes and environments (CV 0.84 and 0.76%, respectively). WA for genotypes ranged from 57.02% to 59.48% and had low variability (CV 1.73%); similarly, we observed a low level of variability for environments. In contrast, for DS, we observe a high level of variability in both genotype effects and environments (CV 51.34% and 46.41%, respectively). The LV for the genotypes ranged from 366.34 to 398.33 cm3 100 g^{-1}; for the environments, it ranged from 370.67 to 392.48 cm3 100 g^{-1}. For LV, we observe a similar level of variability for genotypes and environments (CV 2.65% and 2.37%, respectively).

Table 1. Description statistics for yield, grain quality, and bread-making traits of genotype (a) and environmental (b) variability in spring wheat cultivars across four trial locations in two growing years (2019 and 2020).

a) Genotype

	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation
GY (t ha^{-1})	6.20	5.66	6.40	0.26	4.20
TGW (g)	42.21	38.7	45.26	2.26	5.35
TW (kg hl^{-1})	76.77	73.7	78.88	1.91	2.49
AC (% d.m.)	1.76	1.67	1.82	0.05	2.67
PC (% d.m.)	12.88	11.82	14.00	0.67	5.23
SV (cm^3)	33.79	29.42	41.80	4.39	13.00
WG (%)	22.78	19.49	27.23	2.95	12.95
GI (-)	83.36	57.64	91.27	12.32	14.78
FN (s)	338.76	281.96	375.15	32.15	9.49
FY (%)	77.88	77.24	79.15	0.65	0.84
WA (%)	58.28	57.02	59.48	1.01	1.73
DD (min)	2.35	2.06	3.49	0.49	20.75
DS (min)	2.65	1.63	5.59	1.36	51.34
DSF (FU)	71.54	39.13	85.69	17.82	24.92
QN (-)	51.51	39.13	84.88	16.54	32.12
LV (cm^3 100 g^{-1})	380.34	366.34	398.33	10.22	2.65
CH (N)	7.43	5.69	9.21	1.24	16.71

b) Environmental

	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation
GY (t ha^{-1})	6.20	5.50	6.63	0.49	7.92
TGW (g)	42.21	39.32	44.56	2.42	5.74
TW (kg hl^{-1})	76.77	73.19	81.17	3.41	4.45
AC (% d.m.)	1.76	1.70	1.82	0.05	2.63
PC (% d.m.)	12.88	11.58	13.78	1.02	7.93
SV (cm^3)	33.79	30.35	38.54	3.88	11.50
WG (%)	22.78	20.72	24.96	2.18	9.57
GI (-)	83.36	76.29	92.05	7.45	8.94
FN (s)	338.76	300.40	377.18	35.47	10.47
FY (%)	77.88	77.29	78.69	0.59	0.76
WA (%)	58.28	56.54	60.86	1.88	3.22
DD (min)	2.35	1.79	3.12	0.58	24.68
DS (min)	2.65	1.50	4.38	1.23	46.41
DSF (FU)	71.54	52.79	89.79	15.12	21.13
QN (-)	51.51	39.29	68.82	12.53	24.33
LV (cm^3 100 g^{-1})	380.34	370.67	392.48	9.02	2.37
CH (N)	7.43	6.86	8.62	0.80	10.81

crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV)

A higher average GY was observed for HIM crop management (6.57 t ha^{-1}) than for MIM (5.83 t ha^{-1}) – Table 2. On the other hand, slightly higher variability was observed for MIM (CV 9.61%) than for HIM (CV 8.41%). We observe the same AC values between MIM and HIM (1.76% d.m. for both crop management). Slightly higher variability is observed for MIM (CV 4.06%) compared to HIM (CV 3.63%). For the PC, higher values were for HIM (13.46% d.m.) than for MIM (12.29% d.m.). The variability of this feature was also higher for HIM (CV 11.49%) than for MIM (7.98%). As for PC, higher values and variability of WG and FN are observed in HIM (WG - average 24.22%, CV 19.19%; FN - average 339.51 s, CV 14.63%) than in MIM (WG - average 21.33%, CV 13.86%; FN - average 338.02s, CV 13.22%). We observed higher FY values for HIM (78.16%) than MIM (77.59%). For LV, higher values were for MIM crop management (386.55 cm3 100 g^{-1}) than for HIM (374.13 cm3 100 g^{-1}). The variability of this variable was also observed to be more significant for MIM (3.80%) than for HIM (0.79%).

Table 2. Description statistics for grain yield and bread-making quality traits in both crop management

	Mean		Minimum		Maximum		Standard deviation		Coefficient of variation	
	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM
GY (t ha^{-1})	5.83	6.57	4.83	5.42	6.84	7.46	0.56	0.55	9.61	8.41
TGW (g)	40.70	43.72	31.87	37.50	46.70	50.64	3.47	2.91	8.53	6.66
TW (kg hl^{-1})	75.84	77.71	69.10	68.82	81.87	82.97	3.60	3.70	4.75	4.76
AC (% d.m.)	1.76	1.76	1.61	1.63	1.88	1.87	0.07	0.06	4.06	3.63

PC (% d.m.)	12.29	13.46	10.60	10.58	13.86	16.99	0.98	1.55	7.98	11.49
SV (cm^3)	31.08	36.50	25.47	25.98	42.17	51.39	4.45	6.78	14.33	18.59
WG (%)	21.33	24.22	14.85	18.11	26.11	37.98	2.96	4.65	13.86	19.19
GI (-)	85.82	80.90	38.31	44.36	99.75	98.70	13.95	16.36	16.26	20.22
FN (s)	338.02	339.51	239.61	233.14	394.18	422.71	44.69	49.66	13.22	14.63
FY (%)	77.59	78.16	75.20	76.55	79.40	80.35	1.18	0.93	1.53	1.19
WA (%)	57.88	58.29	54.30	55.40	62.25	63.35	2.11	2.29	3.65	3.92
DD (min)	2.06	2.56	1.20	1.35	2.65	7.70	0.33	1.28	15.82	49.84
DS (min)	2.14	3.02	0.90	0.95	6.55	10.00	1.36	2.25	63.54	74.51
DSF (FU)	73.96	68.05	31.00	7.50	110.50	107.50	20.51	24.09	27.74	35.39
QN (-)	47.13	54.68	26.50	27.50	125.50	123.00	22.56	25.29	47.86	46.26
LV (cm^3 100 g^{-1})	386.55	374.13	371.98	369.35	410.48	377.14	14.68	2.97	3.80	0.79
CH (N)	7.35	7.52	4.60	4.33	12.04	12.79	1.48	1.91	20.14	25.39

crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), high-input management (HIM), loaf volume (LV), moderate-input management (MIM), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV)

Table 3 shows the influence of the individual main and interaction effects for the studied features, determined using the percent of total variance based on the sum of squares. To compare the variance of factors and their interactions, the sum of squares was presented as percentages, the total sum of squares for considerate effects, and it is named as a percent of the total variance. This form of presenting the results allows us to determine the strength of the influence of the main and interactive effects on the studied traits. For agronomic traits such as GY and TGW, the values of these traits were most strongly conditioned by the leading environmental effects (year or location), as well as crop management or interaction effects between them. On the other hand, traits associated with the quality of grain, flour, dough and bread are more often conditioned by genotypic effects and interactions with genotypes. However, we observed a few exceptions; for example, FY and DSF were most strongly determined by the main effect of the year (belonging to the group of environmental impacts).

Table 3. Percent of the total variance of study traits for main and interaction effects

Effect	Degrees of freedom	GY (t ha^{-1})	TGW (g)	TW (kg hl^{-1})	AC (% d.m.)	PC (% d.m.)	SV (cm^3)	WG (%)	GI (-)	FN (s)	FY (%)	WA (%)	DD (min)	DS (min)	DSF (FU)	QN (-)	LV (cm^3 100 g^{-1})	CH (N)
Year (Y)	1	0.01 *	0.01 *	8.21 **	11 **	9.21 **	10.59 *	0.01	22.3 **	0.01	65.21 **	21.39 **	51.23 **	5.62 *	83.49 **	71.96 **	0.01	41.34 **
Menagment (M)	1	26.4 **	20.67 **	4.79 *	0	12.77 **	15.74 **	11.83 **	1.9 *	0.01 *	1.01 *	19.98 **	2.14 *	44.92 **	15.21 **	27.26 **	13.77 **	0.01 *
Location (L)	3	1.01 *	25.12 **	13.2 **	17 **	20.93 **	4.88 *	0.01	5.23 *	0.01	8.12 **	0.08 *	39.45 **	4.21 *	0.05 *	0.11 *	6.21 *	0.01
Y*M	1	0.95 *	2.99 *	0.73 *	3.8 *	5.96 *	0.01	0.01	0.01	0.01	1.11 *	0.05 *	0.05 *	3.15 *	0.05 *	0.11 *	0.01 *	0.01
Genotype (G)	6	5.23 **	21.38 **	11.99 **	24 **	10.93 **	25.85 **	24.64 **	27.72 **	16.4 **	8.1 **	1.33	6.1 *	23.51 **	0.01 *	0.01	0.01	7.69 **
Y*L	3	42.81 **	3.14 *	51.7 **	9.1 *	3.23 *	16.73 **	28.24 **	9.14 *	64.2 **	2.13 *	17.05 **	0.78 *	2.34 *	0.96 *	0.13 *	0.01	34.87 **
L*M	3	3.27 *	8.13 **	3.9 *	0	8.8 *	5.64 *	3.39	1.28 *	0.01 *	0.01	0.05 *	0.05 *	8.57 *	0.01	0.01	79.86 **	0.01
Y*G	6	0.01	9.68 **	0.58 *	0	0.01	0.01	0.01	4.63 *	0.01	4.75 *	19.98 **	0.01	1.23 *	0.01	0.08 *	0.01	0.01
G*M	6	0.01 *	0.01	0.26	0	0.78	1.44	1.72	0.24	0.01	4.51 *	0.05 *	0.05 *	0.01	0.01	0.01	0.01	0.01
Y*L*M	3	0.01	0.04	0.74 *	12 **	5.44 *	17.63 **	0.35	0.01	1.46 **	0.1	0.01	0.01	4.25 *	0.01	0.11 *	0.01	0.01
L*G	18	0.51 *	1.46 *	2.14 *	0	0.37	0.01	0.01	6.15 *	0.01	2.78 *	0.01	0.01	2.15 *	0.05 *	0.01	0.04 *	0.33 *
Y*G*M	6	3.57 *	0.53 *	0.13	3.6 *	0.01	0.01	2.53	0.01	0.01	0.01	19.98 **	0.01	0.01	0.05 *	0.09 *	0.01	0.62 *
Y*L*G	6	9.03 **	3.61 *	0.32 *	5.8 *	1.61	1.45	7.32 *	0.01	11.04 **	2.14 *	0.01	0.05 *	0.01	0.01	0.01	0.01	0.54 *
L*G*M	18	7.18 *	0.01	0.01	5.2 *	0.01	0.01	1.22	0.01	0.63 *	0.01	0.01	0.05 *	0.01	0.01 *	0.01	0.01	0.01
Y*M*L*G	18	0.01	3.21 *	1.3 *	9.1 *	19.95 **	0.01	18.72 **	21.37 **	6.17 **	0.01	0.01	0.01	0.01	0.05 *	0.11	0.01	14.52 **

*, ** Significant at the 0.05 and 0.001 probability levels, respectively; abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV)

We conducted separate MTSI analyses for both management approaches (MIM and HIM), focusing on grain quality and the resulting flour and bread of seven spring wheat cultivars (Table 4). Its parameter interpretation is the same as the commonly used stability index, e.g. Shukla stability variance (lower is better). In the case of MIM, the top two genotypes with the highest quality MTSI were selected using a selection pressure of 15%. This approach helped to determine the selection differentials for genotypes such as Bombona (2.45) and Radocha (3.39), which hold the first and second positions in the stability ranking, respectively. In HIM, the genotypes Izera (2.73) and Bombona (3.04) hold first and second positions in the stability ranking, respectively. The correlation coefficient between MTSI in MIM and HIM crop management was equal to 0.56.

Table 4. The multi-trait stability index for all study traits of seven cultivars in MIM and HIM crop management

	Multi Trait Stability Index (MTSI)			
Cultivars	**MIM**	**Stability ranking MIM**	**HIM**	**Stability ranking HIM**
Bombona	2.45	1	3.04	2
Izera	3.71	4	2.73	1
Ostka Smolicka	4.10	6	3.79	3
Radocha	3.39	2	3.99	4
Torridon	3.52	3	4.75	7
Trappe	5.15	7	4.74	6
Tybalt	4.04	5	4.44	5

high-input management (HIM), moderate-input management (MIM)

The correlation matrix Figure 5 in the upper triangle reveals the associations among the parameters for MIM. Significant positive correlations of the PC with WG (r=0.61), DD (r =0.56), and QN (r=0.46). The positive correlations of the WG with SV (r=0.56), DD (r =0.45), and DS (r =0.43) were observed. Conversely, negative correlations were observed between TGW and AC (r=-0.61) and WA and FN (r=-0.76). On the other hand, we observe weaker significant negative correlations between PC and DSF (r=-0.61) and between WG and DSF (r=-0.59). Moreover, no correlation was observed between DD and CH for management HIM (the lower triangle). Significant positive correlations were identified between DS and DD (r=0.82). We also observed positive correlations of the PC with WG (r=0.54), SV (r= 0.61), WA (r=0.57), DD (r=0.63), and DS (r=0.66). On the other hand, negative correlations were observed between DS and DSF (r=-0.74) with statistical significance at $P < 0.05$. Also, we observed a negative correlation between PC and DSF (r=-0.53). Generally, we observe weaker correlations of WG and FN for HIM crop management with farinographic parameters than for MIM.

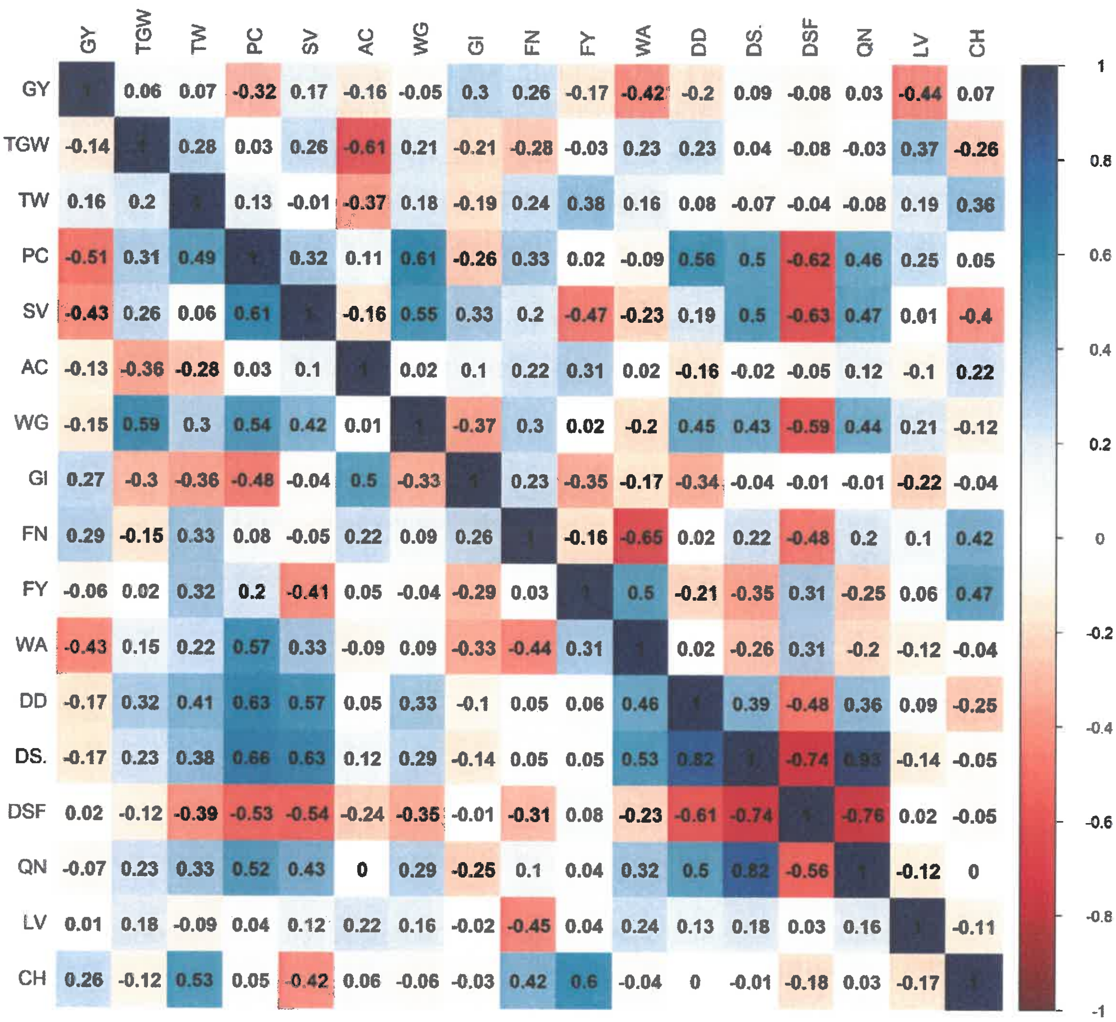

Figure 5. The Pearson correlation analysis of moderate-input management MIM (upper triangle) and high-input management HIM (lower triangle) crop management. Abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

According to the PCA analysis depicted in Figure 6a (MIM crop management), PC1 accounts for 27.7% of the total variance of the parameters, and PC2 explains approximately 24.4% of the variance. When combined, PC1 and PC2 collectively account for 52.1% of the variance observed in all the analyzed parameters. In the PCA of management HIM, as shown in Figure 6b, PC1 accounts for 38.1% of the total variance of the parameters, while PC2 explains approximately 16% of the variance. PC1 and PC2 contribute to 54.1% of the total variance observed in all the analyzed parameters.

Figure 6a represents the PCA of MIM crop management; we observed a negative relationship in agronomic traits (GY and TGW). The quality traits (AC, CH, and GI) showed a positive relationship with each other, and SV with DS and FY with WA also showed a positive correlation. A strong negative relationship was observed between DS and DSF and between BS and DSF, and no correlation was observed between SV and CH. In grain quality traits, PC and FN displayed a strong positive correlation. In contrast, TW and SV displayed a negative correlation. Generally, a strong negative correlation was shown between TGW and FA, TW and AC, DS and DSF, and FN and WA. At the same time, a strong positive correlation was observed between GI and FA.

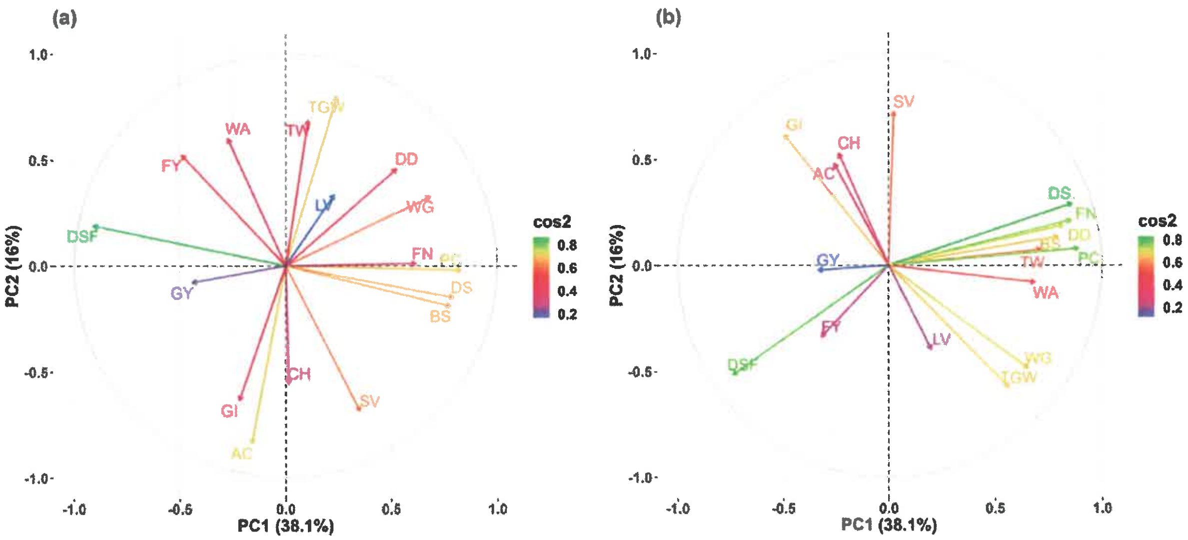

Figure 6. Principal component analysis (PCA) of moderate-input management MIM (a) and high-input management HIM (b) management for all study traits. Abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

In the PCA of management HIM (Figure 6b), agronomic traits (GY and TGW) showed a negative relationship. A positive correlation was observed between AC, GI, and CH in flour quality traits. DS, FN, FY, and DSF showed a significant positive correlation. In comparison, a significant negative correlation was observed between CH and LV. A significant negative correlation was found between PC and GY and between GY and TW. In contrast, a significant positive correlation was found between PC and TW, SV and DD, and CH and FA. In grain quality traits, TW and PC showed a strong positive correlation.

The color-coded indicator values (cos2) in Figures 2a and 2b reflect how well the variables are represented on the primary component. In the present study, the variables LV (Figure 6a) and GY (Figure 6b) had cos2 values below 0.2, suggesting that additional interpretation of these parameters may not be necessary.

4.3 Results for Winter Wheat

The average values and coefficient of variation (CV) of the investigated traits for individual locations are presented in Table 5. Grain yield ranged from 80 dt ha^{-1} (location Bialogard) to 126 dt ha^{-1} (location Lisewo). However, the variability of this trait was also strongly diversified depending on the location; the lowest variability with CV of 4.32% was observed in Jelania Góra, while the highest variability with CV of 23.60% was found in Krzyzewo. The lowest protein content was 11.28% in Jelenia Gora, whereas the highest value was 13.86% in Sulejow. The variability of this trait also strongly depended on the location, ranging from CV=4.43% in Krzyzewo to CV=14.86% in Jelenia Gora.

Table 5. Mean and coefficient of variance (CV) for winter wheat traits of trial locations across trial locations and growing seasons.

Location	Yield (t ha^{-1})		Thousand-Grain Weight (g)		Protein (%)		Falling number (s)		Zeleny Test (ml)	
	Mean	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
Bezek	9.22	12.87	46.29	8.82	13.64	6.03	350.48	24.47	90.25	6.69
Bialogard	8.042	21.18	51.21	8.33	12.66	6.01	319.19	23.87	75.46	12.88
Glubczyce	12.03	6.69	43.38	10.26	12.89	7.46	361.66	18.91	83.21	8.98
Jelenia Góra	10.02	4.32	41.91	8.68	11.28	14.86	351	15.49	79.2	9.53
Kaweczyn	9.73	9.64	46.72	15.78	13.45	12.69	377.05	18.05	86.81	7.39
Koscielna Wies	10.73	14.97	41.5	8.56	13.73	5.98	385.32	16.86	86.02	7.65
Krzyzewo	9.12	23.6	43.21	6.73	13.03	4.43	341.71	25.86	84.04	8.66
Lisewo	12.64	6.57	49.76	6.25	12.21	8.34	347.97	20.26	85.1	8.02
Pawlowice	9.36	9.82	38.43	18.7	13.11	10.63	396.45	16.15	85.34	7.43
Ruska Wies	8.72	15.35	45.5	9.64	12.91	10.17	337.22	22.13	85.6	9
Sulejów	8.57	14.97	38.91	13	13.86	5.97	405.71	11.88	80.6	12.1
Wegrzce	11.13	6.54	50.29	5.99	11.69	9.19	327.5	26.04	80.64	9.61

Table 6. Mean and coefficient of variance (CV) for winter wheat traits of cultivars across trial locations and growing seasons.

Cultivars	Yield (t ha^{-1})		Thousand-Grain Weight (g)		Protein (%)		Falling number (s)		Zeleny test (ml)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Admont	10.18	21.64	44.18	14.69	12.87	6.62	295.83	33.16	83.46	6.99
Ambicja	9.63	11.7	46.83	14.02	13.58	9.43	399	11.26	90.58	4.64
Apostel	9.92	25.95	47.65	11.6	13.02	7.34	363.22	13.53	82.11	7.96
Argument	9.39	10.68	45.52	13.02	13.4	11.04	336.42	17.83	90.88	5.96
Artist	10.45	18.07	46.68	11.85	12.39	12.15	381.91	9.24	88.82	5.62
Bataja	9.17	19.8	44.89	10.2	13.03	7.16	351.94	13.09	87.5	7.47
Blyskawica	9.98	28.15	46.45	9.64	12.58	6.17	201.56	51.5	77.34	9.07
Bonanza	11.69	7.44	47.63	10.55	11.89	9.71	337.5	26.13	78.67	10.75
Bosporus	9.84	16.36	42.26	15.72	12.68	7.71	339.56	14.97	78.61	10.15
Comandor	10.11	23.24	44.33	9.01	13.26	7.54	392.61	12.81	77.53	9.81
Euforia	10.34	25.35	45.02	9.07	13.35	6.9	398	9.95	82.17	7.58
Formacja	9.99	21.35	43.06	12.87	13.2	9.45	382.95	10.1	84.81	6.03
Hybery F1	12.03	8.4	46.28	11.12	11.63	7.27	337.67	14.2	76.08	11.51
Impresja	9.53	15.69	43.7	11.79	14.18	7.35	375.25	13.84	80.92	8.6
Kariatyda	9.67	12.54	46.12	11.77	13.7	9.42	398.33	12.61	84.04	8.71
Kometa	9.47	31.17	43.62	15.33	13.19	14.02	348.67	17.32	68.25	10.2
KWS Donovan	10.12	18.92	43.55	12.69	13.05	7.73	350.88	8.83	74.67	10.64
KWS Firebird	10.60	17.48	43.12	14.66	13.05	10.25	398.8	11.38	91.3	4.32
KWS Spencer	10.38	19.87	47.49	14.22	12.94	12.62	390.13	18	89.83	4.47
KWS Talium	9.46	12.48	41.38	12.06	13.01	10.32	384.08	15.37	87.13	9.4
KWS Universum	9.46	15.42	44.31	13.36	13.52	10.6	371.25	14.3	85.13	8.65
LG Jutta	10.52	11.61	39.78	13.09	12.03	11.19	343.75	16.35	80.42	7.47
LG Keramik	9.88	20.05	43.34	10.79	13.14	5.61	336.78	17.15	91.06	5.41
Lindbergh	10.30	22.97	46.15	9.72	12.62	10.73	353.67	14.36	75.5	5.54
Lokata	9.78	22.74	44.29	8.79	13.26	7.38	401.33	16.92	83.14	8.32
Medalistka	10.76	13.83	48.71	12.55	12.32	10.97	396.5	11.92	84.21	7.25
MHR Promienna	9.34	13.85	41.95	12.1	12.94	9.32	313.33	21.33	84.67	9.28
Moschus	9.11	21.55	45.99	8.48	14.15	7.3	428.06	8.55	90.17	4.85
Nordkap	10.38	20.8	46.08	11.52	12.96	10.28	381.5	14.47	87.46	5
Opcja	9.98	15.51	41.96	16.79	12.45	10.3	313.83	22.38	73.71	6.37
Opoka	9.63	20.39	48.56	12.49	13.41	7.01	377.94	9.46	84.63	7.67
Owacja	10.70	17.92	44.76	12.34	12.72	11.26	311.93	20.76	80.17	6.56
Patras	9.67	23.26	49.86	10.86	13.31	9.11	384.27	19.24	84.4	6.2
Plejada	10.10	28.84	46.19	9.35	12.5	7.46	362.44	15.6	79.44	10.88
Reduta	9.73	21.06	45.37	12.01	13.14	7.7	377.67	14.18	81.14	7.55
RGT Bilanz	10.93	19.83	45.29	10.31	12.49	9.2	378.93	15.92	89.9	4.28
RGT Kilimanjaro	10.24	19.64	45.15	12.76	13.3	9.27	407.9	7.97	89.98	4.85
RGT Metronom	10.34	18.1	48.51	13.41	13.4	11.31	385.6	19.99	87.93	1.97
RGT Provision	9.71	18.27	44.08	10.45	12.9	7.37	288.17	19.99	80.67	6.79

RGT Ritter	10.02	13.57	47.18	11.74	13.07	10.28	373.33	16.86	80.5	6.84
RGT Specialist	9.63	18.77	41.28	11.13	12.88	7.6	369.83	14.74	83.31	5.31
Rivero	10.62	14.45	42.55	14.48	12.22	10.6	387.75	15.07	85.88	5.31
Sfera	10.47	17.44	43.86	17.89	12.65	10.06	349.2	16.46	75.93	8.28
SU Mangold	9.94	10.84	41.45	19.95	13.27	11.26	339.83	29.61	81.88	6.66
SU Petronia	10.08	15.57	44.08	14.62	12.94	12.09	275.67	35.36	70.71	8.27
SU Tarroca	10.18	16.53	48.82	11.74	13.02	10.93	245.67	29.76	62.88	12.12
SU Viedma	9.87	19.94	46.76	15.78	13.39	8.65	284.78	22.62	80.56	10.46
SY Cellist	9.50	15.21	44.2	12.23	13.57	11.29	358.33	18.8	86.21	6.67
SY Dubaj	9.32	20.37	47.69	8.36	13.6	7.45	431.22	7.15	93.81	7.91
SY Orofino	10.21	20.33	46.45	11.14	12.71	6.66	285.28	19.98	85.39	5.44
SY Yukon	9.37	20.32	44.81	10.58	13.12	7.02	439.83	7.28	94.31	5.23
Symetria	9.34	12	38.96	14.54	13.16	9.88	412.58	6.14	80.79	8.79
Titanus	10.65	22.09	48.2	13.06	12.56	9.31	292.87	35.77	92.4	3.95
Tytanika	10.42	19.68	41.3	14.96	12.61	8.31	315.07	28.97	74.5	8.75
Venecja	9.83	18.64	46.69	13.82	13.11	5.14	376.11	10.66	89.56	5.34

The yield for the examined fifty-five varieties ranged from 91.07 dt ha^{-1} (Moschus) to 120.27 dt ha^{-1} for the Hybery cultivar (Table 6). Meanwhile, the coefficient of variation (CV) ranged from 7.44% (cultivar Bonanza) to 31.17% (cultivar Kometa). The average protein content for individual cultivars ranged from 11.63 (Hybery) to 14.18 (Impresja).

A lower value of Shukla variance reflects higher stability. Cultivars containing the least Shukla variance are ranked 1st in the Shukla stability ranking (Table 7). According to the Shukla variance, Bataja, SY Cellist, Bataja Opoka, and RGT Provision were the most stable cultivars in terms of yield, thousand-grain weight, protein, falling number, and Zeleny test, respectively. The cultivars Kometa, SU Mangold, Comandor, Błyskawica, and Plejada displayed the highest Shukla variance and were the least stable in terms of yield, thousand-grain weight, protein, falling number, and Zeleny test, respectively.

Table 7. Ranking Shukla stability variance, their cumulative ranking across all study traits, and the multi-trait stability index.

Cultivars	Ranking of Shukla Stability Variance								MTSI	
	Yield	Thousand-Grain Weight	Protein	Falling Number	Zeleny Test	Sum	Min	Max	Value	Ranking
Admont	38	44	36	54	44	216	36	54	3.85	36
Ambicja	22	20	25	31	7	105	7	31	2.77	14
Apostel	48	47	51	43	54	243	43	54	2.82	16
Argument	35	4	43	32	27	141	4	43	3.46	25
Artist	19	24	49	11	25	128	11	49	2.13	3
Bataja	1	13	1	8	14	37	1	14	3.54	27
Błyskawica	49	48	40	55	50	242	40	55	4.6	46
Bonanza	25	36	11	40	46	158	11	46	3.21	19
Bosporus	17	35	10	10	37	109	10	37	4.53	45

Comandor	32	42	55	39	49	217	32	55	3.84	35
Euforia	50	30	52	29	53	214	29	53	3.34	20
Formacja	6	3	39	22	22	92	3	39	3.78	31
Hybery F1	33	41	13	9	48	144	9	48	3.72	30
Impresja	5	29	17	35	36	122	5	36	4.64	48
Kariatyda	4	50	38	41	20	153	4	50	3.35	21
Kometa	55	32	31	33	19	170	19	55	5.28	54
KWS Donovan	8	18	22	2	31	81	2	31	4.36	42
KWS Firebird	14	14	41	7	28	104	7	41	2.69	13
KWS Spencer	41	52	44	28	40	205	28	52	2.01	2
KWS Talium	11	11	28	46	16	112	11	46	4.19	39
KWS Universum	46	40	33	16	11	146	11	46	4.1	38
LG Jutta	42	6	16	26	38	128	6	42	4.39	44
LG Keramik	44	2	15	17	6	84	2	44	3.39	24
Lindbergh	54	12	19	27	9	121	9	54	3.52	26
Lokata	40	31	54	49	52	226	31	54	3.56	28
Medalistka	37	33	12	15	43	140	12	43	1.81	1
MHR Promienna	15	5	35	37	21	113	5	37	4.73	49
Moschus	43	8	27	12	2	92	2	43	3.79	32
Nordkap	53	37	9	19	12	130	9	53	2.5	8
Opcja	51	25	14	50	18	158	14	51	4.91	50
Opoka	26	21	21	1	15	84	1	26	2.67	12
Owacja	12	26	48	36	47	169	12	48	3.84	34
Patras	31	27	7	24	3	92	3	31	2.25	5
Plejada	52	28	45	42	55	222	28	55	3.36	23
Reduta	24	49	50	44	51	218	24	51	3.71	29
RGT Bilanz	30	23	20	14	33	120	14	33	2.28	6
RGT Kilimanjaro	2	22	18	4	4	50	2	22	2.45	7
RGT Metronom	10	45	46	34	34	169	10	46	2.14	4
RGT Provision	13	16	5	23	1	58	1	23	4.32	41
RGT Ritter	3	53	23	38	32	149	3	53	2.98	18
RGT Specialist	21	7	8	21	10	67	7	21	4.26	40
Rivero	47	10	3	20	24	104	3	47	2.97	17
Sfera	9	51	32	18	41	151	9	51	4.38	43
SU Mangold	18	55	37	48	26	184	18	55	4.61	47
SU Petronia	7	43	53	52	30	185	7	53	5.38	55
SU Tarroca	20	54	42	30	39	185	20	54	5.11	52
SU Viedma	23	46	34	45	29	177	23	46	3.94	37
SY Cellist	34	1	30	25	23	113	1	34	3.83	33
SY Dubaj	28	34	4	5	13	84	4	34	2.62	11
SY Orofino	27	9	47	51	45	179	9	51	3.36	22

SY Yukon	16	17	2	6	5	46	2	17	2.78	15
Symetria	39	39	24	13	8	123	8	39	5.09	51
Titanus	45	15	29	53	35	177	15	53	2.52	9
Tytanika	29	38	26	47	42	182	26	47	5.13	53
Venecja	36	19	6	3	17	81	3	36	2.57	10

In the context of the Shukla stability variance ranking sum for cultivars with the lowest sum are considered the most stable, while those with the highest sum are regarded as least stable. Among all cultivars, Apostel had the highest stability sum (243), signifying the least stability, whereas Bataja emerged as the most stable cultivar with the lowest stability sum (37).

We performed individual Multi-Trait Selection Index (MTSI) analyses for all fifty-five winter wheat cultivars across environments created as a combination of locations and growing seasons, as outlined in Table 7. To identify the most stable performers, we applied a selection pressure of 15%. Among these cultivars, Medalistika (1.81) and KWS Spencer (2.01) emerged as the top-ranked, securing the first and second positions in terms of stability.

Between the stability of varieties measured as the Shukla stability variance ranking sum for all traits and the MTSI parameter, we observe a lack of consistency in the assessment of variety stability. Completely different varieties are considered to be multi-stable when applying the sum of rankings and MTSI parameters. This can be evidenced by a low correlation coefficient value of 0.17 (p-value <0.0001).

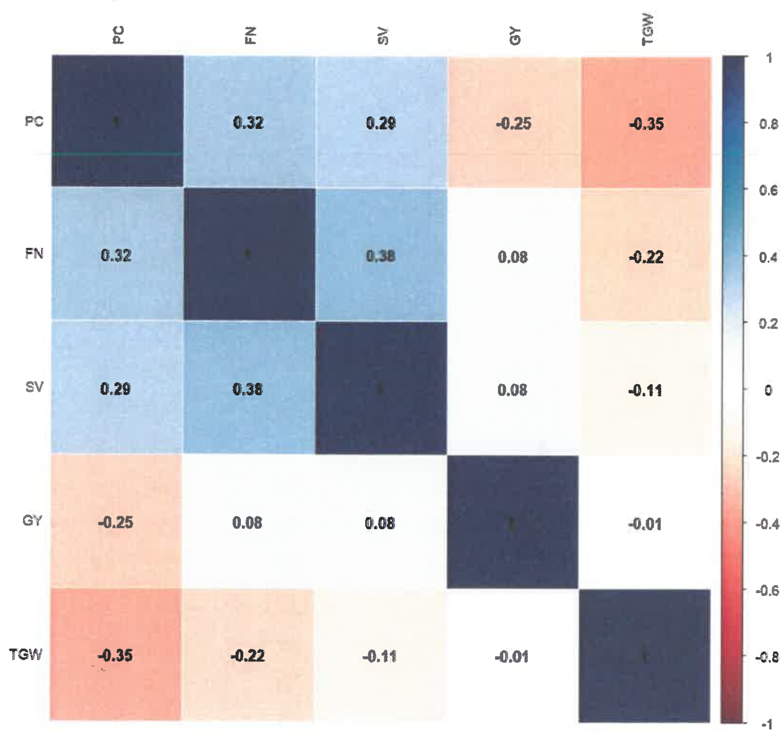

Figure 7. A correlation analysis for all study traits across genotypes and study environments. Protein content, PC, Falling number, FN; Zeleny test, ZT; Grain yield, GY; Thousand grain weight, TGW.

The strongest positive correlation was observed between the Zeleny sedimentation test and the Hagberg falling number, while a negative correlation was found between protein content and thousand-grain weight (Figure 7). We also observe a negative correlation between protein content and yield (-0.25) as well as protein content and thousand-grain weight (-0.35).

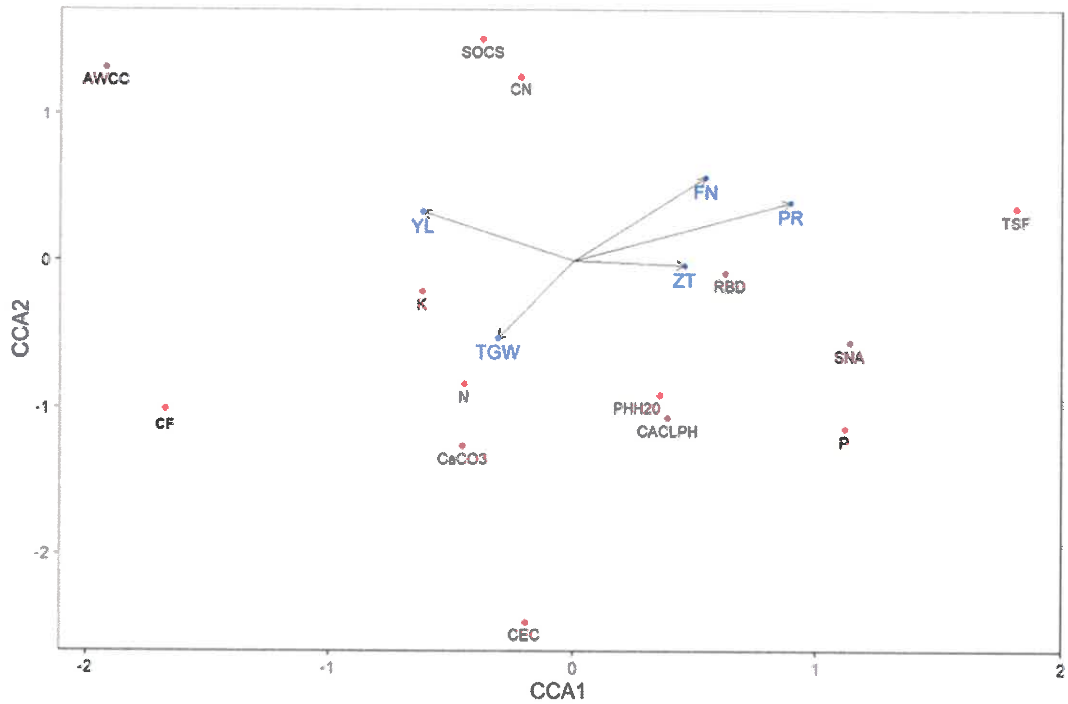

Figure 8. Biplot CCA for trial locations means of the study traits and soil characterizing locations. Reference Bulk Density, RBD; Sand Fraction, SF; Clay Fraction, CF; Soil Nutrient Availability class, SNA; Available Water Capacity class, AWCC; Soil Organic Carbon Stock, SOCS; Calcium carbonates, CaCO3; Cation Exchange Capacity, CEC; C:N, CN; Potassium content, K; Nitrogen content, N; Phosphorus content, P; pH in CaCl, CACLPH; ph in H2O, PHH20; Protein content, PC, Falling number, FN; Zeleny test, ZT; Grain yield, GY; Thousand grain weight, TGW.

In the CCA analysis (Figure 8), we observe relationships between the mean values of the studied traits in locations and the chemical and physical properties of soils in those locations (presented in Table S1). We observe a correlation between yield in the location and the Available Water Capacity class (AWCC) according to the FAO Harmonized World Soil Database and Soil Organic Carbon Stock. For TGW, there is a relationship with the clay fraction. Between traits related to grain quality such as Protein content, falling number, and Zeleny test, they exhibited a similar pattern dependent on Soil Nutrient Availability class, sand fraction, and phosphorus content.

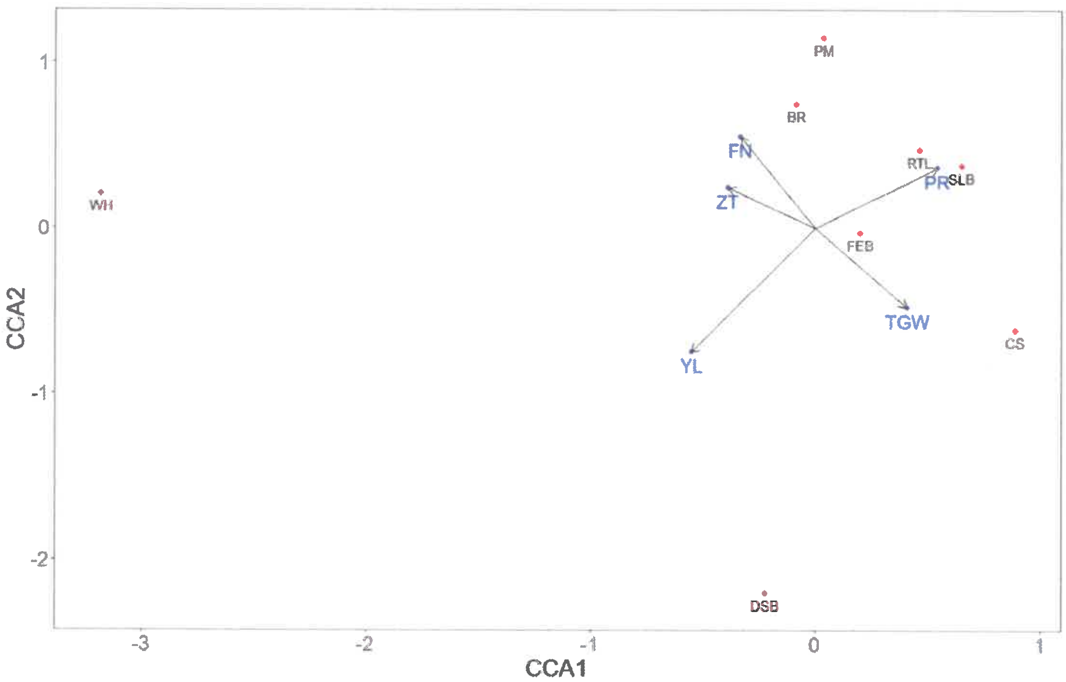

Figure 9. Biplot CCA for cultivars means of the study traits and additional traits characterizing these cultivars. Winter hardiness, WH; Resistance to lodging, RTL; Powdery mildew, PM; Brown rust, BR; Septoria leaf blight, SLB; Chaff Septoria, CS; Diseases of the stem base, DSB; Fusarium ear blight, FEB; Protein content, PC, Falling number, FN; Zeleny test, ZT; Grain yield, GY; Thousand grain weight, TGW.

Figure 9 presents the results of CCA for the mean values of study traits and evaluation of cultivars resistance (from Table S4). We observe a strong correlation between the mean values for protein content and resistance to lodging and septoria leaf blight. The mean thousand-grain weight was dependent on chaff septoria. Unfortunately, for grain yield, falling number, and Zeleny test, it is not possible to identify variables characterizing cultivars that have an impact on the values of these traits.

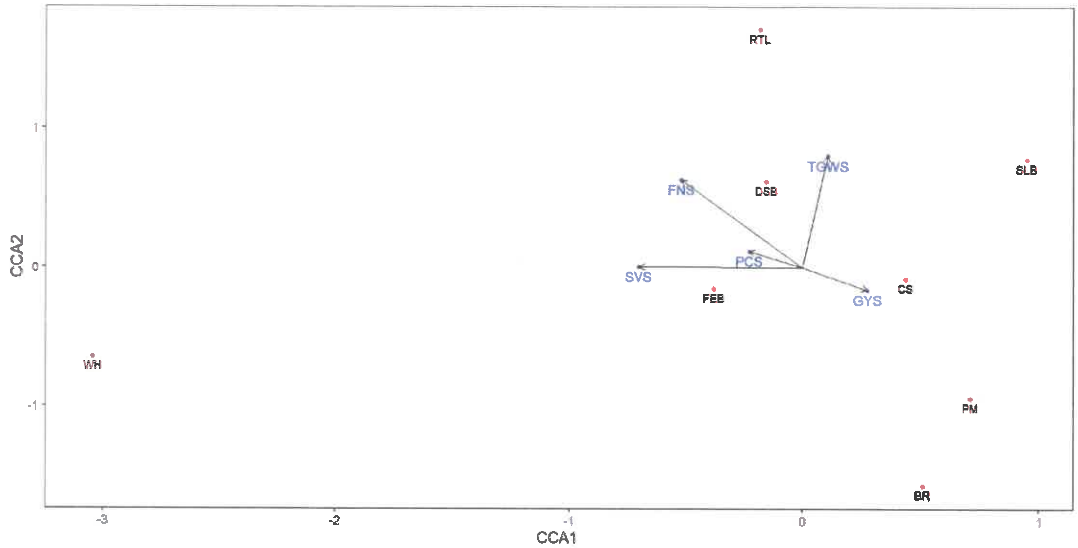

Figure 10. Biplot CCA for cultivars Shukla stability variance of study traits and additional traits characterizing these cultivars. Winter hardiness, WH; Resistance to lodging, RTL; Powdery mildew, PM; Brown rust, BR; Septoria leaf blight, SLB; Chaff Septoria, CS; Diseases of the stem base, DSB; Fusarium ear blight, FEB; Protein content Shukla stability PCS, Falling number Shukla stability, FNS, Zeleny test Shukla stability, SVS; Grain yield Shukla stability, GYS, Thousand-grain weight Shukla stability, TGWS.

Figure 10 presents the results of CCA for cultivars Shukla stability variance of study traits and additional traits characterizing cultivars. We observe a strong correlation between yield stability and resistance to chaff septoria, powdery mildew, and brown rust. Between traits related to grain quality such as protein content, falling number, and Zeleny test, we observe a positive correlation, confirming the results of Pearson correlation analysis presented in Figure 7. The stability of thousand-grain weight was dependent on resistance to lodging and diseases of the stem base. The stability of protein content and the stability of Zeleny sedimentation values were dependent on fusarium ear blight and winter hardiness.

4.3 Results for Winter Rye

The means of grain yield ranged from 6.92 t ha-1 to 9.82 t ha-1 for MIM crop management and 7.64 t ha-1 to 10.90 t ha-1 for HIM (Table 8). The mean grain yield for the tested hybrid varieties was significantly higher than the yield of the population varieties for both MIM (+1.69 t/ha, +22.5%) and HIM (+2.14 t/ha, +25.7%) (MIM – p value <0.0001; HIM – p value <0.0001, Table 9). The highest means were observed for population cultivars for thousand-grain weight in both crop managements (26.9 g for MIM, 26.8 g for HIM). The mean thousand-grain weight did not differ statistically significantly in both study crop managements (MIM – p-value 0.5997; HIM – p-value 0.5651). In terms of protein content, the highest mean in crop management was observed for population cultivars in HIM (9.10%), and in MIM (10.44%). On average, a significantly higher protein content is observed for population varieties than for hybrid cultivars; this effect is observed in both MIM (+0.58 % protein, +6.8%) and HIM (+1.09 % protein, +11.7%) (MIM – p-value <0.0001; HIM – p-value <0.0001).

Table 8. Mean value and Shukla stability variances of rye grain yield, its components, and selected grain quality traits in moderate input management crop management MIM (a) and high input crop management HIM (b) crop management at three locations in Poland, 2018/2019 and 2019/2020.

a) Moderate input crop management (MIM)

	Grain Yield ($t\ ha^{-1}$)		Thousand Grain Weight (g)		Grain Protein Content (%)		Grain Density ($kg\ hl^{-1}$)		Starch Content (%)		Number of Spikes per Head (-)		Grain Weight per Spike (g)	
Cultivars	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla
Agat	7.34b	3.53	26.7ab	0.35	8.91b	0.22	72.4a	0.48	55.0ab	0.24	555e	3396	26.7ab	0.35
Amber	7.86c	2.33	27.0b	2.98	9.23cd	0.23	73.4ab	0.83	55.7b	0.41	545d	2519	27.0b	2.98
Amilo	6.92a	3.80	26.4a	0.98	9.00bc	0.01	75.0c	0.22	54.4a	0.13	491a	1023	26.4ab	0.98
Antoninskie	7.45bc	2.19	27.4b	1.07	9.15c	0.14	73.3a	0.29	55.3b	0.26	491a	579	27.4c	1.07
Binntto†	9.67e	5.75	27.7cb	1.53	8.53a	1.17	73.9b	2.07	55.3b	2.08	605f	1053	27.7c	1.53
Diament	7.22b	0.63	26.6ab	1.21	9.14c	0.07	73.7ab	0.70	55.3b	0.07	487a	932	26.6ab	1.21
Dolaro†	9.53e	14.37	27.6b	0.64	8.41a	0.09	75.0c	0.99	55.7b	0.09	624g	4285	27.6c	0.64
Granat	8.02d	0.39	26.9ab	0.11	9.23cd	0.07	73.8b	0.17	54.8a	0.29	558e	1043	26.9b	0.11
Hadron	7.47bc	5.22	27.8cb	0.83	9.31d	0.30	73.6ab	0.41	55.6b	0.31	500b	2719	27.8c	0.83
Opal	7.21b	0.83	25.3a	0.86	8.94b	0.04	72.5a	1.10	55.4b	0.22	524c	875	25.3a	0.86
Rubin	7.88cd	0.22	27.0b	0.79	8.94b	0.01	74.0b	0.57	55.8b	0.31	547d	1357	27.0b	0.79
Serafino†	9.82e	13.53	26.6ab	3.01	8.37a	0.33	75.0c	2.09	55.7b	0.79	620g	2079	26.6ab	3.01
Skand	7.62c	1.52	26.8ab	0.72	8.94b	0.07	74.7c	0.48	55.5b	0.17	534d	1010	26.8ab	0.72
Tur†	7.72c	14.81	24.5a	2.53	8.78ab	0.73	73.0a	0.53	54.8a	0.68	518c	5834	24.5a	2.53
Turkus	7.54bc	8.61	28.0c	1.54	9.30d	0.07	73.8b	1.75	55.5b	0.17	520c	1342	28.0c	1.54

b) High input crop management (HIM)

	Grain Yield ($t\ ha^{-1}$)		Thousand Grain Weight (g)		Grain Protein Content (%)		Grain Density ($kg\ hl^{-1}$)		Starch Content (%)		Number of Spikes per Head (-)		Grain Weight per Spike (g)	
Cultivars	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla	Mean	Shukla
Agat	8.31b	0.421	26.0ab	0.418	10.4c	0.02	71.6b	1.73	53.6a	0.02	610d	551	26.0ab	0.42
Amber	8.43b	4.678	27.3b	0.525	10.4c	0.29	72.6b	3.16	54.5b	0.32	588c	3400	27.3b	0.53
Amilo	7.94ab	3.204	27.4b	2.65	10.2c	0.85	73.9bc	0.08	53.7a	2.18	547b	1781	27.4bc	2.65
Antoninskie	7.64a	1.939	27.2b	2.19	10.7c	0.52	72.4b	0.40	53.9a	0.34	513a	2376	27.2b	2.19
Binntto†	10.68d	14.681	27.1b	4.87	9.27ab	0.23	72.2b	1.50	54.6b	0.50	705g	4621	27.1b	4.87

Diament	8.03ab	1.412	27.0b	3.12	10.6c	0.10	66.4a	222	53.9a	0.11	516a	1662	27b	3.12
Dolaro†	10.90e	11.886	27.2b	2.75	9.3ab	0.25	74.4c	2.37	54.6b	0.46	664e	2585	27.2b	2.75
Granat	8.45b	2.841	25.5ab	1.84	10.5c	0.01	72.6b	0.14	53.4a	0.06	588c	2346	25.5a	1.84
Hadron	8.43b	1.878	27.7b	0.466	10.4c	0.58	72.3b	3.41	54.2ab	1.02	586c	549	27.7c	0.47
Opal	8.01ab	1.47	24.2a	1.52	10.4c	0.16	70.9b	0.74	53.4a	0.33	578bc	1251	24.2a	1.52
Rubin	8.47b	1.775	26.7b	0.405	10.6c	0.21	72.6b	3.68	53.8a	0.50	565b	2201	26.7b	0.41
Serafino†	10.81e	5.617	25.3ab	0.147	9.16a	0.30	74.1bc	2.90	54.8c	0.86	680f	405	25.3a	0.15
Skand	8.52b	10.583	26.8b	3.86	10.3c	0.08	73.9bc	2.78	54.2ab	0.52	538b	4995	26.8b	3.86
Tur†	9.35c	4.861	25.9ab	2.09	9.66b	0.71	71.8b	1.23	54.2ab	0.51	562b	2640	25.9ab	2.09
Turkus	9.1c	0.734	28.6c	3.99	10.3c	0.14	73.8bc	0.36	54.1ab	0.20	569b	562	28.6d	3.99

† Hybrid cultivar

Table 9. Comparison of rye population and hybrid cultivars across crop management system for grain yield, gain quality, and yield components at three locations in Poland, averaged for 2018/2019 and 2019/2020

Mean		Grain Yield (t ha^{-1})	Thousand Grain Weight (g)	Grain Protein Content (%)	Grain Density (kg hl^{-1})	Starch Content (%)	Number of Spikes per Head (-)	Grain Weight per Spike (g)
Moderate input crop management (MIM)	Population cultivars	7.50	26.9	9.10	73.7	55.3	523	26.9
	Hybrid cultivars	9.19	26.6	8.52	74.2	55.4	592	26.6
	p value	<0.0001	0.5997	<0.0001	0.2607	0.7643	0.0039	0.5997
High input crop management (HIM)	Population cultivars	8.30	26.8	10.44	72.1	53.9	563	26.8
	Hybrid cultivars	10.44	26.4	9.35	73.1	54.6	653	26.4
	p value	<0.0001	0.5652	<0.0001	0.3811	0.0041	0.0024	0.5652
Population cultivars		7.90	26.8	9.77	72.9	54.6	543	26.8
Hybrid cultivars		9.81	26.5	8.94	73.7	55.0	622	26.5
p value		<0.0001	0.6632	0.0032	0.2819	0.8803	<0.0001	0.6615
Moderate input crop management (MIM)		7.95	26.82	8.95	73.8	55.3	541	26.8
High input crop management (HIM)		8.87	26.66	10.15	72.4	54.1	587	26.7
p value		<0.0001	0.6811	<0.0001	0.3091	0.8221	0.0021	0.6221

The contribution of yield components to rye grain yield variation was evaluated using the path analysis (Figure 11). The influence of study yield components on the yield was very similar for both crop management and in both cultivar types. The number of spikes had the strongest influence on yield, and this component explained about 50% of yield variability. The second was thousand-grain weight, which explained, regardless of the applied crop management and type of variety, about 35% of rye yield variation. Rye yield was least affected by the number of grains per spike by 15%. All path coefficients in both crop managements and in both types of cultivar were significant. The relationships between the yield components (correlation coefficient) depended on the type of cultivar used. For population cultivars, we observe only a statistically significant positive correlation between the number of grains per spike and thousand-grain weight in both crop management (0.288 for MIM and 0.296 for HIM). Other correlations between the yield components were not statistically significant. The relationships between the components of hybrid cultivars depended on crop management. For MIM crop management, we observe a significant negative correlation between the number of grains per spike and thousand-grain weight. While for HIM, the only significant correlation was the relationship between the number of spikes and the number of grains per spike (-0.323).

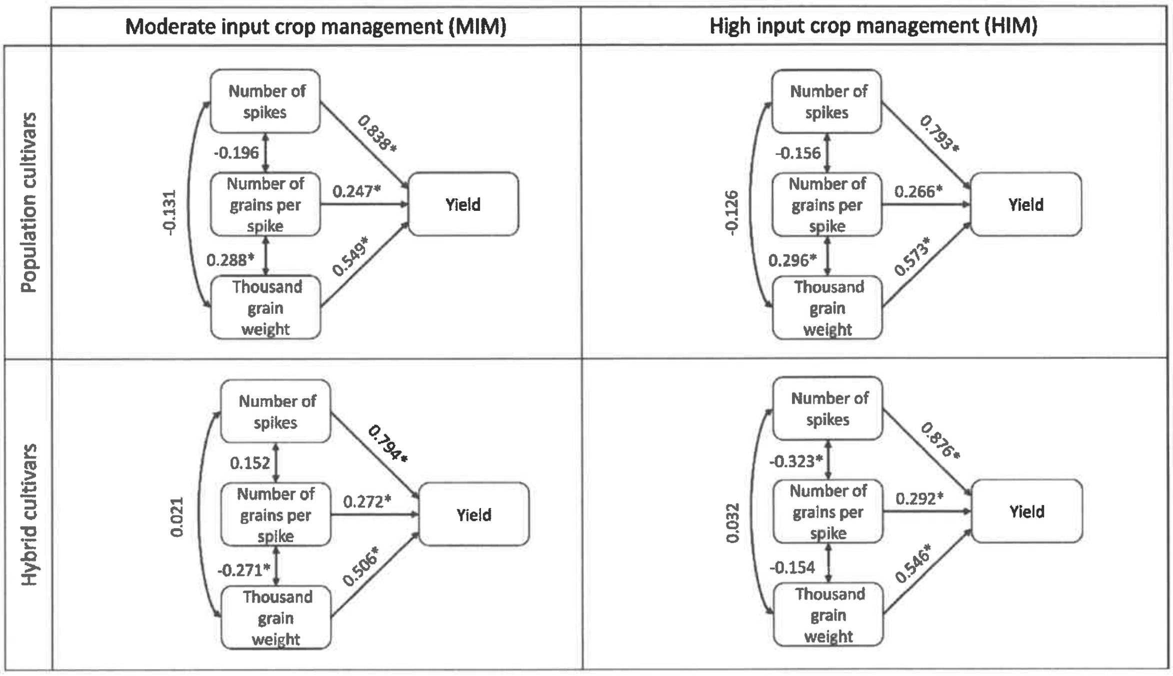

Figure 11. Path analysis diagrams show the direct influence (single-headed arrow) on rye grain yield, its components, and the correlation (double-headed arrow) between yield components in two crop managements and type of cultivars among three locations in Poland (2018/2019, 2019/2020) {*Significant value of path coefficient or correlation coefficient at $\alpha=0.05$.}

In MIM crop management, population cultivar Rubin was the most stable regarding grain yield according to the Shukla stability variance (Table 8a). The stability ranking of study traits of the cultivars is shown in Supplementary material Table S8. Moreover, in accordance with this stability parameter, the lowest stability cultivar was hybrid (Tur, even with a higher mean yield than population cultivars). The higher grain yield of hybrid cultivar (Serafino) possesses the 13th stability ranking. According to the Shukla variance in HIM crop management similar to MIM crop management, population cultivars were the most stable cultivars in terms of grain yield, and the most unstable was the hybrid cultivar (Binntto).

We compared compatibility cultivars order between MIM and HIM crop management for Shukla stability variance for grain yield. They are in a completely different order. Spearman's rank correlation coefficient can be used to measure its compatibility; in this case, it was 0.21 ($p=0.4131$).

Regarding protein content, the lowest values of Shukla variance were in population cultivars. The greatest value of Shukla variance was in hybrid cultivars, which indicated more hybrid instability than population cultivars. At the same time, consideration of Shukla variance and mean protein content revealed that population cultivars ranked least and higher in protein content than hybrid cultivars. All population cultivars showed lower Shukla variance of grain density, starch content, number of spikes, and grain weight per spike except Turkus, which displayed the highest stability (ranked 1st in stability ranking). While all hybrid cultivars except

Binntto and Turkus (population cultivars) showed higher Shukla variance and less stability than other cultivars. Overall, for MIM crop management, the sum of ranking Shukla stability variance across all study traits hybrid cultivars were less stable than population cultivars.

In the HIM crop management, we observed differences in stability between population and hybrid cultivars. Population cultivars generally exhibited lower Shukla variance, indicating higher stability. However, hybrid cultivars are less stable, which may be due to the greater sensitivity of this type of cultivars to weather conditions.

A comparison of the order of cultivars for the sum ranking of cultivars based on Shukla stability variance across all study traits and between the crop managements is presented in Figure 12. The greatest decrease/increase was observed for the Skand population cultivars, which for MIM was second in terms of stability, while for HIM, it was last. The concordance of cultivar order for sum of rankings for all features of Shukla stability variance between MIN and HIM crop managements measured by the Spearman correlation was 0.19, but this coefficient was insignificant.

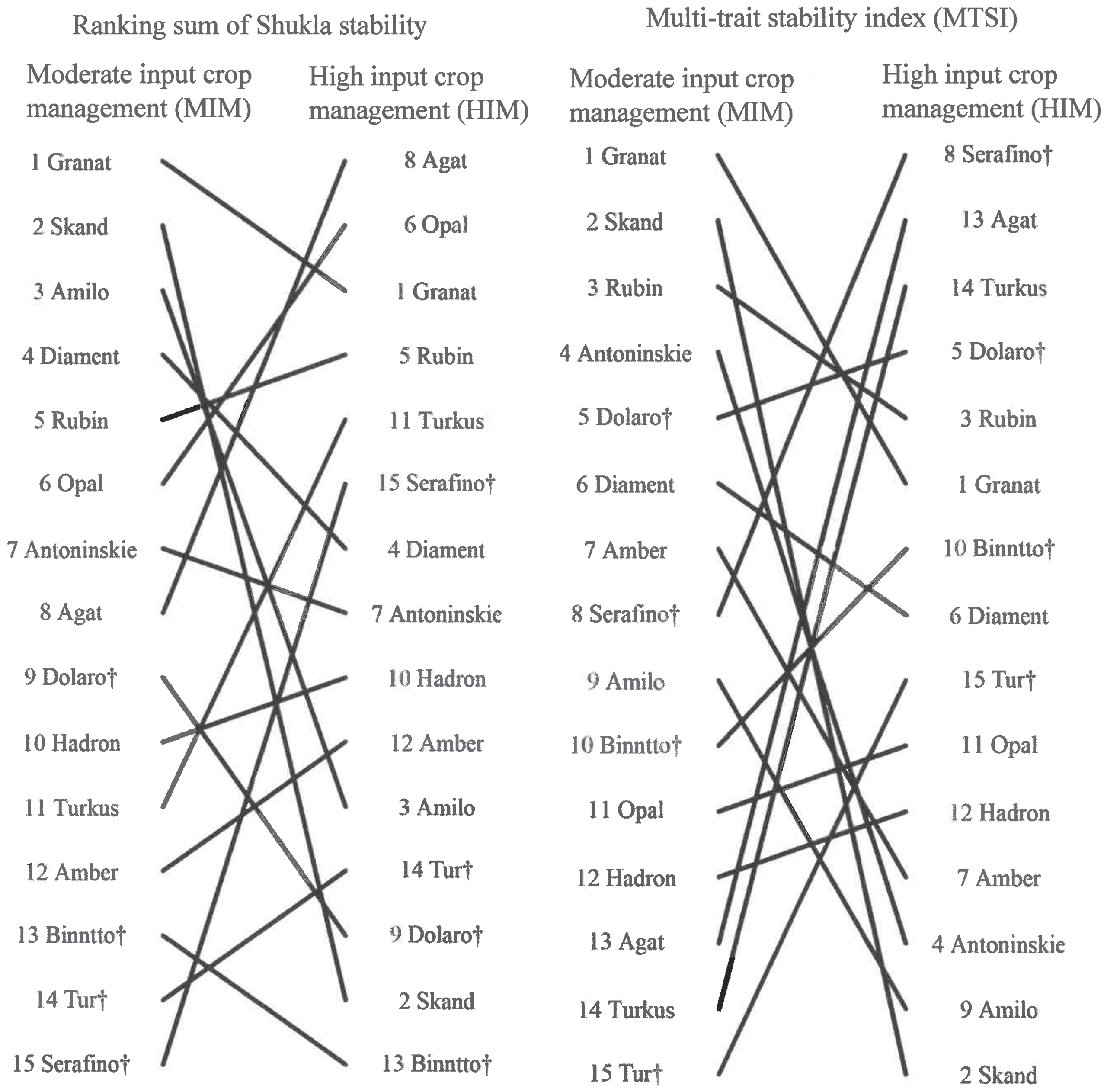

Figure 12. The comparison of rye cultivar's order of the values for ranking sum Shukla stability variance and multi-trait stability index (MTSI) parameter across study traits in moderate input management crop management MIM and high input crop management HIM for three locations in Poland (2018/2019, 2019/2020) † hybrid cultivar

Table 8 represents the MTSI of yield, its components, and grain quality traits. In this experiment, the two top-performing cultivars for MTSI in MIM crop management were selected using a 15% selection pressure. The improvement in traits is expressed as selection differentials. In both managements, populations performed well versus hybrids. The concordance of cultivar order for sum of rankings for MTSI between MIM and HIM crop management measured by the Spearman correlation was -0.20, but this coefficient was not significant.

Comparing the order of cultivars for MIM crop management for stability assessments between the sum of ranks of Shukla variance and MSTI, the agreement was relatively high, and the value of the Spearman correlation was 0.63 (p=0.0023). On the other hand, for HIM crop management, the value for agreement of the order of cultivars between stability parameters was 0.50 (p=0.0167).

To determine the most important characteristics of winter rye cultivars based on an official registration study in affecting the sum of ranking Shukla stability variance or MTSI value, a regression tree was fitted using the CART method. These results for MIM and HIM crop management are presented in Figure 13. The residency of septoria leaf blotch was the most important predictor in explaining the sum of ranking Shukla stability variance in both study crop management. The value of residency for septoria leaf blotch greater than around 7 in a 9-point scale (9 being the most favorable condition, 1 being the least favorable condition) resulted in the smaller means the sum of ranking Shukla stability variance (47 in MIM, 51 in HIM) then that is less resistant to this disease – lower than 7 (81 in MIM, 75 in HIM). The MIM crop management group of highest residence for septoria leaf blotch was further divided by the resistance to stem-based diseases. Cultivars characterized by values greater than or equal to 7.4 have a lower mean value of the sum of ranking Shukla stability variance. On the other hand, for HIM, the second important variable is time to fully ripe, and the most stable were those cultivars that had less than 200 days to this development phase.

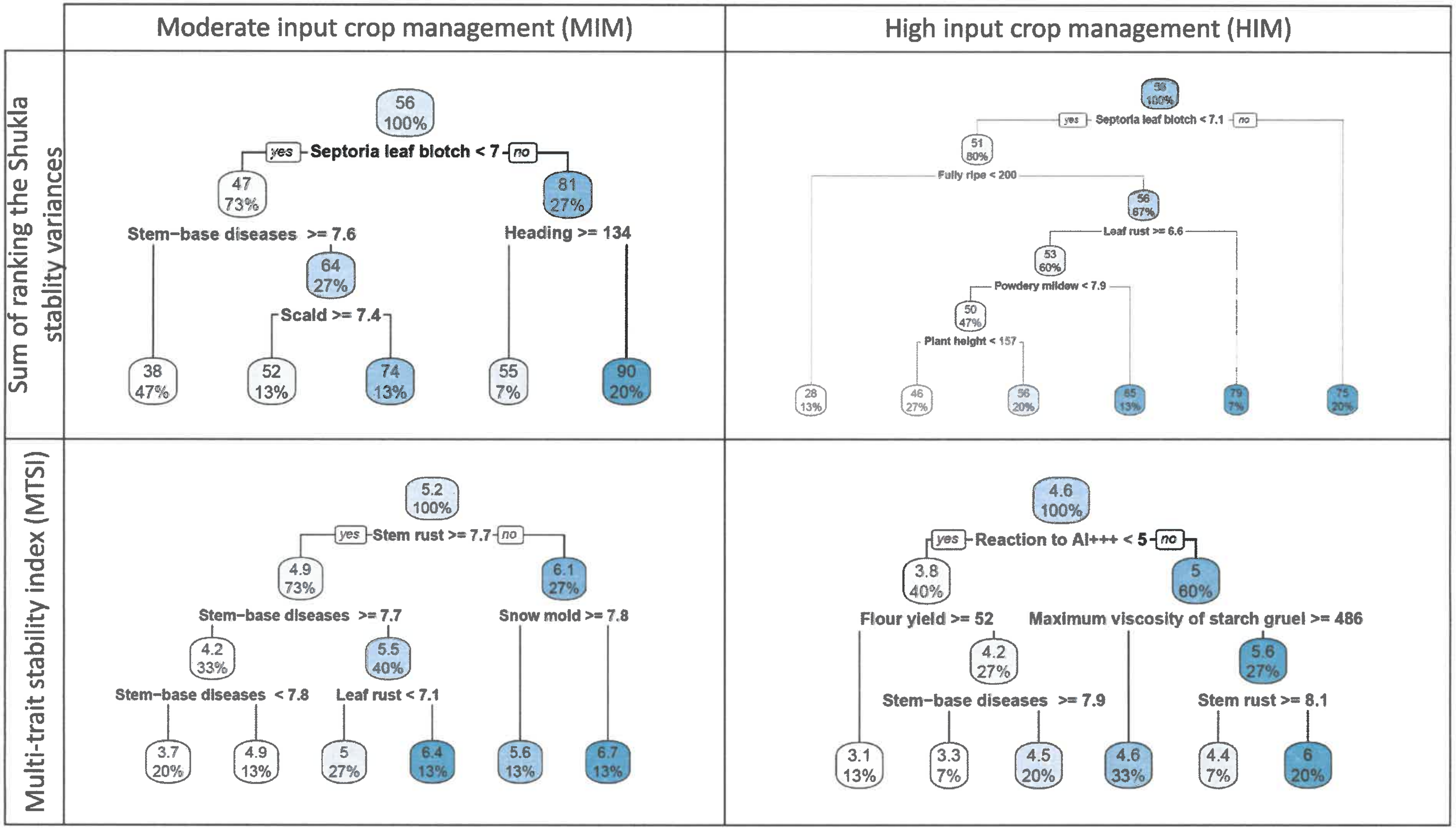

Figure 13. Regression tree based on the CART method predicting the value of the sum of ranking Shukla stability variance and MTSI from characteristics of winter rye cultivars grown at three locations in Poland (2018/2019, 2019/2020). In the box, the first line presents the mean value of stability parameters, and the second line shows the percentage of cultivars included in each group.

The explanation of the value of MTSI by characteristics of winter rye cultivars based on official registration using the CART method was dependent on crop management. For lower intensity crop management MIM, the variable MTSI variability the most was residence on stem rust. Cultivars with a value greater or equal to 7.7 on a 9-point scale resulted in smaller means of the MTSI. Then, the subset with greater residence on stem rust was further divided by resistance to stem-base diseases. When it was higher or equal than 7.7, the cultivars had a lower value of MTSI than those with a small resistance value on stem-base diseases. When examining MTSI value in HIM crop management, the most contributing variable was a reaction to aluminum. When it was higher than 5 on a 9-point scale, cultivars had more stability across considerate traits (lower mean value of MTSI).

CHAPTER V DISCUSSION

5.1 Overview

This chapter discusses the performance and stability of wheat (spring and winter) and rye cultivars under varying agronomic practices and environmental conditions. It integrates genotype-environment interactions (GEI), the role of crop management intensity, and the efficacy of multi-trait selection tools, primarily the Multi-Trait Stability Index (MTSI) and Shukla's stability variance. The discussion draws on multi-environment trial results and focuses on key traits such as grain yield, protein content, and dough/baking quality indicators. Crop-specific differences and implications for breeding strategies in the context of climate variability are also explored.

5.2 Discussion - Spring Wheat

Our study explored the interaction between genotype, environment, and crop management in shaping the yield and quality traits of seven spring wheat cultivars, evaluated under moderate-input (MIM) and high-input (HIM) systems across four locations and two growing seasons. Grain yield variability was strongly governed by the interaction of location and growing season, accounting for approximately 50% of total variation. This high interaction effect complicates predictive yield modeling and highlights the unpredictability of spring wheat performance across environments. The crop management system alone contributed about 25% to yield variation, indicating its substantial role, which has not been as extensively reported in previous trials. Although numerous studies on winter and durum wheat have confirmed the dominant influence of environment and its interactions (Johansson et al., 2020; Mitura, Cacak-Pietrzak, Feledyn-Szewczyk, Szablewski, & Studnicki, 2023; Rozbicki et al., 2015; Srivastav, Dhyani, Ranjan, Madhav, & Sillanpää, 2021). However, our findings emphasize a relatively larger-than-usual impact of crop management, which has not been fully explored in past spring wheat trials.

Protein content (PC), a core trait for evaluating the milling and baking quality of wheat (Dziki et al., 2017; Mitura et al., 2023), was largely influenced by environmental conditions, with only about 10% of its variability attributed to genotype. This is expected, considering PC's dependence on nitrogen availability and temperature conditions during grain filling. The gluten-forming proteins, gliadins and glutenins, which together form the viscoelastic dough matrix upon hydration (Khan, 2016; Mitura et al., 2023). Furthermore, the complex four-way interaction of year × location × genotype × crop management significantly influenced PC, WG, and GI, complicating the development of universal recommendations. As previously reported by Dziki et al. (Dziki et al., 2017) and supported by our findings, the considerable influence of genotype on gluten-related traits indicates that cultivar selection must account for both performance and stability under specific agronomic conditions.

Crop management had a particularly strong effect on dough properties, especially dough stability (DS), where it accounted for approximately 45% of observed variability. Similarly, parameters such as water absorption (WA) and quality number (QN) were also significantly shaped by input level. These findings are especially important given that WA directly impacts dough productivity and thus the economic viability of bakery operations (Wysocka, Cacak-Pietrzak, Feledyn-Szewczyk, & Studnicki, 2024). Understanding that traits such as WA and QN are responsive to crop management allows producers to mitigate the effects of environmental stress through more intensive or targeted agronomic interventions.

Notably, wider genotypic variation was observed for WG and GI, consistent with findings by Sułek *et al.* (Sułek et al., 2023) and Feledyn-Szewczyk et al. (Feledyn-Szewczyk, Cacak-Pietrzak, Lenc, Gromadzka, & Dziki, 2021) in spring wheat, and Ma et al. (Rabanus-Wallace et al., 2021) and Rozbicki et al. (Rozbicki et al., 2015) in winter wheat. Falling number (FN), a trait indicative of amylase activity and grain maturity, was also primarily influenced by genotype, a result mirrored by studies in Poland and India (Farhad et al., 2022; Sułek et al., 2023). Nonetheless, in our trial, environmental interactions (year and location) contributed about 60% to FN variability, similar to earlier reports in temperate winter wheat (Rozbicki et al., 2015) and spring wheat (Mitura et al., 2023). For loaf volume (LV), the most substantial sources of variability were crop management and its interaction with location, jointly explaining nearly 80% of total variance. These dependencies are consistent with previous findings in both spring and winter wheat. (Rozbicki et al., 2015; Wysocka et al., 2024).

Using the Multi-Trait Stability Index (MTSI), we separately analyzed cultivar stability under MIM and HIM systems across agronomic, flour, dough, and bread traits. The MTSI analysis revealed that different cultivars exhibited stability under different input regimes, and correlation coefficients between MIM and HIM rankings were low. This indicates that multi-trait stability is highly dependent on the crop management system employed. The cultivar Bombona stood out as it was the most stable under MIM and second most stable under HIM, highlighting its potential for use in breeding programs aimed at developing multi-trait stable wheat cultivars for both low- and high-input systems.

Under MIM conditions, negative correlations between WA and sedimentation value (SV) suggested that cultivars with lower water absorption and dough softening have higher baking quality scores (Khan, 2016). In contrast, under HIM, the positive correlation between dough development (DD) and DS indicates a stronger link between dough formation and its mechanical strength. The DSF trait, indicative of dough weakening, tended to be lower in genotypes with a favorable glutenin-to-gliadin ratio (Khan, 2016). Additional correlations, such as between flour ash (FA), crumb hardness (CH), and GI, imply that stronger gluten structure and protein levels correlate with higher mineral content, a finding consistent with durum wheat (Ficco et al., 2020) and dough strength studies (Indrani, Manohar, Rajiv, & Rao, 2007). Moreover, HIM systems tended to enhance PC and WG, which in turn improved WA and dough properties (Zhang et al., 2017).

In HIM systems, a strong positive correlation between TGW and PC suggested that larger kernels tend to accumulate more protein (Khan, 2016). However, negative correlations between TGW or grain yield (GY) and several quality parameters highlighted the common trade-off between productivity and quality. Managing this balance is a key breeding objective. For instance, the positive relationship between FY and WA indicates that genotypes producing higher flour yields also tend to have greater water absorption capacity, possibly due to higher dietary fiber content (Miś, Nawrocka, & Dziki, 2017; Warechowska, Markowska, Warechowski, Miś, & Nawrocka, 2016).

Importantly, we observed significant differences in trait interrelationships between MIM and HIM systems. Under HIM, stronger negative correlations were seen between GY and PC, as well as between PC and FN, indicating greater sensitivity of PC to productivity in high-input systems. Some trait relationships even reversed direction across management systems, for example, PC and WA were positively correlated under MIM but negatively under HIM. These shifts may result from differences in biotic and abiotic stress buffering, as HIM systems typically involve optimized fertilization and crop protection. While dissecting the effect of individual input elements would require a separate experimental design, our results clearly demonstrate that the type and intensity of crop management substantially alter both trait expression and interdependence.

5.3 Discussion - Winter Wheat

Assessing the phenotypic stability of winter wheat cultivars is a critical consideration for both genetic progress and agronomic adaptation, particularly in the face of increasing climate variability (Macholdt, Gyldengren, Diamantopoulos, & Styczen, 2020; Macholdt & Honermeier, 2017). Stability analysis not only aids in identifying genotypes best suited for specific environmental conditions and management regimes but also plays a central role in cultivar recommendation systems implemented by national testing agencies and producer organizations (Pennacchi et al., 2019). Although these recommendations are often regionally tailored and temporally constrained due to rapid cultivar turnover, broader insights into the traits contributing to stability can yield valuable information for breeders and researchers (Fadda & Van Etten, 2019).

In this study, we employed both univariate and multivariate statistical approaches to evaluate stability across multiple traits, with a particular emphasis on integrating agronomic and grain quality parameters. The use of Shukla's stability variance allowed for trait-specific stability rankings, while summing these rankings across all traits provided a synthetic measure of overall cultivar stability. However, this additive method is limited by the potential masking of instability in certain traits when overall rankings are averaged. To address this, we also reported the minimum and maximum stability rankings for each cultivar to better capture trait-specific vulnerabilities. Furthermore, we applied the Multi-Trait Stability Index (MTSI), a factor analysis-based model that condenses multi-trait stability into a single value, thus facilitating robust genotype comparison (Olivoto, Lúcio, da Silva, Sari, & Diel, 2019). Notably, we observed a low level of agreement between the MTSI values and summed Shukla rankings, a discrepancy that mirrors earlier findings in stability studies across species and environments (Greveniotis et al., 2023).

Despite methodological differences, certain cultivars consistently emerged as stable across evaluation methods. For example, Bataja and SY Yukon were among the most stable based on summed Shukla rankings, while Medalistika and KWS Spencer ranked highest using the MTSI parameter. These genotypes hold promise as potential donor lines in breeding programs focused on developing high-performing and climate-resilient cultivars.

To further investigate the factors contributing to trait stability, we applied canonical correspondence analysis (CCA), which linked trait performance with cultivar characteristics. The analysis revealed strong associations between protein content and resistance to lodging and septoria leaf blight, suggesting that disease resistance contributes to protein trait stability in winter wheat (El Chami et al., 2023; Luckert, Toubia-Rahme, Steffenson, Choo, & Molnar, 2012). In contrast, grain yield stability could not be directly linked to any of the available cultivar descriptors, likely due to a limited number of genotypic traits included in the analysis. Nevertheless, this highlights the need to expand trait databases for more effective modeling in future studies.

In examining the environmental modulation of stability, the CCA results also indicated that disease resistance plays a key role in stabilizing grain yield. Specifically, resistance to chaff septoria, powdery mildew, and brown rust emerged as critical determinants of yield stability under fluctuating weather conditions (Prahl, Klink, Hasler, Verreet, & Birr, 2023; Te Beest, Paveley, Shaw, & Van Den Bosch, 2008). Cultivars with enhanced resistance to these fungal diseases exhibited reduced yield variability, reinforcing the importance of disease-resistance breeding for agronomic stability. On the other hand, for grain quality traits, winter hardiness was a decisive factor in maintaining consistent performance across environments. Cultivars with strong post-winter health retained stable protein and functional quality traits regardless of seasonal fluctuations, while those with poor winter survival exhibited highly variable trait expression.

Understanding which cultivar characteristics influence both traits means and their stability is essential for guiding phenotype-based and molecular breeding programs. While some characteristics, such as disease resistance or winter hardiness, were linked to either trait performance or stability, others showed differential associations, complicating the selection process. Ideally, traits contributing to high mean performance would also promote stability; however, the observed divergence emphasizes the need for trait-specific selection strategies. By focusing on the selection of traits that promote stability, either directly or through the use of associated molecular markers, breeding efficiency can be significantly improved (Happ et al., 2021; Kraakman, Niks, Van den Berg, Stam, & Van Eeuwijk, 2004; Xavier et al., 2018).

5.4 Discussion - Winter Rye

Our multi-environment evaluation revealed a consistent and significant yield advantage of hybrid rye cultivars over their population counterparts, with an average increase of approximately 24.2%, irrespective of the crop management system applied. This finding aligns well with prior national and European studies. For instance, Laidig et al. (Laidig et al., 2017) reported an 18.1% yield improvement in hybrid rye cultivars in German registration trials, while similar advantages of hybrid breeding have been documented for other cereals such as wheat, with ~5.5% yield increases observed in southeastern Germany ((Prey, Kipp, Hu, & Schmidhalter, 2019). The superiority of hybrid rye cultivars was further corroborated by Kučerová (KučeroVá, 2009), who demonstrated that hybrid cultivar Picasso outperformed open-pollinated lines such as Dankowskie Nowe and Selgo in grain yield, thousand-grain weight, and kernel uniformity under Czech agroecological conditions. These collective findings confirm the reliability of hybrid vigor in boosting productivity across different environments and management intensities.

While hybrid cultivars demonstrated clear advantages in terms of grain yield, this increase came at the cost of reduced grain protein content when compared to population cultivars. The extent of protein reduction varied with crop management intensity, approximately 3% under moderate-input management (MIM) and up to 6.5% under high-input management (HIM). These findings reflect the well-documented negative correlation between grain yield and protein content, particularly in cereal crops managed under high nitrogen regimes. In our study, additional nitrogen fertilization under HIM conditions did not mitigate the decline in protein content for hybrids, emphasizing the physiological trade-offs associated with increased sink strength for carbohydrate accumulation. Given rye's continued relevance in bread production throughout Europe, this decline in protein quality highlights a key challenge in breeding: reconciling productivity gains with nutritional quality. Enhancing the bioactive and nutritional composition of rye, while accounting for both genetic and agronomic influences, remains a priority for sustainable food systems and global food security initiatives.

Understanding the mechanisms underlying the yield advantage of hybrid cultivars requires a closer look at yield formation and the relative importance of its components. Our results revealed no substantial differences between hybrid and population cultivars in terms of how yield components, number of spikes per square meter, grains per spike, and thousand-grain weight, contributed to final yield. This pattern remained consistent under both MIM and HIM systems, with the number of spikes emerging as the most influential component, followed by thousand-grain weight, and finally grains per spike. Such a hierarchy aligns with previously reported findings in cereals grown in temperate climates (Chmielewski & Köhn, 2000; Zając et al., 2014). However, hybrid cultivars grown under HIM exhibited altered interdependencies among yield components, likely due to compensatory mechanisms enabled by enhanced nitrogen availability. This suggests that hybrids may be better able to modulate internal resource allocation under favorable conditions, supporting previous theories on yield component compensation and plasticity under intensive inputs (Makary, Schulz, Müller, & Pekrun, 2020; Sadras & Slafer, 2012; Slafer, Savin, & Sadras, 2014; Xiong, Tang, Zhong, He, & Chen, 2018).

In evaluating the stability of rye cultivars, both trait-specific and multi-trait approaches were employed using Shukla's stability variance and the Multi-Trait Stability Index (MTSI). When ranked using Shukla's variance for grain yield alone, hybrid cultivars displayed noticeably lower stability, occupying the lowest positions among the tested genotypes. This outcome is understandable, as higher yielding cultivars often exhibit greater variability due to a broader range of responses across environments. Consequently, comparing stability across all cultivar types without stratification can be misleading. Ideally, separate assessments should be conducted for hybrid and population cultivars to capture true relative stability within each genetic group. Nevertheless, the multi-trait approach offered additional insights. The sum of Shukla's variances across traits provided a simple, interpretable measure of overall cultivar stability, while the MTSI method, based on factor analysis, allowed for a more integrated analysis of performance and stability (Olivoto et al., 2019). Under MIM conditions, both methods yielded similar stability rankings, particularly for the top-performing cultivars, suggesting limited differentiation due to lower trait variability. In contrast, under HIM conditions, the rankings diverged more substantially, reflecting the increased genetic expression and trait differentiation that accompany higher input intensities.

The comparative analysis of multi-trait stability under different crop management levels revealed clear distinctions between hybrid and population cultivars. Under the moderate-input MIM system, characterized by average fertilization and limited plant protection, population cultivars exhibited greater overall stability across the evaluated traits. This reflects their suitability for low-input systems, such as those found in Poland and Canada, where rye is commonly grown on marginal soils and with minimal investment (Wilde, Schmiedchen, Menzel, Gordillo, & Brian Fowler, 2017). In these regions, the economic feasibility of hybrid technology is limited. Conversely, under the high-input HIM system, hybrid cultivars outperformed population types in terms of both trait expression and multi-trait stability. In fact, one hybrid cultivar ranked first using the MTSI measure. This suggests that under optimized agronomic conditions, hybrids can realize their full genetic potential, not only achieving higher yields but also doing so consistently across multiple quality and agronomic traits. These results underscore the importance of tailoring cultivar recommendations to specific management intensities and production goals.

CHAPTER VI CONCLUSIONS

This study investigated the stability, performance, and trait interdependencies of spring wheat, winter wheat, and winter rye cultivars under varying environmental and crop management conditions. Through multi-environment trials and the application of both univariate and multivariate statistical techniques, we demonstrated that genotype-by-environment interactions and management practices are central to shaping both yield and quality outcomes in cereal crops (confirming H1). The integration of the Multi-Trait Stability Index (MTSI) and other statistical tools provided a robust framework for identifying cultivars with desirable agronomic and quality traits across contrasting conditions (supporting H2).

In spring wheat, significant genotype × environment × management interactions were observed for yield and key bread-making traits. High-input systems improved yield and protein content, whereas moderate-input systems favored traits like loaf volume and dough quality. The MTSI revealed variability in cultivar stability depending on management intensity, highlighting the need for breeding programs to prioritize multi-trait stability for reliable performance across climatic and agronomic gradients (reinforcing H1 and H2).

In winter wheat, the discussion emphasized not only identifying stable genotypes but also understanding the underlying traits contributing to that stability. Grain yield stability was primarily influenced by resistance to chaff septoria, powdery mildew, and brown rust, whereas grain quality trait stability was linked to winter hardiness. The application of canonical correspondence analysis (CCA) proved effective in establishing relationships between cultivar characteristics and trait stability, recommending a path forward for more informed selection strategies in winter wheat breeding under temperate conditions (supporting H3).

In winter rye, hybrid cultivars consistently yielded higher than population cultivars, irrespective of crop management intensity. However, this yield advantage was accompanied by reduced protein content, particularly under high-input systems, reinforcing the common yield–quality trade-off. The number of spikes emerged as the most influential yield component across cultivar types and management levels. Stability assessments using Shukla's variance and MTSI showed that hybrid cultivars were generally less stable under moderate-input systems but could outperform population cultivars in stability under intensive management when coupled with traits like aluminum resistance. The CART analysis emphasized that resistance to fungal diseases and soil acidification are key determinants of stability, depending on the level of cultivation intensity (affirming H3).

Our findings underscore the complexity of breeding and recommending cultivars that are both high-yielding and stable across environments. It is clear that stability is not an intrinsic cultivar property, but one shaped by a combination of genetic, environmental, and management factors (reiterating H1). Future research and breeding efforts should integrate multi-trait stability frameworks with trait-informed modeling approaches to enhance the resilience of cereal production systems, particularly under the pressures of climate change and evolving agricultural practices. Cultivars that balance yield, quality, and stability across a range of input systems will be central to ensuring food security and sustainable agricultural development in temperate and marginal environments.

6.1 Recommendations

Based on the findings of this research, several key recommendations can be proposed to enhance the effectiveness of cereal breeding and cultivation strategies under varying agroecological conditions. Firstly, breeding programs should integrate multi-trait stability analysis, such as the Multi-Trait Stability Index (MTSI), as a standard approach to identify genotypes that consistently perform well across various environments and traits. Focusing solely on yield or quality may overlook complex trait interdependencies that affect cultivar adaptability under climate variability. Secondly, cultivar selection and recommendation should be tailored to the level of crop management intensity. Population cultivars may offer more excellent stability and resilience in low-input or organic systems, whereas hybrid cultivars demonstrate superior performance under high-input, intensively managed conditions. Thirdly, resistance to key biotic and abiotic stresses, particularly fungal diseases and soil acidity must be prioritized in breeding objectives to ensure yield and quality stability. Traits such as resistance to septoria, brown rust, and aluminum toxicity should be integrated into selection indices to develop cultivars better suited for current and future agricultural demands. Furthermore, advanced analytical tools like canonical correspondence analysis (CCA) and classification and regression trees (CART) have proven valuable in revealing the underlying trait-environment relationships. These methods should be increasingly adopted in breeding programs to inform marker-assisted selection and predictive modeling of genotype behavior. Lastly, policy frameworks and cultivar recommendation systems should evolve to incorporate trait stability metrics, enabling more nuanced, data-driven cultivar guidance for farmers. By aligning breeding strategies, statistical tools, and extension services, the agricultural sector can better support resilient and productive cereal systems under changing climatic and management conditions.

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Supplementary materials

Table S1. The characteristics of soil and climate conditions at the trial locations in two growing seasons of spring wheat

Location	Latitude N	Longitude E	Growing season	Soil texture type	pH	Arable land suitability groups[a]	Sum of precipitation from April to July [mm]	Mean temperature from April to July [°C]	Climatic water balance [mm]
Chrząstowo	53.0946	17.3504	2013	sandy loam	7.10	2	274.9	15.25	-180.10
			2014	sandy loam	7.30	2	246.2	15.64	-227.70
Lućmierz	51.5336	19.2208	2013	sandy loam	5.40	5	384.2	15.62	-73.64
			2014	sandy loam	5.80	4	359.0	16.05	-129.35
Seroczyn	52.0039	21.5511	2013	sandy loam	6.50	2	344.5	15.92	-126.76
			2014	sandy loam	6.80	2	402.2	15.27	-59.25
Węgrzce	50.0709	19.5844	2013	silty loam	5.40	2	392.2	16.75	-105.60
			2014	silty loam	6.40	1	497.1	16.27	1.65

[a] System of evaluation in Poland for arable land suitability from 1–9, where 1 determines the best suitability for wheat production.

Table S2. Descriptions of study spring wheat cultivars

Cultivar	Year of registration	Grain quality group[a]	Country of origin	Time of ear emergence	Plant: length	Resistance to fungal diseases (scale 9°)[b]							Lodging resistance (scale 9°)[b]
						Stem base diseases	Powdery mildew	Wheat leaf rust	Brown spot	Leaf Septoria	Chaff septoria	Fusarium ear blight	
Bombona	2005	E	Poland	medium	medium	8.1	7.6	6.1	7.2	6.5	7.5	7.7	7.5
Izera	2012	A	Poland	early	medium	8.2	7.8	7.5	7.4	6.7	7.6	7.9	7.3
Torridon	2012	A	United Kingdom	medium	very short	8.1	7.9	7.8	7.6	7.1	7.1	7.5	8.3
Ostka Smolicka	2010	A	Poland	medium	medium	7.9	7.3	6.5	7.3	6.6	7.6	7.9	6.8
Radocha	2011	C	Poland	medium	short	8.1	7.1	6.9	7.1	6.4	6.9	7.1	7.2
Trappe	2008	B	Germany	medium	short to medium	8.2	7.5	7.2	7.4	6.9	7.2	7.7	7.8
Tybalt	2005	A	Netherlands	late	short	8.1	8.4	7.9	7.3	6.8	7.1	7.3	7.2

[a] Polish quality scheme: E, superior cultivar; A, good quality cultivar; B, bread cultivar; C, non-baking cultivar; [b] 9° scale 1-worst condition, 9-worst condition

Table S3. Soil characteristics of study location of winter wheat

Location	Longitude and latitude	Reference Bulk Density (g cm^{-3})	Sand Fraction (%)	Clay Fraction (%)	Soil Nutrient Availability class (scale 5°)†	Available Water Capacity class(scale 5°)†	Soil Organic Carbon Stock (g m$_{-2}$)	Calcium carbonates (g kg^{-1})	Cation Exchange Capacity (meq/100 g)	C:N (ratio)	Potassium content (g kg^{-1})	Nitrogen content (%)	Phosphorus content (g kg^{-1})	pH in CaCl	ph in H2O
Bezek	51.11; 23.15	1.73	87	4	3	3	47.86	4.89	14.94	11.19	124.94	1.32	35.38	5.42	6.21
Białogard	54.0; 15.59	1.41	37	19	2	1	55.89	13.37	10.30	11.70	108.89	1.44	44.81	5.23	5.91
Głubczyce	50.194,1782	1.41	42	20	1	5	126.21	3.15	10.41	22.55	110.05	1.56	13.33	3.19	3.93
Jelenia Góra	50.856, 15.70	1.4	42	22	1	5	70.45	0.09	13.19	10.03	148.96	2.23	31.64	5.48	6.20
Kawęczyn	52.168, 20.34	1.62	80	8	1	1	46.25	1.84	5.85	10.23	52.50	1.17	40.00	5.06	5.42
Kościelna Wieś	51.48, 18.01	1.7	85	5	2	3	57.68	2.47	3.55	19.02	96.65	1.04	25.09	3.79	4.54
Krzyżewo	53.025, 22.75	1.4	32	19	3	1	53.59	5.38	6.73	13.00	83.79	0.93	35.83	4.87	5.59
Lisewo	54.195, 18.52	1.25	23	48	1	5	49.37	20.14	15.09	12.71	124.34	1.68	25.16	5.17	5.61
Pawłowice	50.454, 22.75	1.73	39	21	3	1	53.17	13.47	7.82	12.39	134.24	1.38	40.86	4.71	5.60
Ruska Wieś	53.79, 22.20	1.32	35	32	2	1	52.92	5.27	34.64	11.40	56.75	2.14	32.80	5.83	6.37
Sulejów	51.351, 19.867	1.59	82	10	2	1	76.22	2.44	5.62	11.83	121.99	1.29	35.60	4.61	5.31
Wegrzce	50.119, 19.082	1.4	41	22	2	1	50.48	6.36	9.00	15.11	179.82	1.44	19.76	4.10	4.86

†According to Harmonized World Soil Database.

Table S4. Descriptions of study of winter wheat cultivars.

Cultivars	Resistance (scale 9°)‡							
	Winter hardiness	Resistance to lodging	Powdery mildew	Brown rust	Septoria leaf blight	Chaff septoria	Diseases of the stem base	Fusarium ear blight
Admont	4.5	8	5	2	5	5	6	5
Ambicja	3.5	8	7.2	8.2	7.2	7.1	7.1	7
Apostel	4	7	7.6	7.6	6.9	7.2	7.2	7.4
Argument	3.5	7.4	8.5	8.8	7	8.4	8	8.5
Artist	4	7	7.7	7.1	6.5	7.5	7.8	7.5
Bataja	4.5	7.4	7.7	7.1	6.4	7.2	7.1	7.9
Błyskawica	4	8.1	7	8.1	7	7	8.1	7
Bonanza	4	7	8.15	7.75	6.1	6.85	8.2	7.45
Bosporus	4	7.5	8.9	6.8	7.4	8.1	7.5	7.9
Comandor	4.5	7.4	7.7	8	6.9	7.8	7.5	7.9
Euforia	5.5	8	8.1	6	6.9	7.6	8	7.5
Formacja	4.5	7.8	7.7	7.7	6.5	7.7	7.5	7.8
Hybery F1	3.5	5	4	5	5	5	6	5
Impresja	5	7.7	7.9	7.5	7.2	7.8	8.4	7.8
Kariatyda	4.5	7.5	7.8	7.3	6.8	7.4	7.5	7.6
Kometa	3	6.8	7	7	7	7	7	7
KWS Donovan	3	6.7	4	3	5	5	5	5
KWS Firebird	4	6	5	5	5	5	5	5
KWS Spencer	3.5	5	5	5	5	5	5	5
KWS Talium	4.5	7	5	5	5	4	5	5
KWS Universum	3	7	5	5	5	5	5	5
LG Jutta	5.5	7	8.4	8.2	7.2	7.5	7.4	8.2
LG Keramik	4	6	7.5	7.7	6.9	7.4	7.6	7.1
Lindbergh	2.5	6	8	8	7	7	7	5
Lokata	5.5	7	6	6	6	6	6	6
Medalistka	5.5	6.9	4	5	4	5	5	5
MHR	4	7	7	7	7	7	7	7

Promienna Moschus	4	8.5	9	8	8	8	6	8
Nordkap	4	6	5	5	5	5	5	5
Opcja	4	6	5	5	5	5	5	5
Opoka	4.5	7	8	7	7	8	9	7
Owacja	4.5	6.7	8.1	8.1	7.4	7.7	8.2	8.2
Patras	4	7	8	8	8	8	8	8
Plejada	5	7.6	6	6	5	6	5	6
Reduta	4.5	8	7.1	7.2	6.7	7.3	7.8	8
RGT Bilanz	4.5	8	8	7.5	7.5	7.5	8.5	7.5
RGT Kilimanjaro	4.5	8	8	7.5	7.5	7.5	8.5	7.5
RGT Metronom	4.5	9	8.5	7	7.5	7.5	8	7.5
RGT Provision	4	8	8.5	7	6.5	7.5	7.5	7.5
RGT Ritter	3	8.5	7.5	7.5	8.5	7.5	7.5	7.5
RGT Specialist	4	8	8.5	8	6.5	8	8.5	9
Rivero	3.5	8	8.1	7.9	7.3	7.4	7.4	7.6
Sfera	4	7.2	8.1	7.5	6.9	7.2	7.9	7.1
SU Mangold	3.5	8.4	7.7	6.5	7.4	8.2	8	7.8
SU Petronia	4	6	5	5	5	5	5	5
SU Tarroca	2.5	7.9	7.1	6.9	7.1	7.9	7.2	7.8
SU Viedma	4	6	5	5	5	5	5	5
SY Cellist	3	6	5	5	5	5	5	5
SY Dubaj	4.5	6	8	8	7	7.6	8	7.4
SY Orofino	4	6	8.1	8.6	7.7	8	8.1	7.9
SY Yukon	5	8.1	8.2	8.2	8	7.8	8	8
Symetria	4	6.6	6	6	6	4	4	4
Titanus	4	6	5	5	5	5	5	5
Tytanika	5	4	7	8.1	6	7.7	7.7	7.7
Venecja	4	7.6	7.6	7.1	5.9	7.6	8.1	6.5

‡ 9° scale 1-worst condition, 9-best condition.

Table S5. Characteristics of winter rye cultivars based on official registration test.

Name of cultivar	Year of registration	Breeding institution	Type of cultivar	Resistance to diseases (scale 9°)‡							Reaction to Al (scale 9°)‡	Plant height (cm)	Lodging resistance (scale 9°)‡	Heading (days from January 1)*	Fully ripe(days from January 1)	Resistance to grain sprouting in spikes (scale 9°)‡	Flour yield (%)	Maximum viscosity of starch gruel (amylograph units)	Total sugar content (%)
				Snow mold	Stem-base diseases	Powdery mildew	Leaf rust	Stem rust	Scald	Septoria leaf blotch									
Agat	1987	DANKO Plant Breeding Ltd (Poland)	population	7.50	8.00	7.80	7.20	7.50	7.30	6.90	4	148	5.9	130	198	5	51.8	442	62.3
Amber	2010	DANKO Plant Breeding Ltd (Poland)	population	7.40	7.40	7.90	6.90	7.70	7.30	6.60	5	160	5.7	131	202	5	52.8	583	64.5
Amilo	1989	DANKO Plant Breeding Ltd (Poland)	population	8.10	8.00	7.90	6.90	7.50	7.60	6.70	5	152	5.1	132	201	6	51.2	456	61.9
Antoninskie	2013	Poznańska Hodowla Roślin Ltd. (Poland)	population	7.80	7.40	7.80	7.00	8.00	7.40	6.80	5	166	5.3	132	202	5	53.2	433	62.7
Binntto	2016	KWS SE (Germany)	hybrid	7.90	7.50	8.10	6.70	7.90	7.70	7.20	5	136	6.8	131	198	5	52.8	757	63.6
Diament	2005	DANKO Plant Breeding Ltd (Poland)	population	8.00	7.90	7.50	6.60	7.90	7.40	6.60	5	159	6.1	132	202	5	51.8	603	62.9
Dolaro	2016	KWS SE (Germany)	hybrid	7.60	7.80	8.00	6.50	8.00	7.70	7.10	4	143	6.7	134	203	5	51	832	63.5
Granat	2015	DANKO Plant Breeding Ltd (Poland)	population	7.70	7.70	7.70	7.20	8.00	7.40	6.80	5	155	5.8	131	202	5	51.9	591	62.8
Hadron	2016	DANKO Plant Breeding Ltd (Poland)	population	7.20	7.50	7.80	7.20	8.00	7.40	6.80	4	157	5.5	131	202	5	52.2	561	63.4
Opal	1988	DANKO Plant Breeding Ltd (Poland)	population	8.10	7.80	7.60	6.50	7.60	7.10	6.80	4	153	6.6	130	198	4	52.1	458	62.1
Rubin	2013	DANKO Plant Breeding Ltd (Poland)	population	7.80	7.70	7.80	6.90	8.10	7.20	6.70	5	156	5.6	131	201	5	52.2	440	62.4
Serafino	2017	KWS SE (Germany)	hybrid	8.00	7.60	7.80	7.00	8.00	7.60	7.00	4	148	5.6	133	202	5	52.4	1190	64.2
Skand	2017	DANKO Plant Breeding Ltd (Poland)	population	7.90	7.70	7.50	6.50	8.00	7.30	6.70	5	154	6.0	130	201	5	52.3	373	63.4
Tur	2013	DANKO Plant Breeding Ltd (Poland)	hybrid	7.50	8.00	7.80	6.50	7.60	7.60	7.10	6	155	5.7	132	202	5	50.8	515	63.6
Turkus	2016	DANKO Plant Breeding Ltd (Poland)	population	7.80	7.50	7.80	7.30	8.00	7.30	6.70	4	156	5.8	131	201	5	52.3	562	63

Table S6. The field conditions for each of the three sites in both growing seasons of winter rye.

Location	Season	Planting date (MIM, HIM)*	Seeding density (MIM, HIM)*	Fungicides (HIM)*	Plant growth regulators (HIM)*	Timing and doses of nitrogen fertilization (MIM, HIM)*	Harvest date (MIM, HIM)*
Choryń	2018/2019	19.09.2018	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. prothioconazole - 200 g/l, proquinazid - 50 g/l 2. fluxapyroxad - 41.6 g/l, epoxiconazole - 41.6 g/l, pyraclostrobin - 66.6 g/l	chlormequat chloride - 750 g/l, trinexapac ethyl	MIM 1 - start of vegetation (50 kg)† 2- shooting in the stalk (40 kg)† HIM 1 - start of vegetation (50 kg)† 2- shooting in the stalk (40 kg)†, 3 - heading (30 kg)‡	09.07.2019
	2019/2020	21.09.2019	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. fenpropidin 333 g/l , prochloraz - 300 g/l, tebuconazole 500g/l, proquinazid 200 g/l 2. fenpropimorph - 250 g/l, epoxiconazole - 84 g/l	chlormequat chloride - 750 g/l, trinexapac ethyl	MIM 1 - start of vegetation (70 kg)† 2- shooting in the stalk (40 kg)† HIM 1 - start of vegetation (70 kg)† 2- shooting in the stalk (40 kg)†, 3 - heading (30 kg)‡	21.07.2020
Sobiejuchy	2018/2019	22.09.2018	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. prothioconazole 175 g/l, trifloxystrobin 150 g/l 2. prothioconazole - 100 g/l, Fluoxastrobin - 50 g/l, Bixafen - 40 g/l	ethyl trinexapac 250 g, chlormequat chloride	MIM 1 - start of vegetation (34 kg)† 2- shooting in the stalk (34 kg)† HIM 1 - start of vegetation (34 kg)† 2- shooting in the stalk (51 kg)†, 3 - heading (23 kg)‡	10.07.2019

	2019/2020	23.09.2019	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. prothioconazole 175 g/l, trifloxystrobin 150 g/l 2. prothioconazole - 100 g/l, Fluoxastrobin - 50 g/l, Bixafen - 40 g/l	ethyl trinexapac 250 g, chlormequat chloride	MIM 1 - start of vegetation (34 kg)† 2- shooting in the stalk (34 kg)† HIM 1 - start of vegetation (34 kg)† 2- shooting in the stalk (51 kg)†, 3 - heading (23 kg)‡	23.07.2020
Laski	2018/2019	21.09.2018	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. prochloraz - 200 g/l, tebukonazol 2. prothioconazole 100 g/l, fluoxastrobin 100 g/l	chlormequat chloride - 750 g/l, trinexapac ethyl	MIM 1 - start of vegetation (40 kg)† 2- shooting in the stalk (50 kg)† HIM 1 - start of vegetation (50 kg)† 2- shooting in the stalk (60 kg)†, 3 - heading (20 kg)‡	06.08.2019
	2019/2020	23.09.2019	population cultivars - 300 grains per meter, hybrid cultivars - 250 grains per meter	1. prochloraz - 200 g/l, tebukonazol 2. prothioconazole 100 g/l, fluoxastrobin 100 g/l	chlormequat chloride - 750 g/l, trinexapac ethyl	MIM 1 - start of vegetation (40 kg)† 2- shooting in the stalk (50 kg)† HIM 1 - start of vegetation (50 kg)† 2- shooting in the stalk (60 kg)†, 3 - heading (20 kg)‡	22.07.2020

*MIM - moderate input crop management, HIM - high input crop management; † ammonium nitrate form; ‡ urea form

Table S7. Ranking of cultivars based on value of Shukla stability variance and the sum of cultivars ranking across all study traits of winter rye.

a) Moderate input crop management (MIM)

Cultivars	Grain Yield ($t\ ha^{-1}$)	Thousand Grain Weight (g)	Grain Protein Content (%)	Grain Density ($kg\ hl^{-1}$)	Starch Content (%)	Number of Spikes per Head (-)	Grain Weight per Spike (g)	Sum	Min	Max
Agat	8	2	10	6	7	13	2	48	2	13
Amber	7	14	11	10	12	11	14	79	7	14
Amilo	9	8	2	2	3	5	8	37	2	9
Antoninskie	6	9	9	3	8	1	9	45	1	9
Binntto†	11	11	15	14	15	7	11	84	7	15
Diament	3	10	4	9	1	3	10	40	1	10
Dolaro†	14	3	8	11	2	14	3	55	2	14
Granat	2	1	7	1	9	6	1	27	1	9
Hadron	10	6	12	4	10	12	6	60	4	12
Opal	4	7	3	12	6	2	7	41	2	12
Rubin	1	5	1	8	11	9	5	40	1	15
Serafino†	13	15	13	15	14	10	15	95	10	15
Skand	5	4	5	5	5	4	4	32	4	5
Tur†	15	13	14	7	13	15	13	90	7	15
Turkus	12	12	6	13	4	8	15	70	4	15

a) High input crop management (HIM)

Cultivars	Grain Yield ($t\ ha^{-1}$)	Thousand Grain Weight (g)	Grain Protein Content (%)	Grain Density ($kg\ hl^{-1}$)	Starch Content (%)	Number of Spikes per Head (-)	Grain Weight per Spike (g)	Sum	Min	Max
Agat	1	3	2	8	1	3	3	21	1	8
Amber	10	5	10	12	5	13	5	60	5	13
Amilo	9	10	15	4	15	7	10	70	4	15
Antoninskie	7	9	12	2	7	10	9	56	2	12
Binntto†	15	15	8	7	9	14	15	83	8	15
Diament	3	12	4	15	3	6	12	55	3	15
Dolaro†	14	11	9	9	8	11	11	73	8	14

Granat	8	7	1	3	2	9	7	37	1	9
Hadron	6	4	13	13	14	2	4	56	2	14
Opal	4	6	6	1	6	5	6	34	1	6
Rubin	5	2	7	14	10	8	2	48	2	14
Serafino†	12	1	11	11	13	1	1	50	1	13
Skand	13	13	3	10	12	15	13	79	3	15
Tur†	11	8	14	6	11	12	8	70	8	14
Turkus	2	14	5	5	4	4	14	48	2	14

† hybrid cultivar

Table S8. The cultivars value of multi-trait stability index (MTSI) in moderate input (MIM) and HIM crop managements of winter rye.

Cultivars	Moderate input crop management (MIM)		High input crop management (HIM)	
	Multi-trait stability index (MTSI)	Ranking	Multi-trait stability index (MTSI)	Ranking
Agat	6.58	13	3.29	2
Amber	4.96	7	4.78	12
Amilo	5.31	9	6.09	14
Antoninskie	4.6	4	5.52	13
Binntto†	5.55	10	4.53	7
Diament	4.9	5	4.63	8
Dolaro†	4.9	6	4.06	4
Granat	3.09	1	4.51	6
Hadron	6.22	12	4.77	11
Opal	5.91	11	4.69	9
Rubin	4.21	3	4.39	5
Serafino†	5.02	8	2.81	1
Skand	3.82	2	6.32	15
Tur†	6.78	15	4.69	10
Turkus	6.62	14	3.36	3

† hybrid cultivar

Author's Resume

Name; Abuzar Ghafoor, Male, Born on 12/07/1996, from Okara, Punjab, Islamic Republic of Pakistan.

1. Wykształcenie i doświadczenie zawodowe (Education and professional experience)

2014. 09—2018.07 B.Sc. (Hons) from Per Mehr Ali Shah Arid Agriculture University, Pakistan.

2018.09—2021.06 Master's from Sichuan Agricultural University, P.R. China.

2. Nagrody (Scholarships).

1. 2014 USAID Merit Based Fully Funded Scholarship from Per Mehr Ali Shah Arid Agriculture University, Pakistan.
2. 2017 Voice Chancellor Talented Scholarship from Per Mehr Ali Shah Arid Agriculture University, Pakistan.
3. 2018 International Outstanding Talented Student Scholarship, China.
4. 2022 Award of best international student a STER scholarship Under the Project "Actions towards Internationalization of the Doctoral School of the Warsaw University of Life Sciences - SGGW" as part of the STER program.
5. 2024 Award of best international student a STER scholarship Under the Project "Actions towards internationalization of the Doctoral School of the Warsaw University of Life Sciences - SGGW" as part of the STER program.

3. Granty (Projects)

1. 07/09/2018 – 06/2021 Co-investigator: Sichuan Rapeseed Innovation Sichuan Rapeseed Innovation Team (sccxtd-03) and National Key R&D Program of China (Reg. No: 2016YFD0300300)
2. 2024-01-03 – 2027-01-02 Principal Investigator: Modeling the effect of climate change and soil organic carbon on baking quality traits of winter wheat cultivars in temperate climate. PRELUDIUM 22 (Reg. No:2023/49/N/NZ9/00430) project from the National Science Center, Poland (NCN)

Publications (Publikacje)

1) **Ghafoor A.Z.**, Wijata M., Rozbicki J., Krysztofik R., Banaszak K. , Derejko A., Studnicki M. "*Influence of crop management on stability rye yield and grain quality traits*". Agronomy Journal. 2024;116:2263–2274. (DOI: 10.1002/agj2.21647. **(140 pkt)**
2) **Abu Zar Ghafoor**, Alicja Cegli ́nska, Hassan Karim, Magdalena Wijata, Grzegorz Sobczy ́nski, Adriana Derejko, Marcin Studnicki, Jan Rozbicki and Gra ̇zyna Cacak-Pietrzak (2024). "*Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars*". Agriculture 2024, 14, 2131. https://doi.org/10.3390/agriculture14122131 **(100 pkt)**
3) **Abu Zar Ghafoor,** Hassan Karim, Marcin Studnicki, Ali Raza, Hafiz Hassan Javed, Muhammad Ahsan Asghar (2024) "*Climate Change and Rye (Secale cereale L.) Production: Challenges, Opportunities, and Adaptations*". Journal of Agronomy and Crop Science. DOI: 10.1111/jac.12725) **(pkt 140)**
4) **Ghafoor AZ**, Derejko A, Studnicki M. "*Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates*". Agronomy. 2024; 14(4):779. https://www.mdpi.com/2073-4395/14/4/779 **(100 pkt)**
5) **Abuzar Ghafoor**, Hassan Karim, Muhammad Ahsan Asghar, Ali Raza, M. Iftikhar Hussain, Hafiz Hassan Javed, Iram Shafiq, Peng Xiao, Hu Yue, Bushra Ahmad, Amir Manzoor, Ummar Ali & Yongcheng Wu (2021) "*Carbohydrates accumulation, oil quality and yield of rapeseed genotypes at different nitrogen rates*". Plant Production Science, DOI: 10.1080/1343943X.2021.1943464 **(40 pkt)**
6) **Abuzar Ghafoor**, Hassan Karim, Muhammad Ahsan Asghar, Hafiz Hassan Javed, Peng Xiao and Yongcheng Wu. "*Effect of high-temperature, drought and nutrients availability on morphophysiological and molecular mechanisms of rapeseed; an overview*". Pak. J. Bot, 53, http://dx.doi.org/10.30848/PJB2021-6(32) **(40 pkt)**
7) **Abu Zar Ghafoor**, Hassan karim, Hafiz Hassan Javed, Ali Raza, Iram Shafiq, Muhammad Ahsan Asghar, Hu Yue, Peng Xiao and Yongcheng wu. "*Effect of defoliation and silique removal on carbohydrates accumulation, seed quality, and yield of rapeseed (Brassica napus L.)*". Pak. J. Bot., 55(5). **(40 pkt)**
8) Shunfu Xiao, Yulu Ye, Shuaipeng Fei, Haochong Chen, Bingyu zhang, Qing li, Zhibo Cai, Yingpu Che, Qing Wang, **Abu Zar Ghafoor**, Kaiyi Bi, Ke Shao, Ruili Wang, Yan Guo, Baoguo Li, Rui Zhang, Zhen Chen, Yuntao Ma. "*High-throughput calculation of organ-scale traits with reconstructed accurate 3D canopy structures using a UAV RGB camera with an advanced cross-circling oblique route*". ISPRS Journal of Photogrammetry and Remote Sensing 201 (2023): 104-122 (**200 pkt**)
9) Meiyan Shu, Qing Li, **Abuzar Ghafoor**, Jinyu Zhu, Baoguo Li, Yuntao Ma. "*Using the plant height and canopy coverage to estimation maize aboveground biomass with UAV digital images*". European Journal of Agronomy, Volume 151,126957, ISSN 1161-0301 **(140 pkt)**

10) Li, H., **A. Ghafoor**, H. Karim, S. Guo, Z. Li, Y. Wu, Y. Sun, and F. Yan. (2019) *"Optimal nitrogen fertilizatizer management of seed-sowing Rapeseed in Yangtze River Basin of China".* Pakistan Journal of Biological Sciences: Pjbs 22, no. 6 (2019): 291-298. **(40 pkt)**

11) Ali Raza; Muhammad Ahsan Asghar; Sajad Hussain; Cheng Bin; Irshan Ahmad; **Abuzar Ghafoor**; Hassan Karim; Tauseef Iqbal; Wenyu Yang; Liu Weiguo (2020). "*Optimal NH4+/NO3- ratios enhanced the shade tolerance of soybean seedlings under low light conditions*". Plant Biology 23, no. 3 (2021): 464-472 **(70 pkt)**

12) Hu, Yue, Hafiz Hassan Javed, Muhammad Ahsan Asghar, Xiao Peng, Marian Brestic, Milan Skalický, **Abu Zar Ghafoor**, Hafsa Nazir Cheema, Fang-Fang Zhang, and Yong-Cheng Wu "*Enhancement of Lodging Resistance and Lignin Content by Application of Organic Carbon and Silicon Fertilization in Brassica napus L.*". Frontiers in Plant Science 13 (2022): 807048-807048. **(140 pkt)**

13) Shafiq, I., Hussain, S., Hassan, B., Raza, A., Ahmad, I., Asghar, M.A., Wang, Z., Tan, T., LI, S., Tan, X. and **Ghafoor, A.**, 2021. *"Crop responses and management strategies under shade and drought stress*". Photosynthetica, 59(4), pp.664-682. **(70 pkt)**

14) Asghar, Muhammad Ahsan, Bushra Ahmad, Ali Raza, Bilal Adil, Hafiz Hassan Javed, Muhammad Umer Farooq, **Abuzar Ghafoor** et al. "*Shade and microbes enhance drought stress tolerance in plants by inducing phytohormones at molecular levels: A review.*" Journal of Plant Ecology (2022). **(100 pkt)**

15) Raza, A., Yin, C., Asghar, M.A., Ihtisham, M., Shafiq, I., Cheng, B., **Ghafoor, A.**, Javed, H.H., Iqbal, T., Khan, N. and Liu, W. "*Foliar Application of NH4+/NO3–Ratios Enhance the Lodging Resistance of Soybean Stem by Regulating the Physiological and Biochemical Mechanisms Under Shade Conditions*" Frontiers in Plant Science, 13 (2022). **(140 pkt)**

16) Hafiz Hassan Javed, Yue Hu, Muhammad Ahsan Asghar, Marian Brestic, eMajid Ali Abbasi, Muhammad Hamzah Saleem, Xiao Peng, Abu Zar Ghafoor, Wen Ye, Jing Zhou, Xiang Guo and Yong-Cheng Wu "*Effect of intermittent shade on nitrogen dynamics assessed by 15N trace isotopes, enzymatic activity and yield of Brassica napus L.*" Frontiers in Plant Science 13 (2022). **(140 pkt)**

17) Xingmei Xu, Lu Wang, Meiyan Shu, Xuewen Liang, **Abu Zar Ghafoor**,Yunling Liu,Yuntao Ma and Jinyu Zhu. "*Detection and Counting of Maize Leaves Based on Two-Stage Deep Learning with UAV-Based RGB Image."* Remote Sensing 14, no. 21 (2022): 5388. **(140 pkt)**

18) Gujar, A., Asghar, M.A., Alenezi, M.A., Kubar, M.S., Kubar, K.A., Raza, A., Saleem, K., Javed, H.H., **Ghafoor, A.Z.**, Iftikhar Hussain, M. and Ullah, A., 2023. Assessment of the phycosphere microbial dynamics of microbial community associated with red algae culture under different cultural conditions. Environment, Development and Sustainability, pp.1-20. **(40 pkt)**

19) Xiao, S., Ye, Y., Fei, S., Chen, H., Cai, Z., Che, Y., Wang, Q., **Ghafoor, A.**, Bi, K., Shao, K. and Wang, R., 2023. "High-throughput calculation of organ-scale traits with reconstructed accurate 3D canopy structures using a UAV RGB camera with an advanced cross-circling oblique route" ISPRS Journal of Photogrammetry and Remote Sensing, 201, pp.104-122 (200 pkt)
20) Meiyan Shu, Qing Li, **Abuzar Ghafoor**, Jinyu Zhu, Baoguo Li, Yuntao Ma. "Using the plant height and canopy coverage to estimation maize aboveground biomass with UAV digital images". European Journal of Agronomy, Volume 151,126957, ISSN 1161-0301,
21) **Abu Zar Ghafoor**, Tomasz Lenartowicz, Adriana Derejko, Patrycja Ojdowsk1, Marcin Studnicki. "Temporal variability of the yield, flour, dough, and bread-making quality traits of winter wheat in temperate climate". Under review in Scientific Reports (e9552fc9-b33d-44bd-ad54-18ee8730b0e4) **(140 pkt)**

Conferences (Konferencje)

1) International Conference on Sustainable Food Security Solution, Pakistan (**Oral presentation**) "Performance and Stability Analysis of Hybrid and Population Rye Cultivars under Different Crop [29/05/2023 – 31/05/2023]
2) 3rd Edition of Global Conference on Agriculture and Horticulture, **(Oral Presentation)** "Influence of crop management on stability rye yield and some grain quality traits Management Intensities: Implications for Sustainable Resource Management" [Valencia, Spain, 11/09/2023 – 13/09/2023]
3) VI Doctoral Students Conference, FOUR ELEMENTS – CONTEMPORARY PROBLEMS IN LIFE SCIENCES, Poland (**Oral presentation**) "Optimizing Rye Cultivation: Insights from a Comprehensive Study on the Performance, Stability, and Sustainability of Hybrid and Population Cultivars
4) 2nd International Virtual Conference on Food Science & Nutrition (Virtual Conference) organized by Research Wave International, UK (**Oral presentation**) [05/03-2024–05/04/2024]
5) International Horticulture Conference Pakistan, 2018. (**Oral presentation**) "Per Mehr Ali Shah Arid Agricultural University," [24/04/2018 – 26/04/2018]

Courses (Kursy)

1) IDOCOS a peer-reviewed doctoral course (**obtained certificate**) "Digital transformation, sustainability and implementation thought projects" Erasmus+ project funded by the European Commission [08/02/2023 – 31/05/2023]

2) Discover Best Practice Farming for a Sustainable 2050 (**obtained certificate**), An online non-credit course authorized by the University of Western Australia and offered through Coursera [06/06/2023]
3) Algae Biotechnology (**obtained certificate**), An online non-credit course authorized by the University of California San Diego and offered through Coursera [17/06/2023]
4) Ecosystem Services: a Method for Sustainable Development (**obtained certificate**), An online non-credit course authorized by the University of Geneva and offered through Coursera [17/06/2023]
5) Summer school "**Sustainable development-Theory and Practice**" ELLS Bioeconomy for PhD education and research. (**obtained certificate**), at Warsaw University of Life Sciences [22/06/2022-23/06/2022]
6) **Intercultural Communication Workshop** at Warsaw University of Life Sciences [10/20/2023]
7) Participated in the contest for the best presentation during the SGGW doctoral school week **(obtained certificate)** [05/14/2024]
8) Scientific reviewer in "**Journal of Agronomy and Crop Sciences**" and "**African Journal of Botany**"
9) Attended seminars conducted by Professor Sulhattin Yaşar of Karamanoglu Mehmetbey at SGGW (**Obtained certificates**)
    i. 05/12/2023 (Tuesday), 17:00 – Design of Experiments and Advanced Statistical Analysis of Scientific Data: Applications in MINITAB
    ii. 07/12/2023 (Thursday), 17:00 – Practical Applications of Infrared Spectroscopy for the characterizations and quantifications of organic and biological samples
10) Completed a course **"Introduction to Climate Change and Human Rights"** This course is a collaboration between UN CC:Learn and the United Nations Development Programme (UNDP)-United Nations Environment Programme (UNEP) Poverty-Environment Action for Sustainable Development (PEA) (**obtained certificate**),
11) Completed a course **"Advancing Sustainable Development in Practice"** This course has been developed by the Paris Committee on Capacity-building with support from the Office of the United Nations High Commissioner for Human Rights and the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), with funding support from Germany's Federal Ministry for Economic Cooperation and

Development (BMZ) through the German Corporation for International Cooperation GmbH (GIZ) (**obtained certificate**),

12) Study week at Wageningen University & Research with the FOEBE Erasmus+ project (**obtained certificate**). This initiative equips bioeconomy skills to become successful sustainable entrepreneurs. Collaborated with 7 European Life Sciences universities [22/04/2024 – 27/04/2024]

13) Completed a course **"Cities and Climate Change"** focusing on climate change in urban areas, covering how cities are affected by climate change, how they contribute to it, as well as how they plan for it **(obtained certificate).**

Internship (Staż)

1 October 2024 to 31 December 2024, Completed internship in the Sustainable Field Crops program at the IRTA Institute of Agrifood Research and Technology, Lleida, Spain. During the stay I participated in the research project: Advancing Cereal Adaptation Strategies to Climate Change.

Summer School (Szkoła Letnia)

1. 07/05/2025 – 09/05/2025 **Summer School in Agroecology at Instituto Nacional de Investigação Agrária e Veterinária, Elvas, Portugal**. I participated in an international agroecology summer school focused on sustainable food systems, climate-resilient farming, and biodiversity conservation. The program combined field visits, interdisciplinary lectures, and practical workshops across diverse agroecological contexts.
2. 22/06/2022 – 23/06/2022 **Summer School in Sustainable Development-Theory and Practice.** The summer school offered an engaging program focused on foundational and advanced topics in science and technology, designed to enhance students' academic and research skills. It includes expert lectures, hands-on sessions, and interactive activities to foster deep learning and collaboration.

Appendices

Appendix 1

1.1 Copies of the Publications

1.1.1 Full Text of the Published Article 1

Title: Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars

Authors: Abu Zar Ghafoor, Alicja Ceglińska, Hassan Karim, Magdalena Wijata, Grzegorz Sobczyński, Adriana Derejko, Marcin Studnicki, Jan Rozbicki, Grażyna Cacak-Pietrzak

Journal: Agriculture (MDPI)

Volume: 14

Year: 2024

Article number: 2131

DOI: https://doi.org/10.3390/agriculture14122131 agriculture

MDPI

Article

Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars

Abu Zar Ghafoor [1], Alicja Ceglińska [2], Hassan Karim [3], Magdalena Wijata [4], Grzegorz Sobczyński [4], Adriana Derejko [1], Marcin Studnicki [1,*], Jan Rozbicki [4] and Grażyna Cacak-Pietrzak [2]

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Abstract: Obtaining optimal wheat cultivars that balance high productivity and grain processing quality in diverse environmental and crop management conditions requires a comprehensive assessment of the influence of genetic and environmental factors and their interactions. This study investigated the influence of these factors on yield, grain quality, and bread-making traits in spring wheat (*Triticum aestivum* L.) cultivars. The study was conducted at four trial locations in the temperate climate area over two consecutive growing seasons, each with two different crop management approaches (moderate and high input). We observed a strong influence of genotype on grain quality (e.g., protein content, test weight) and farinographic in spring wheat. Environmental factors strongly influenced the variability of dough softening and quality number among the studied rheological traits. However, we observed that crop management significantly impacted dough stability. The strength of the relationships between yield, grain quality, and bread-making traits depended on the specific crop management used. The multi-trait stability of genotypes in yield, grain quality, and bread-making traits also varied, depending on the crop management method.

Keywords: farinograph analysis; gluten; grain protein content; stability

Citation: Ghafoor, A.Z.; Ceglińska, A.; Karim, H.; Wijata, M.; Sobczyński, G.; Derejko, A.; Studnicki, M.; Rozbicki, J.; Cacak-Pietrzak, G. Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars. *Agriculture* **2024**, *14*, 2131. https://doi.org/10.3390/agriculture14122131

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1. Introduction

Wheat is one of the most important cultivated crops globally, with winter wheat being the dominant form in the temperate climate zones of Europe. However, spring wheat (*Triticum aestivum* L.) is grown less due to its lower grain yield and smaller grain size than winter wheat. However, it offers a higher protein content, which translates into better baking quality [1–3]. In the face of climate change and decreasing snow cover in Europe, the importance of spring wheat is increasing, attracting more attention from farmers, breeders, and researchers [4–7]. This crop is often used to replace winter crops, such as rapeseed or winter wheat, which may suffer from frost damage after harsh winters.

The grain yield and bread-making quality of different wheat forms depend on the interaction between genotype (G), environment (E), and their interaction (G × E). This interaction focuses on the variability in genotype performance under different environmental conditions, influencing the selection of optimal genotypes for high-quality grain. In addition to environmental and genetic factors, crop management practices such as sowing time, fertilization, and pesticide use are increasingly crucial for yield and bread-making quality [2,7–9].

Bread-making quality in wheat depends primarily on protein content, wet gluten content, gluten quality, and amylolytic enzyme activity [3,9–11]. Certain traits, like protein content and gluten characteristics, are mainly determined by genotype and environmental factors, influencing grain yield, thousand kernel weight, and sedimentation volume [6,12]. The relationship between environmental conditions, cultivation practices, and bread-making quality is complex, and the effects on various quality traits still need to be understood. Environmental factors like temperature and precipitation primarily influence certain parameters, such as yield and test weight, grain hardness, and Zeleny sedimentation volume in different forms of wheat and different climatic zones [13–15]. Rainfall, for example, in durum wheat, impacts yield and protein content, with more potent effects in favorable years than during drought conditions [7,16]. On the other hand, the stronger impact of genotype on the traits of protein content and wet gluten content may be related to nitrogen use efficiency (NUE) [17]. Stronger pressure of fungal diseases, e.g., Fusarium head blight, affects yield and other important features [18,19], which may be revealed especially in the case of improper or incomplete plant protection as part of crop management. While numerous studies have examined the influence of genotype, environment, and crop management on wheat yield, few have comprehensively assessed their effects on bread-making traits. Furthermore, most research has focused on individual aspects of crop management, such as nitrogen fertilization, without considering a more holistic approach. This study aims to fill this literature gap by emphasizing how crop management influences bread-making quality, thus providing valuable insights into optimizing spring wheat cultivation to produce high-quality grains for bread production.

In the context of climate change, the selection of stable spring wheat genotypes becomes increasingly important. However, the interaction between genotype and environment on yield and quality makes it difficult for farmers to recommend cultivars. Therefore, before introducing new hybrids with high stability, it is necessary to study the genotype-environment interaction to evaluate new lines in different environments. So far, the stability assessment has mainly focused on grain yield or selected single traits [20]. Stability should be evaluated across multiple traits, not just individual characteristics. The multi-trait stability index (MTSI) proposed by Olivoto et al. [21] provides a framework for assessing stability across various bread-making traits. This method combines simultaneous selection for stability of several traits into a single, easy-to-interpret index. Enhancing grain quality and selecting stable genotypes with superior characteristics is critical for producing high-quality, market-preferred products.

This study has three main objectives: (i) to identify spring wheat genotypes with stable performance in yield and bread-making quality across different environments, (ii) to assess the impact of genotype, environment, and crop management on yield, flour, dough, and bread-making quality traits, and (iii) to evaluate the relationships between yield and various quality traits in spring wheat.

2. Materials and Methods

2.1. Field Experiments

The seven spring wheat cultivars were evaluated in 4 trial locations and two growing seasons (2019 and 2020). Table S1 presented descriptions of soil and wheatear in study trial locations and growing seasons. The seven spring wheat (*Triticum aestivum* L.) cultivars included Bombona, Izera, Ostka Smolicka, Radocha, Torridon, Trappe, and Tybalt. The descriptions of study cultivars are shown in Table S2. The spring wheat cultivars were grown at two levels of crop management: moderate-input management (MIM) and conventional, high-input management (HIM). The MIM included fungicide seed treatment before sowing, N fertilization, and the use of herbicides. Depending on the location, the total rate of N for the MIM is about 90 kg ha^{-1}, with 40–60 kg N ha^{-1} applied before sowing and the rest used at Zadoks Growth Stage (GS) 49. In addition to the MIM level N dose of 40 kg ha^{-1} at GS 59, foliar microelements fertilizer (MgO 250 g ha^{-1}, Cu 50 g ha^{-1}, Mn 150 g ha^{-1}, Zn 80 g ha^{-1}), two fungicides at GS 31–32 (carbendazim, 625 g ha^{-1}) and GS

49–60 (fenpropidin, 550 g ha^{-1}), and a growth regulator (trinexapac-ethyl, 125 g ha^{-1}) at GS 31 were applied at the HIM level. The sowing density, set at 450 seeds per m^2, did not depend on crop management levels. The sowing date for individual locations ranged from 23 March to 29 March in 2019 and from 25 March to 1 April in 2020. Harvesting occurred between 28 July and 5 August 2019 and 1 August and 7 August 2020. Individual trials were established as a two-factorial (cultivar and crop management) strip-plot design with two blocks. The crop management levels were assigned in the whole plot, and cultivars were assigned in the subplot. The size of the plot was 15 m^2. The grain yield and thousand-grain weight TGW were determined from a 1 m^2 sample collected from the center of the plot.

The quality traits were evaluated from grain samples, including end-use quality traits: test weight (TW), grain ash content (AC), grain protein content (PC), wet gluten content (WG), gluten index (GI), Zeleny sedimentation value (SV), falling number (FN), flour yield (FY); the Farinograph traits: water absorption (WA), dough development (DD), dough stability (DS), dough softening (DSF), and quality number (QN); and the baking properties: loaf volume (LV), and crumb hardness (CH).

2.2. *Methods*

2.2.1. Properties of Grain

The test weight was determined using AACC Method 55-10. The ash content was determined with the incineration method (AACC Method 08-01.01) using an FCF S muffle furnace (Czylok, Jastrzębie Zdrój, Poland). The protein content (N × 5.7) was determined according to the Kjeldahl method (AACC Method 46-11.02) using a Kjeltec 8200 apparatus (Foss Tecator, Hillerod, Denmark). The wet gluten content and gluten index were determined using the mechanical method (AACC Method 38-12) on the Glutomatic 2200 (Perten Instruments, Stockholm, Sweden). The Zeleny method obtained the sedimentation value (AACC Method 56-61.02). The falling number was determined using the Hagberg-Perten method (AACC Method 56-81B) on the Falling Number test apparatus, type 1400 (Perten Instruments, Stockholm, Sweden).

2.2.2. Grain Grinding

The grain samples were ground in a two-passage laboratory mill Quadrumat Senior (Brabender GmbH & Co. KG, Duisburg, Germany). Before milling, the grains were cleaned on granules (Brabender GmbH & Co. KG, Duisburg, Germany) and conditioned to 14.5% humidity. Based on the milling balance, the total flour yield was calculated.

2.2.3. Properties of Flour and Dough

The water absorption of flour and rheological properties of the dough was determined using the AACC Method 54-21 on the Farinograph-E model 810114 (Brabender GmbH & Co. KG, Duisburg, Germany) [22,23]. The water absorption of flour was determined based on the amount of water added from a burette needed to achieve a dough consistency of 500 FU. The rheological properties of the dough (dough development, dough stability, and dough softening after 12 min of mixing) and quality number were determined from the normal curve graph using the Farinograph v.5 computer program.

2.2.4. Baking Procedure and Properties of Bread

The recipe for the bread dough included 500 g of flour, 15.0 g of fresh compressed yeast, 7.5 g of salt, and water in the amount necessary to achieve a dough consistency of 350 FU. The amount of water added was calculated based on the determined farinographic water absorption. The dough ingredients were mixed in an SP-800A mixer (Spar Food Machinery, Taichung, Taiwan) for 4 min at speed level 2. The dough was fermented in a fermentation chamber DC-32 (Sveba Dahlen, Fristad, Sweden) for 90 min, with punching performed after 60 min. After fermentation, the dough was divided into 250 g portions, shaped by hand, placed in molds, and subjected to proof for 30 min in the fermentation chamber.

Baking took place in the DC-32 oven (Sveba Dahlen, Fristad, Sweden) at a temperature of 230 °C for 30 min.

The properties of bread were determined 24 h after baking. The loaf volume was measured using a 3D scanner (NextEngine, West Los Angeles, CA, USA) according to the methodology of Romankiewicz et al. [24] and then converted to 100 g of bread. The crumb hardness was assessed on a texture analyzer TA-XT2i (Stable MicroSystem, Surrey, UK), according to the methodology of Romankiewicz et al. [24]. The assay relied on a dual compression of the crumb sample (thickness of slices—25 mm). A cylindrical mandrel with a 25 mm diameter was used in the measurement. The speed test was 1 mm s^{-1}. 40% penetration of the sample was applied, with a 45 s break between the first and second pressure.

2.3. Statistical Methods

The grain yield and bread-making quality traits were analyzed using a two-stage approach. In the first steps, individual trials were analyzed using the linear mixed model (LMM) typical for strip-plot design. In the second stage, we used the combined linear mixed model method, as shown below:

$$Xijkl = \mu + Yi + Lj + YLij + Gk + GYki + GLkj + GLYijk + Ml + MYli + MLjl + MLYijl + GMkl + GMYkli + GMLlkj + GMLYijkl + eijkl \quad (1)$$

where Xijkl is the value of the studied trait; μ is the overall mean; Yi is the random of ith year; Lj is the random effect of jth location; YLij is the random effect of interaction between jth location and ith year; Gk is the fixed effect of kth cultivars; GYki is the random effect of interaction between kth cultivars and ith year; GLkj is the random effect of interaction between kth cultivars and jth location; GLYijk is the random effect of interaction between ith year and jth location and kth cultivars; Ml is the fixed effect of lth crop management; MYli is the random effect of interaction between lth crop management and ith year; MLjl is the random effect of interaction between jth location and lth crop management; MLYijl is the random effect of interaction between ith year and jth location and lth crop management; GMkl is the fixed effect of interaction between kth cultivars and lth crop management; GMYkli is the random effect of interaction between kth cultivars and lth crop management and ith year; GMLlkj is the random effect of interaction between lth crop management and kth cultivars and jth location; GMLYijkl is the random effect of interaction between kth cultivars and lth crop management and jth location and ith year; eijkl is the random residual effect.

Descriptive statistics (the means, minimum, maximum, standard deviations SD, and coefficients of variability CV) were conducted based on adjusted means obtained from model (1) calculated for all study traits. The corrected means calculated this way were also used to assess the varieties' stability and study their relationships. We evaluated the relationship between all study traits using the Pearson correlation coefficient and principal components analysis (PCA). We used a multi-traits stability parameter (MTSI) to evaluate the stability of cultivars across all study traits [21]. This parameter allows for the simultaneous assessment of genotype stability for many characteristics, which in turn allows for the selection of genotypes with the highest degree of stability for all the traits considered simultaneously. The MTSI parameter is based on factor analysis for the matrix of the means of the standardized study trials, and the standardization of means is performed using the value of genotype-environment interaction effects. The MTSI indicators were assessed separately for crop management, and combinations of year and location were considered environments.

We are also interested in determining the significance and strength of the influence of main effects and their interactions on the variability of the studied traits. For this purpose, in model (1), we have changed the assumptions about the type of effects; all effects are treated as fixed. This allowed for the determination of the sum of squares for study effects. The Wald F test was used to evaluate the significance of the effects.

The statistical analyses were performed using R 4.2.1 software. The MTSI parameters were obtained using the metan package.

3. Results

The variability of the studied traits was assessed separately for genotype and environmental effects and is presented in Table 1. The GY for the genotypes ranged from 5.66 to 6.40 t ha^{-1}; for the environments, it ranged from 5.50 to 6.63 t ha^{-1}. For yield, variability was greater for environmental effects (CV 7.92%) than for genotypic effects (CV 4.20%). The AC for genotypes means ranged from 1.67 to 1.82% d.m.; for the environments, it ranged from 1.70 to 1.82% d.m. For this trait, we observe a similar level of variability for genotypes and environments (CV 2.67 and 2.63%, respectively). PC for genotypes ranged from 11.82 to 14.00% d.m. We observed a range of 11.58 to 13.78% d.m. for environmental effects. As for PC, we observed greater variability for environments (CV 7.93%) than for genotypes (CV 5.23%). For WG, genotypes ranged from 19.49 to 27.23%, and for environments ranged from 20.72 to 24.96%. For this trait, greater variability was observed for genotypes (CV 12.95%) than for environments (9.57%). For the FN, the values for genotypes ranged from 281.96 to 375.15 s, while for environments, ranging from 300.40 to 377.18 s. The variability was greater for environments (CV 10.47%) than for genotypes (CV 9.49%). The FY for the genotypes ranged from 77.24 to 79.15%; for the environments, it ranged from 77.29 to 78.69%. For FY, we observe a similar level of variability for genotypes and environments (CV 0.84 and 0.76%, respectively). WA for genotypes ranged from 57.02% to 59.48% and had low variability (CV 1.73%); similarly, we observed a low level of variability for environments. In contrast, for DS, we observe a high level of variability in both genotype effects and environments (CV 51.34% and 46.41%, respectively). The LV for the genotypes ranged from 366.34 to 398.33 cm^3 100 g^{-1}; for the environments, it ranged from 370.67 to 392.48 cm^3 100 g^{-1}. For LV, we observe a similar level of variability for genotypes and environments (CV 2.65% and 2.37%, respectively).

Table 1. Description statistics for yield, grain quality, and bread-making traits of genotype (**a**) and environmental (**b**) variability in spring wheat cultivars across four trial locations in two growing years (2019 and 2020).

(a) Genotype					
	Mean	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
GY (t ha^{-1})	6.20	5.66	6.40	0.26	4.20
TGW (g)	42.21	38.7	45.26	2.26	5.35
TW (kg hL^{-1})	76.77	73.7	78.88	1.91	2.49
AC (% d.m.)	1.76	1.67	1.82	0.05	2.67
PC (% d.m.)	12.88	11.82	14.00	0.67	5.23
SV (cm^3)	33.79	29.42	41.80	4.39	13.00
WG (%)	22.78	19.49	27.23	2.95	12.95
GI (-)	83.36	57.64	91.27	12.32	14.78
FN (s)	338.76	281.96	375.15	32.15	9.49
FY (%)	77.88	77.24	79.15	0.65	0.84
WA (%)	58.28	57.02	59.48	1.01	1.73
DD (min)	2.35	2.06	3.49	0.49	20.75
DS (min)	2.65	1.63	5.59	1.36	51.34
DSF (FU)	71.54	39.13	85.69	17.82	24.92
QN (-)	51.51	39.13	84.88	16.54	32.12
LV (cm^3 100 g^{-1})	380.34	366.34	398.33	10.22	2.65
CH (N)	7.43	5.69	9.21	1.24	16.71

Table 1. *Cont.*

(b) Environmental					
	Mean	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
GY (t ha^{-1})	6.20	5.50	6.63	0.49	7.92
TGW (g)	42.21	39.32	44.56	2.42	5.74
TW (kg hL^{-1})	76.77	73.19	81.17	3.41	4.45
AC (% d.m.)	1.76	1.70	1.82	0.05	2.63
PC (% d.m.)	12.88	11.58	13.78	1.02	7.93
SV (cm^3)	33.79	30.35	38.54	3.88	11.50
WG (%)	22.78	20.72	24.96	2.18	9.57
GI (-)	83.36	76.29	92.05	7.45	8.94
FN (s)	338.76	300.40	377.18	35.47	10.47
FY (%)	77.88	77.29	78.69	0.59	0.76
WA (%)	58.28	56.54	60.86	1.88	3.22
DD (min)	2.35	1.79	3.12	0.58	24.68
DS (min)	2.65	1.50	4.38	1.23	46.41
DSF (FU)	71.54	52.79	89.79	15.12	21.13
QN (-)	51.51	39.29	68.82	12.53	24.33
LV (cm^3 100 g^{-1})	380.34	370.67	392.48	9.02	2.37
CH (N)	7.43	6.86	8.62	0.80	10.81

Crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

A higher average GY was observed for HIM crop management (6.57 t ha^{-1}) than for MIM (5.83 t ha^{-1})—Table 2. On the other hand, slightly higher variability was observed for MIM (CV 9.61%) than for HIM (CV 8.41%). We observe the same AC values between MIM and HIM (1.76% d.m. for both crop management). Slightly higher variability is observed for MIM (CV 4.06%), compared to HIM (CV 3.63%). For the PC, higher values were for HIM (13.46% d.m.) than for MIM (12.29% d.m.). The variability of this feature was also higher for HIM (CV 11.49%) than for MIM (7.98%). As for PC, higher values and variability of WG and FN are observed in HIM (WG—average 24.22%, CV 19.19%; FN—average 339.51 s, CV 14.63%) than in MIM (WG—average 21.33%, CV 13.86%; FN—average 338.02 s, CV 13.22%). We observed higher FY values for HIM (78.16%) than MIM (77.59%). For LV, higher values were for MIM crop management (386.55 cm^3 100 g^{-1}) than for HIM (374.13 cm^3 100 g^{-1}). The variability of this variable was also observed to be more significant for MIM (3.80%) than for HIM (0.79%).

Table 3 shows the influence of the individual main and interaction effects for the studied features, determined using the percent of total variance based on the sum of squares. To compare the variance of factors and their interactions, the sum of squares was presented as percentages, the total sum of squares for considerate effects, and it is named as a percentage of the total variance. This form of presenting the results allows us to determine the strength of the influence of the main and interactive effects on the studied traits. For agronomic traits, such as GY and TGW, the values of these traits were most strongly conditioned by the leading environmental effects (year or location), as well as crop management or interaction effects between them. On the other hand, traits associated with the quality of grain, flour, dough, and bread are more often conditioned by genotypic effects and interactions with genotypes. However, we observed a few exceptions; for example, FY and DSF were most strongly determined by the main effect of the year (belonging to the group of environmental impacts).

Table 2. Description statistics for yield, grain quality, and bread-making traits for moderate-input management (MIM) and high-input management (HIM) in spring wheat cultivars across four trial locations in two growing years (2019 and 2020).

	Mean		Minimum		Maximum		Standard Deviation		Coefficient of Variation	
	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM
GY (t ha^{-1})	5.83	6.57	4.83	5.42	6.84	7.46	0.56	0.55	9.61	8.41
TGW (g)	40.70	43.72	31.87	37.50	46.70	50.64	3.47	2.91	8.53	6.66
TW (kg hL^{-1})	75.84	77.71	69.10	68.82	81.87	82.97	3.60	3.70	4.75	4.76
AC (% d.m.)	1.76	1.76	1.61	1.63	1.88	1.87	0.07	0.06	4.06	3.63
PC (% d.m.)	12.29	13.46	10.60	10.58	13.86	16.99	0.98	1.55	7.98	11.49
SV (cm^3)	31.08	36.50	25.47	25.98	42.17	51.39	4.45	6.78	14.33	18.59
WG (%)	21.33	24.22	14.85	18.11	26.11	37.98	2.96	4.65	13.86	19.19
GI (-)	85.82	80.90	38.31	44.36	99.75	98.70	13.95	16.36	16.26	20.22
FN (s)	338.02	339.51	239.61	233.14	394.18	422.71	44.69	49.66	13.22	14.63
FY (%)	77.59	78.16	75.20	76.55	79.40	80.35	1.18	0.93	1.53	1.19
WA (%)	57.88	58.29	54.30	55.40	62.25	63.35	2.11	2.29	3.65	3.92
DD (min)	2.06	2.56	1.20	1.35	2.65	7.70	0.33	1.28	15.82	49.84
DS (min)	2.14	3.02	0.90	0.95	6.55	10.00	1.36	2.25	63.54	74.51
DSF (FU)	73.96	68.05	31.00	7.50	110.50	107.50	20.51	24.09	27.74	35.39
QN (-)	47.13	54.68	26.50	27.50	125.50	123.00	22.56	25.29	47.86	46.26
LV (cm^3 100 g^{-1})	386.55	374.13	371.98	369.35	410.48	377.14	14.68	2.97	3.80	0.79
CH (N)	7.35	7.52	4.60	4.33	12.04	12.79	1.48	1.91	20.14	25.39

Abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), high-input management (HIM), loaf volume (LV), moderate-input management (MIM), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

We conducted separate MTSI analyses for both management approaches (MIM and HIM), focusing on grain quality and the resulting flour and bread of seven spring wheat cultivars (Table 4). Its parameter interpretation is the same as the commonly used stability index, e.g., Shukla stability variance (lower is better). In the case of MIM, the top two genotypes with the highest quality MTSI were selected using a selection pressure of 15%. This approach helped to determine the selection differentials for genotypes, such as Bombona (2.45) and Radocha (3.39), which hold the first and second positions in the stability ranking, respectively. In HIM, the genotypes Izera (2.73) and Bombona (3.04) hold first and second positions in the stability ranking, respectively. The correlation coefficient between MTSI in MIM and HIM crop management was equal to 0.56.

The correlation matrix Figure 1 in the upper triangle reveals the associations among the parameters for MIM. Significant positive correlations of the PC with WG (r = 0.61), DD (r = 0.56), and QN (r = 0.46). The positive correlations of the WG with SV (r = 0.56), DD (r = 0.45), and DS (r = 0.43) were observed. Conversely, negative correlations were observed between TGW and AC (r = −0.61) and WA and FN (r = −0.76). On the other hand, we observe weaker significant negative correlations between PC and DSF (r = −0.61) and between WG and DSF (r = −0.59). Moreover, no correlation was observed between DD and CH for management HIM (the lower triangle). Significant positive correlations were identified between DS and DD (r = 0.82). We also observed positive correlations of the PC with WG (r = 0.54), SV (r= 0.61), WA (r = 0.57), DD (r = 0.63), and DS (r = 0.66). On the other hand, negative correlations were observed between DS and DSF (r = −0.74) with statistical significance at $p < 0.05$. Also, we observed a negative correlation between PC and DSF (r = −0.53). Generally, we observe weaker correlations of WG and FN for HIM crop management with farinographic parameters than for MIM.

Table 3. Percent of the total variance (the sum of all variance components) of yield, grain quality, and bread-making traits for main effects (year, crop management, location, and genotype) and its interaction effects in spring wheat cultivars across four trial locations in two growing years (2019 and 2020).

Effect	Degrees of Freedom	GY (t ha^{-1})	TGW (g)	TW (kg hL^{-1})	AC (% d.m.)	PC (% d.m.)	SV (cm^3)	WG (%)	GI (-)	FN (s)	FY (%)	WA (%)	DD (min)	DS (min)	DSF (FU)	QN (-)	LV (cm^3 100 g^{-1})	CH (N)
Year (Y)	1	0.01 *	0.01 *	8.21 **	11 **	9.21 **	10.59 *	0.01	22.3 **	0.01	65.21 **	21.39 **	51.23 **	5.62 *	83.49 **	71.96 **	0.01	41.34 **
Menagment (M)	1	26.4 **	20.67 **	4.79 *	0	12.77 **	15.74 **	11.83 **	1.9 *	0.01 *	1.01 *	19.98 **	2.14 *	44.92 **	15.21 **	27.26 **	13.77 **	0.01 *
Location (L)	3	1.01 *	25.12 **	13.2 **	17 **	20.93 **	4.88 *	0.01	5.23 *	0.01	8.12 **	0.08 *	39.45 **	4.21 *	0.05 *	0.11 *	6.21 *	0.01
YxM	1	0.95 *	2.99 *	0.73 *	3.8 *	5.96 *	0.01	0.01	0.01	0.01	1.11 *	0.05 *	0.05 *	3.15 *	0.05 *	0.11 *	0.01 *	0.01
Genotype (G)	6	5.23 **	21.38 **	11.99 **	24 **	10.93 **	25.85 **	24.64 **	27.72 **	16.4 **	8.1 **	1.33	6.1 *	23.51 **	0.01 *	0.01	0.01	7.69 **
YxL	3	42.81 **	3.14 *	51.7 **	9.1 *	3.23 *	16.73 **	28.24 **	9.14 *	64.2 **	2.13 *	17.05 **	0.78 *	2.34 *	0.96 *	0.13 *	0.01	34.87 **
LxM	3	3.27 *	8.13 **	3.9 *	0	8.8 *	5.64 *	3.39	1.28 *	0.01 *	0.01	0.05 *	0.05 *	8.57 *	0.01	0.01	79.86 **	0.01
YxG	6	0.01	9.68 **	0.58 *	0	0.01	0.01	0.01	4.63 *	0.01	4.75 *	19.98 **	0.01	1.23 *	0.01	0.08 *	0.01	0.01
GxM	6	0.01 *	0.01	0.26	0	0.78	1.44	1.72	0.24	0.01	4.51 *	0.05 *	0.05 *	0.01	0.01	0.01	0.01	0.01
YxLxM	3	0.01	0.04	0.74 *	12 **	5.44 *	17.63 **	0.35	0.01	1.46 **	0.1	0.01	0.01	4.25 *	0.01	0.11 *	0.01	0.01
LxG	18	0.51 *	1.46 *	2.14 *	0	0.37	0.01	0.01	6.15 *	0.01	2.78 *	0.01	0.01	2.15 *	0.05 *	0.01	0.04 *	0.33 *
YxGxM	6	3.57 *	0.53 *	0.13	3.6 *	0.01	0.01	2.53	0.01	0.01	0.01	19.98 **	0.01	0.01	0.05 *	0.09 *	0.01	0.62 *
YxLxG	6	9.03 **	3.61 *	0.32 *	5.8 *	1.61	1.45	7.32 *	0.01	11.04 **	2.14 *	0.01	0.05 *	0.01	0.01	0.01	0.01	0.54 *
LxGxM	18	7.18 *	0.01	0.01	5.2 *	0.01	0.01	1.22	0.01	0.63 *	0.01	0.01	0.05 *	0.01	0.01 *	0.01	0.01	0.01
YxMxLxG	18	0.01	3.21 *	1.3 *	9.1 *	19.95 **	0.01	18.72 **	21.37 **	6.17 **	0.01	0.01	0.01	0.01	0.05 *	0.11	0.01	14.52 **

*, **: significant at the 0.05 and 0.001 probability levels, respectively; abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

Table 4. The multi-trait stability index for spring wheat cultivars in moderate-input management (MIM) and high-input management (HIM) across four trial locations in two growing years (2019 and 2020).

Cultivars	Multi Trait Stability Index (MTSI) MIM	Stability Ranking MIM	HIM	Stability Ranking HIM
Bombona	2.45	1	3.04	2
Izera	3.71	4	2.73	1
Ostka Smolicka	4.10	6	3.79	3
Radocha	3.39	2	3.99	4
Torridon	3.52	3	4.75	7
Trappe	5.15	7	4.74	6
Tybalt	4.04	5	4.44	5

High-input management (HIM); moderate-input management (MIM).

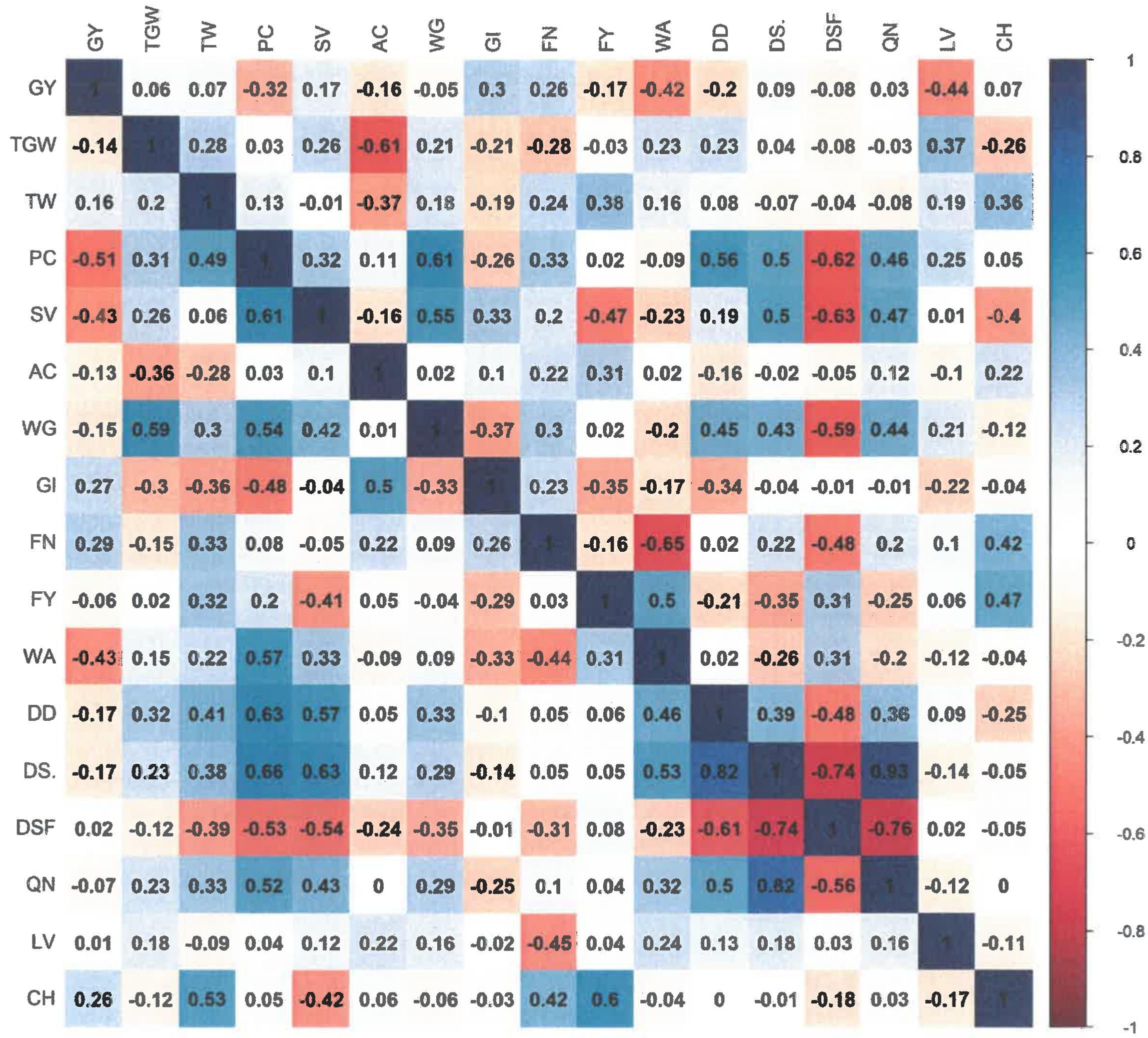

Figure 1. The Pearson correlation analysis of moderate-input management MIM (upper triangle) and high-input management HIM (lower triangle) crop management for yield, grain quality, and bread-making traits in spring wheat cultivars across four trial locations in two growing years (2019 and 2020). Abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

According to the PCA depicted in Figure 2a (MIM crop management), PC1 accounts for 27.7% of the total variance of the parameters, and PC2 explains approximately 24.4% of the variance. When combined, PC1 and PC2 collectively account for 52.1% of the variance observed in all the analyzed parameters. In the PCA of management HIM, as shown in Figure 2b, PC1 accounts for 38.1% of the total variance of the parameters, while PC2 explains approximately 16% of the variance. PC1 and PC2 contribute to 54.1% of the total variance observed in all the analyzed parameters.

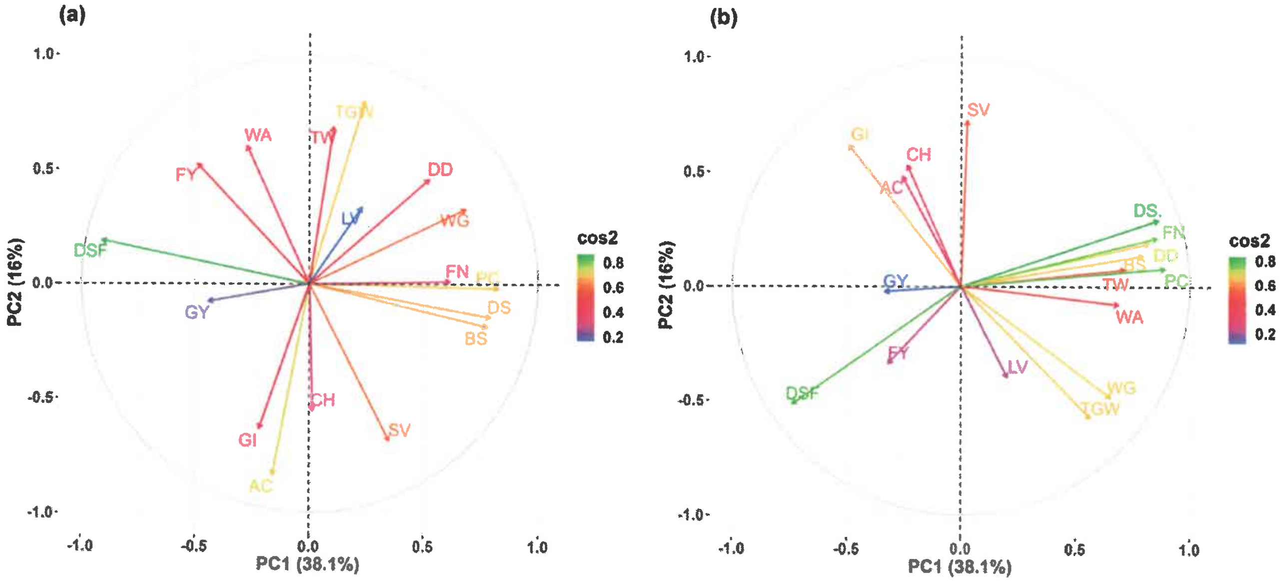

Figure 2. Principal component analysis (PCA) of moderate-input management MIM (**a**) and high-input management HIM (**b**) for yield, grain quality, and bread-making traits in spring wheat cultivars across four trial locations in two growing years (2019 and 2020). Abbreviation: crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), loaf volume (LV), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

Figure 2a represents the PCA of MIM crop management; we observed a negative relationship in agronomic traits (GY and TGW). The quality traits (AC, CH, and GI) showed a positive relationship with each other, and SV with DS and FY with WA also showed a positive correlation. A strong negative relationship was observed between DS and DSF and between BS and DSF, and no correlation was observed between SV and CH. In grain quality traits, PC and FN displayed a strong positive correlation. In contrast, TW and SV displayed a negative correlation. Generally, a strong negative correlation was shown between TGW and FA, TW and AC, DS and DSF, and FN and WA. At the same time, a strong positive correlation was observed between GI and FA.

In the PCA of management HIM (Figure 2b), agronomic traits (GY and TGW) showed a negative relationship. A positive correlation was observed between AC, GI, and CH in flour quality traits. DS, FN, FY, and DSF showed a significant positive correlation. In comparison, a significant negative correlation was observed between CH and LV. A significant negative correlation was found between PC and GY and between GY and TW. In contrast, a significant positive correlation was found between PC and TW, SV and DD, and CH and FA. In grain quality traits, TW and PC showed a strong positive correlation.

The color-coded indicator values (cos2) in Figure 2a,b reflect how well the variables are represented on the primary component. In the present study, the variables LV (Figure 2a) and GY (Figure 2b) had cos2 values below 0.2, suggesting that additional interpretation of these parameters may not be necessary.

4. Discussion

Our study explored genotype, environmental, and crop management effects on seven spring wheat cultivars across four trial locations under two farming conditions over two growing seasons, emphasizing yield size and quality traits. We found that grain yield spring wheat variations strongly stemmed from location and growing seasons interaction effects, explaining about 50% of the yield variability. Such a large impact of this interactive effect makes it difficult to predict the yield and justify its value. The main effect of crop management also had a significant share in the yield variability, at approximately 25%. Wheat research, including winter and durum forms, shows a powerful influence of environmental effects and their interactions [2,9,25–27]. However, in our study, we observe a relatively high impact of crop management effects on yield, which has yet to be fully explored before.

PC is one of the most important parameters used to assess the suitability of wheat grain for selecting raw material for milling into baking flour [2,5]. The PC depends on environmental effects (location and year) and crop management, but only 10% were influenced by genetic factors. Among wheat proteins, particular importance is attributed to storage proteins (gliadins, glutenins), which, when combined with water, form a viscoelastic gluten structure [28]. In our study, WG was more dependent on genotype than environmental influence. On the other hand, the GI, reflecting the quality of the protein, was already influenced by the genotype by over 25% and, to a minimal extent (about 2%), by crop management. Unfortunately, PC, WG, and GI values were significantly conditioned by the four-way interaction effect among year x location x genotype x crop management. Unfortunately, the substantial contribution of this interaction effect in shaping these characteristics makes it challenging to formulate appropriate recommendations and guidelines.

Scarce studies include the assessment of the impact of genotypic, environmental, and crop management effects on grain quality and bread-making quality traits. We detected a significant impact of crop management on DS, accounting for approximately 45% of the variability. However, we also observe a relatively large effect of crop management on features such as WA and QN. The WA is an essential parameter on which the productivity of dough and bread depends, which translates into the economic effects of the bakery [3]. The knowledge that these traits are determined by crop management may contribute to protection from the impact of unfavorable weather during the growing season and, as a result, will allow the delivery of the appropriate quality product, for example, by increasing the intensification of plant protection or fertilization.

Our study revealed wider genotypic variation in WG and GI. These results are consistent with the studies on spring wheat by Sułek et al. [7] and Feledyn-Szewczyk et al. [29] and on winter wheat by Ma et al. [30] and Rozbicki et al. [9], emphasizing the dominant role of genetics in wet gluten content in wheat grain. Genotypic effects also impact FN, reflect wheat grain development, and are too strongly influenced by genotypic effects. It was also found for spring wheat in Poland by Sułek et al. [7] and in India by Farhad et al. [31] that genotypic factors exert a greater influence on falling number variation than environmental factors. Moreover, for FN, we observe a significant contribution to the interaction of environmental factors (year and location), explaining about 60% of the variability of this trait. A considerable impact of environmental effects on shaping this trait was noted for winter wheat in a temperate climate in the studies by Rozbicki et al. [9] and Mitura et al. [2] in the case of spring wheat. For LV, the decisive effects were crop management and location. However, the most influence is observed in the interaction between location and crop management, which explains almost 80% of the variability. Similar dependencies were demonstrated by Rozbicki et al. [9] for winter wheat and by Wysocka et al. [3] for spring wheat.

We conducted separate Multi Trait Stability Index (MTSI) analyses for MIM and HIM approaches, assessing seven spring wheat cultivars across agronomic, grain, flour, dough, and bread traits. It turns out that entirely different cultivars can be considered stable in MIM and different in HIM crop management. Unfortunately, our study cultivars do not observe consistency in cultivar evaluation between MIM and HIM, as indicated by a relatively low correlation coefficient. Indirectly, we can conclude that multi-trait stability depended on the crop management type used. The recommendation of stable cultivars in terms of many traits will allow for maintaining the standards of the final product even in unfavorable weather conditions during the growing season. Selecting such multi-trait stable cultivars becomes essential in breeding crops grown in uncertain, changing climate conditions. Cultivars with consistent performance across traits and practices are valuable for stable wheat production; however, identifying such cultivars is often impossible or difficult. The Bombona cultivar is worth noting as it turned out to be the most stable for MIM and the second most stable for HIM. It may be worth introducing to breeding programs to obtain more stable multi-traits new cultivars.

Under MIM, negative correlations between WA and SV suggest wheat cultivars with lower softening and water absorption have higher baking scores [28]. A solid positive DS-DD correlation in HIM suggests that improved dough development contributes to better dough strength and baking scores. However, in MIM, this relationship between these features was much weaker but still positive. Lower DSF often signifies a balanced ratio of glutenin and gliadin proteins, enhancing dough strength [28]. A positive relationship among FA, CH, and GI suggests higher protein and gluten strength correlate with increased ash content, associated with more minerals, similar to durum wheat in the study of Ficco et al. [32], and improved dough strength [33]. Positive correlations were found between FN and DS, as well as FY and WA. A higher supply of nitrogen in high input management (HIM) contributes to an increase in PC and WG, which translates into higher WA and better rheological properties of the dough [34].

A strong positive correlation between TGW and PC in HIM suggests larger grains can store more proteins, leading to increased PC [28]. Negative correlations between agronomic traits (GY and TGW) and grain/flour quality suggest a trade-off between maximizing yield and optimizing bread quality. Selecting management and cultivars balancing yield and quality is crucial in plant breeding.

The positive correlation between FY and WA indicates that cultivars with higher flour yield may possess increased water absorption capacity, impacting dough hydration and final bread quality [35]. This results from a higher dietary fiber content with high water absorbency [36].

Between MIM and HIM, we observe differences in the strength of the relationships between characteristics. We observe a significantly stronger negative correlation between GY and protein content PC or between PC and FN in HIM compared to MIM. This makes the protein content more sensitive to spring wheat productivity in HIM. Generally, in HIM, we observe more substantial dependencies of PC on other considered characteristics. We also observe a change in the type of relationship between levels of crop management. We see this situation for PC and WA; for MIM, this relationship is positive, and for HIM, it is negative. These crop management methods are not optimal and contribute to biotic and abiotic stresses in plants, unlike in HIM, where optimal fertilization and plant protection are applied. Unfortunately, a different field experiment would have to be conducted to indicate a single element of applied crop management to demonstrate this. These elements would be studied as separate factors, which would significantly complicate the statistical analysis of this type of multi-environment trial.

This complicates the formulation of clear recommendations and obtaining a homogeneous raw material. These results are specific to spring wheat cultivars and MIM/HIM crop managements; outcomes may differ for other wheat types, regions, or approaches.

5. Conclusions

This study assessed the influence of genotype, environment, and crop management practices on yield and bread-making quality traits in spring wheat cultivars. Our findings revealed significant genotype-environment interactions, particularly emphasizing the role of location and crop management in shaping both yield and grain quality. While high-input management systems generally enhanced yield and protein content, moderate-input systems showed improved loaf volume and bread-making traits, indicating that no single management practice universally optimizes all desired characteristics. The multi-trait stability index (MTSI) analysis emphasized the variability in cultivar stability across environments, with specific genotypes excelling in different management systems. This underlines the importance of considering crop management and the environment when selecting genotypes for stable wheat production in a changing climate.

Future breeding programs should focus on multi-trait stability to identify genotypes that maintain high grain quality and yield under varying environmental conditions. Such efforts will be crucial to ensure stable and high-quality wheat production under the pressures of climate change.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14122131/s1, Table S1: The characteristics of soil and climate conditions at the trial locations in two growing seasons. Table S2: Descriptions of study spring wheat cultivars.

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Abbreviations

Crumb hardness (CH), dough development (DD), dough softening (DSF), dough stability (DS), flour yield (FY), gluten index (GI), grain ash content (AC), grain protein content (PC), grain yield (GY), falling number (FN), high-input management (HIM), loaf volume (LV), moderate-input management (MIM), test weight (TW), thousand-grain weight (TGW), quality number (QN), water absorption (WA), wet gluten content (WG), Zeleny sedimentation value (SV).

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1.1.2 Full Text of the Published Article 2

Title: Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates

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Article

Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates

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Abstract: This study examines the significant variability in grain yield, thousand-grain weight, protein content, sedimentation value, and falling number among winter wheat cultivars across diverse trial locations, elucidating the profound influence of environmental factors on these traits. Employing Shukla's stability variance and a multi-trait stability index (MTSI), cultivar stability is comprehensively assessed across multiple traits. Cultivars are ranked based on stability variance and cumulative ranking across all traits, with Bataja emerging as the most stable cultivar according to Shukla variance, while Apostel exhibits the lowest stability. Contrarily, MTSI rankings reveal distinct top performers, such as Medalistika and KWS Spencer. Canonical correspondence analysis (CCA) is utilized to discern relationships between stability and genotype characteristics, as well as trait values and soil properties/weather conditions. These findings contribute to the recommendation of stable cultivars for breeding programs and the optimization of crop management practices. Furthermore, this study underscores the need to explore causal relationships between accompanying variables, facilitating informed recommendations for plant breeders and advancing breeding progress amidst a changing climate. The use of multivariate statistical methods, including CCA, enhances our understanding of cultivar traits and stability, offering valuable insights for sustainable agriculture.

Keywords: Shukla stability variance; multi-trait stability index; protein contents; canonical correspondence analysis

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1. Introduction

Wheat is one of the most important crops grown worldwide and plays a crucial role in ensuring global food security [1,2]. Different forms of this species are cultivated, which are also related to its intended purpose and later use. In the temperate climate of Central Europe, the most popular form is winter wheat, characterized by high yields and good bread-making properties. Spring wheat, unfortunately, very often has a one-third lower yield, which is why it is not very popular [3].

Ongoing climate change and the associated various types of extreme weather phenomena have a negative impact both on yield value and on important grain quality traits [4]. Therefore, in such conditions, it becomes important to search for stable and widely adapted genotypes not only in terms of yield but also other important quality traits [5]. Until now, the common practice was to assess the stability of cereal cultivars for yield alone, neglecting the assessment of other grain quality traits that could be considered important for obtaining a good quality final product, such as bread.

Many previous studies have focused on assessing the stability of genotypes, mostly descriptively presenting stable and unstable genotypes. There has been no attempt to explain why certain genotypes are less or more stable. One method of finding the cause of the degree of stability may be by investigating causal relationships or other relationships between accompanying variables, e.g., those that characterize cultivars (e.g., disease resistance). Finding such relationships and connections will allow for the preparation of appropriate recommendations for plant breeders, which will facilitate both the phenotypic and genotypic selection of genotypes. Understanding the factors affecting the degree of cultivar stability will increase breeding progress and contribute to increased food security in a changing climate.

Multivariate statistical methods can be used to search for relationships between cultivar's traits and their stability. One method that can be applied in this case is canonical correspondence analysis CCA [6], which is widely used in ecological research [7,8]. These methods have been used in other scientific fields as well. CCA is used to study the relationships between species abundance and environmental characteristics. CCA is one method in the group of ordination analysis methods [9], similar to the well-known and widely used PCA in agronomic research. The only difference is that CCA can search for relationships between two data sets (data matrix). We would like to propose and present the CCA method for exploring the relationship between cultivar stability and plant descriptions as well as environments. Finding such relationships will increase the efficiency of breeding efforts in the search for stable cultivars. It also serves an important scientific purpose, allowing for the justification or identification of traits that make certain genotypes stable while others are unstable. In addition to presenting the CCA method, we would like to investigate whether resistance to fungal diseases and lodging will influence the stability of yield and quality traits in winter wheat. Identifying such variables will lead to better recommendations for cultivar selection and the discovery of valuable parental forms. Therefore, the aim of the study is to (1) evaluate the stability of yield and other quality traits of winter wheat cultivars using both univariate and multivariate methods, (2) identify relationships between stability and genotype characteristics, and (3) investigate the relationships between trait values and soil properties.

2. Materials and Methods

2.1. Field Experiment and Study Traits

This study used data from multi-environment trials (METs) conducted within the framework of the Polish cultivar recommendation system for farmers, which is supervised by the Polish Research Centre for Cultivar Testing (COBORU). The MET included 55 winter wheat varieties tested in 12 locations over 5 growing seasons (2015/2016–2019/2020), constituting 60 environments. Each experiment in the MET was conducted in an alpha-design with 2 replicates, and the area of each plot was 15 m^2. The soil characteristics of trial locations including, among others, reference bulk density, soil organic carbon stock, and cation exchange capacity are presented in Table S1. These data are presented as average values from all growing seasons. Due to low variability and to ensure soil health, these values constitute a permanent characteristic of specific locations. Crop management in each experiment included two fungicide applications at the Zadoks growth stage (GS) 31–32 [10] and GS 49–60, as well as a growth regulator (trinexapac-ethyl) application at GS 31. Fungicidal active agents (azoxystrobin, cyproconazole, and propiconazole) were selected depending on the severity of the occurrence of fungal diseases. A nitrogen dose of 40 kg ha^{-1} higher than the optimal dose for the given conditions at the location was also applied. Data for five variables were used: grain yield, thousand-grain weight, protein content, sedimentation value, and falling number.

The grain yield (GY) and thousand-grain weight (TGW) were determined from a 1 m^2 sample collected from the center of the whole plot. The protein content (PC) ($N \times 5.7$) was determined according to the Kjeldahl method (AACC Method 46-11.02), and the sedimentation value (SV) was obtained by the Zeleny method (AACC Method 56-61.02). The falling number (FN) was determined using the Hagberg–Perten method (AACC Method 56-81B).

In addition to these variables, we utilized the evaluation of variety resistance to winter survival (WH), lodging (RTL), and major fungal diseases (including powdery mildew, PM; brown rust, BR; Septoria leaf blight, SLB; chaff Septoria, CS; diseases of the stem base, DSB; and Fusarium ear blight, FEB). The evaluation was conducted on a 9-point scale, where 1 represents the worst condition and 9 the best condition for plants. These data are presented in Table S2 as average values across environments (comprising combinations of 12 locations and 5 growing seasons) (Supplementary Materials).

2.2. Statistical Methods

The statistical analysis of all study traits was performed using a single-stage approach for a linear mixed model (LMM) with the restricted maximum likelihood (REML) method, based on models shown below:

$$y_{ijklhn} = \mu + g_k + l_j + a_i + ga_{ki} + gl_{kj} + la_{ji} + gla_{kji} + r_{jih} + b_{jihn} + e_{ijklhn} \quad (1)$$

where y_{ijklhn} is the value of the trait under consideration; μ is the overall mean; g_k is the fixed effect of kth cultivar; l_j is the random effect of jth location; a_i is the random effect of ith growing season; ga_{ki} is the random interaction effect of the kth cultivar and ith growing season; gl_{kj} is the random interaction effect of the kth cultivar and jth location; la_{ji} is the random interaction effect of the ith growing season and jth location; gla_{kji} is the random interaction effect of kth cultivar, jth location, and ith growing season; r_{ji} is the random effect of the hth replication nested in the jth location during the ith growing season; b_{jihn} is the random effect of the nth block nested in the hth replication at the jth location during the ith growing season; and e_{ijklhn} is the random error associated with the trait under observation y_{ijklhn}.

Based on a linear mixed model (1), we calculated adjusted means of yield and studied grain quality traits for the main effects of cultivars and locations, as well as cultivar × location × growing season combinations, using the algorithm described by [11]. These calculated adjusted means will serve as the basis for determining stability parameters and other statistical measures.

We utilized Shukla's stability variance [12] to assess the cultivar stability of each study trait individually. Additionally, we employed a multi-trait stability parameter (MTSI) as described by [13] to evaluate stability across all study traits simultaneously. This parameter facilitates the assessment of genotype stability across multiple traits concurrently, enabling the identification of genotypes with the highest degree of stability across all considered traits. The MTSI parameter is based on factor analysis for the matrix of standardized study trial means, with means standardized using the value of genotype–environment interaction effects. Its parameter interpretation aligns with commonly used stability indices, such as Shukla stability variance, where lower values indicate better stability. The MTSI indicators and Shukla stability variance for the combinations of year and location were treated as distinct environments.

We examined the relationship between the value of Shukla stability variance for all study traits and the characteristics of cultivars from Table S1 using canonical correspondence analysis (CCA). Furthermore, CCA was utilized to evaluate the relationships between the characteristics of locations presented in Table S2 and the mean values of yield and other traits in those locations. CCA is a technique that enables the description of response variable matrices as a linear combination of predictor variable matrices. The results of the analysis are visualized on a biplot graph, with interpretation similar to other widely used methods.

All statistical analyses were conducted using R 4.3.0 software [14]. Shukla's stability variance and MTSI were derived using the metan package [15], while the CCA approach was implemented using the vegan package.

3. Results

The average values and coefficients of variation (CV) of the investigated traits for individual locations are presented in Table 1. Grain yield ranged from 80 dt ha^{-1} (location Bialogard) to 126 dt ha^{-1} (location Lisewo). However, the variability in this trait was also strongly diversified depending on the location; the lowest variability with a CV of 4.32% was observed in Jelania Góra, while the highest variability with a CV of 23.60% was found in Krzyzewo. The lowest protein content was 11.28% in Jelenia Gora, whereas the highest value was 13.86% in Sulejow. The variability in this trait also strongly depended on the location, ranging from CV = 4.43% in Krzyzewo to CV = 14.86% in Jelenia Gora.

Table 1. Mean and coefficient of variance (CV) for winter wheat traits of trial locations across trial locations and growing seasons.

Location	Yield (t ha^{-1})		Thousand-Grain Weight (g)		Protein (%)		Falling Number (s)		Zeleny Test (mL)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Bezek	9.22	12.87	46.29	8.82	13.64	6.03	350.48	24.47	90.25	6.69
Bialogard	8.042	21.18	51.21	8.33	12.66	6.01	319.19	23.87	75.46	12.88
Glubczyce	12.03	6.69	43.38	10.26	12.89	7.46	361.66	18.91	83.21	8.98
Jelenia Góra	10.02	4.32	41.91	8.68	11.28	14.86	351	15.49	79.2	9.53
Kaweczyn	9.73	9.64	46.72	15.78	13.45	12.69	377.05	18.05	86.81	7.39
Koscielna Wies	10.73	14.97	41.5	8.56	13.73	5.98	385.32	16.86	86.02	7.65
Krzyzewo	9.12	23.6	43.21	6.73	13.03	4.43	341.71	25.86	84.04	8.66
Lisewo	12.64	6.57	49.76	6.25	12.21	8.34	347.97	20.26	85.1	8.02
Pawlowice	9.36	9.82	38.43	18.7	13.11	10.63	396.45	16.15	85.34	7.43
Ruska Wies	8.72	15.35	45.5	9.64	12.91	10.17	337.22	22.13	85.6	9
Sulejów	8.57	14.97	38.91	13	13.86	5.97	405.71	11.88	80.6	12.1
Wegrzce	11.13	6.54	50.29	5.99	11.69	9.19	327.5	26.04	80.64	9.61

The yield for the examined fifty-five varieties ranged from 91.07 dt ha^{-1} (Moschus) to 120.27 dt ha^{-1} for the Hybery cultivar (Table 2). Meanwhile, the coefficient of variation (CV) ranged from 7.44% (cultivar Bonanza) to 31.17% (cultivar Kometa). The average protein content for individual cultivars ranged from 11.63 (Hybery) to 14.18 (Impresja).

A lower value of Shukla variance reflects higher stability. Cultivars containing the least Shukla variance are ranked 1st in the Shukla stability ranking (Table 3). According to the Shukla variance, Bataja, SY Cellist, Bataja Opoka, and RGT Provision were the most stable cultivars in terms of yield, thousand-grain weight, protein, falling number, and Zeleny test, respectively. The cultivars Kometa, SU Mangold, Comandor, Błyskawica, and Plejada displayed the highest Shukla variance and were the least stable in terms of yield, thousand-grain weight, protein, falling number, and Zeleny test, respectively.

In the context of the Shukla stability variance ranking sum, cultivars with the lowest sum are considered the most stable, while those with the highest sum are regarded as the least stable. Among all cultivars, Apostel had the highest stability sum (243), signifying the least stability, whereas Bataja emerged as the most stable cultivar with the lowest stability sum (37).

We performed individual multi-trait selection index (MTSI) analyses for all fifty-five winter wheat cultivars across environments created as a combination of locations and growing seasons, as outlined in Table 3. To identify the most stable performers, we applied a selection pressure of 15%. Among these cultivars, Medalistika (1.81) and KWS Spencer (2.01) emerged as the top-ranked, securing the first and second positions in terms of stability.

In terms of the stability of varieties, measured as the Shukla stability variance ranking sum for all traits, and the MTSI parameter, we observe a lack of consistency between metrics in the assessment of variety stability. Completely different varieties are considered to be multi-stable when applying the sum of rankings and MTSI parameters. This can be shown through a low correlation coefficient value of 0.17 (p-value < 0.0001).

Table 2. Mean and coefficient of variance (CV) for winter wheat traits of cultivars across trial locations and growing seasons.

Cultivars	Yield (t ha^{-1})		Thousand-Grain Weight (g)		Protein (%)		Falling Number (s)		Zeleny Test (mL)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Admont	10.18	21.64	44.18	14.69	12.87	6.62	295.83	33.16	83.46	6.99
Ambicja	9.63	11.7	46.83	14.02	13.58	9.43	399	11.26	90.58	4.64
Apostel	9.92	25.95	47.65	11.6	13.02	7.34	363.22	13.53	82.11	7.96
Argument	9.39	10.68	45.52	13.02	13.4	11.04	336.42	17.83	90.88	5.96
Artist	10.45	18.07	46.68	11.85	12.39	12.15	381.91	9.24	88.82	5.62
Bataja	9.17	19.8	44.89	10.2	13.03	7.16	351.94	13.09	87.5	7.47
Blyskawica	9.98	28.15	46.45	9.64	12.58	6.17	201.56	51.5	77.34	9.07
Bonanza	11.69	7.44	47.63	10.55	11.89	9.71	337.5	26.13	78.67	10.75
Bosporus	9.84	16.36	42.26	15.72	12.68	7.71	339.56	14.97	78.61	10.15
Comandor	10.11	23.24	44.33	9.01	13.26	7.54	392.61	12.81	77.53	9.81
Euforia	10.34	25.35	45.02	9.07	13.35	6.9	398	9.95	82.17	7.58
Formacja	9.99	21.35	43.06	12.87	13.2	9.45	382.95	10.1	84.81	6.03
Hybery F1	12.03	8.4	46.28	11.12	11.63	7.27	337.67	14.2	76.08	11.51
Impresja	9.53	15.69	43.7	11.79	14.18	7.35	375.25	13.84	80.92	8.6
Kariatyda	9.67	12.54	46.12	11.77	13.7	9.42	398.33	12.61	84.04	8.71
Kometa	9.47	31.17	43.62	15.33	13.19	14.02	348.67	17.32	68.25	10.2
KWS Donovan	10.12	18.92	43.55	12.69	13.05	7.73	350.88	8.83	74.67	10.64
KWS Firebird	10.60	17.48	43.12	14.66	13.05	10.25	398.8	11.38	91.3	4.32
KWS Spencer	10.38	19.87	47.49	14.22	12.94	12.62	390.13	18	89.83	4.47
KWS Talium	9.46	12.48	41.38	12.06	13.01	10.32	384.08	15.37	87.13	9.4
KWS Universum	9.46	15.42	44.31	13.36	13.52	10.6	371.25	14.3	85.13	8.65
LG Jutta	10.52	11.61	39.78	13.09	12.03	11.19	343.75	16.35	80.42	7.47
LG Keramik	9.88	20.05	43.34	10.79	13.14	5.61	336.78	17.15	91.06	5.41
Lindbergh	10.30	22.97	46.15	9.72	12.62	10.73	353.67	14.36	75.5	5.54
Lokata	9.78	22.74	44.29	8.79	13.26	7.38	401.33	16.92	83.14	8.32
Medalistka	10.76	13.83	48.71	12.55	12.32	10.97	396.5	11.92	84.21	7.25
MHR Promienna	9.34	13.85	41.95	12.1	12.94	9.32	313.33	21.33	84.67	9.28
Moschus	9.11	21.55	45.99	8.48	14.15	7.3	428.06	8.55	90.17	4.85
Nordkap	10.38	20.8	46.08	11.52	12.96	10.28	381.5	14.47	87.46	5
Opcja	9.98	15.51	41.96	16.79	12.45	10.3	313.83	22.38	73.71	6.37
Opoka	9.63	20.39	48.56	12.49	13.41	7.01	377.94	9.46	84.63	7.67
Owacja	10.70	17.92	44.76	12.34	12.72	11.26	311.93	20.76	80.17	6.56
Patras	9.67	23.26	49.86	10.86	13.31	9.11	384.27	19.24	84.4	6.2
Plejada	10.10	28.84	46.19	9.35	12.5	7.46	362.44	15.6	79.44	10.88
Reduta	9.73	21.06	45.37	12.01	13.14	7.7	377.67	14.18	81.14	7.55
RGT Bilanz	10.93	19.83	45.29	10.31	12.49	9.2	378.93	15.92	89.9	4.28
RGT Kilimanjaro	10.24	19.64	45.15	12.76	13.3	9.27	407.9	7.97	89.98	4.85
RGT Metronom	10.34	18.1	48.51	13.41	13.4	11.31	385.6	19.99	87.93	1.97
RGT Provision	9.71	18.27	44.08	10.45	12.9	7.37	288.17	19.99	80.67	6.79
RGT Ritter	10.02	13.57	47.18	11.74	13.07	10.28	373.33	16.86	80.5	6.84
RGT Specialist	9.63	18.77	41.28	11.13	12.88	7.6	369.83	14.74	83.31	5.31
Rivero	10.62	14.45	42.55	14.48	12.22	10.6	387.75	15.07	85.88	5.31
Sfera	10.47	17.44	43.86	17.89	12.65	10.06	349.2	16.46	75.93	8.28
SU Mangold	9.94	10.84	41.45	19.95	13.27	11.26	339.83	29.61	81.88	6.66
SU Petronia	10.08	15.57	44.08	14.62	12.94	12.09	275.67	35.36	70.71	8.27
SU Tarroca	10.18	16.53	48.82	11.74	13.02	10.93	245.67	29.76	62.88	12.12
SU Viedma	9.87	19.94	46.76	15.78	13.39	8.65	284.78	22.62	80.56	10.46
SY Cellist	9.50	15.21	44.2	12.23	13.57	11.29	358.33	18.8	86.21	6.67
SY Dubaj	9.32	20.37	47.69	8.36	13.6	7.45	431.22	7.15	93.81	7.91
SY Orofino	10.21	20.33	46.45	11.14	12.71	6.66	285.28	19.98	85.39	5.44
SY Yukon	9.37	20.32	44.81	10.58	13.12	7.02	439.83	7.28	94.31	5.23
Symetria	9.34	12	38.96	14.54	13.16	9.88	412.58	6.14	80.79	8.79
Titanus	10.65	22.09	48.2	13.06	12.56	9.31	292.87	35.77	92.4	3.95
Tytanika	10.42	19.68	41.3	14.96	12.61	8.31	315.07	28.97	74.5	8.75
Venecja	9.83	18.64	46.69	13.82	13.11	5.14	376.11	10.66	89.56	5.34

Table 3. Ranked Shukla stability variances, the cultivars' cumulative ranking across all study traits, and the multi-trait stability index.

Cultivars	Ranking of Shukla Stability Variance								MTSI	
	Yield	Thousand-Grain Weight	Protein	Falling Number	Zeleny Test	Sum	Min	Max	Value	Ranking
Admont	38	44	36	54	44	216	36	54	3.85	36
Ambicja	22	20	25	31	7	105	7	31	2.77	14
Apostel	48	47	51	43	54	243	43	54	2.82	16
Argument	35	4	43	32	27	141	4	43	3.46	25
Artist	19	24	49	11	25	128	11	49	2.13	3
Bataja	1	13	1	8	14	37	1	14	3.54	27
Błyskawica	49	48	40	55	50	242	40	55	4.6	46
Bonanza	25	36	11	40	46	158	11	46	3.21	19
Bosporus	17	35	10	10	37	109	10	37	4.53	45
Comandor	32	42	55	39	49	217	32	55	3.84	35
Euforia	50	30	52	29	53	214	29	53	3.34	20
Formacja	6	3	39	22	22	92	3	39	3.78	31
Hybery F1	33	41	13	9	48	144	9	48	3.72	30
Impresja	5	29	17	35	36	122	5	36	4.64	48
Kariatyda	4	50	38	41	20	153	4	50	3.35	21
Kometa	55	32	31	33	19	170	19	55	5.28	54
KWS Donovan	8	18	22	2	31	81	2	31	4.36	42
KWS Firebird	14	14	41	7	28	104	7	41	2.69	13
KWS Spencer	41	52	44	28	40	205	28	52	2.01	2
KWS Talium	11	11	28	46	16	112	11	46	4.19	39
KWS Universum	46	40	33	16	11	146	11	46	4.1	38
LG Jutta	42	6	16	26	38	128	6	42	4.39	44
LG Keramik	44	2	15	17	6	84	2	44	3.39	24
Lindbergh	54	12	19	27	9	121	9	54	3.52	26
Lokata	40	31	54	49	52	226	31	54	3.56	28
Medalistka	37	33	12	15	43	140	12	43	1.81	1
MHR Promienna	15	5	35	37	21	113	5	37	4.73	49
Moschus	43	8	27	12	2	92	2	43	3.79	32
Nordkap	53	37	9	19	12	130	9	53	2.5	8
Opcja	51	25	14	50	18	158	14	51	4.91	50
Opoka	26	21	21	1	15	84	1	26	2.67	12
Owacja	12	26	48	36	47	169	12	48	3.84	34
Patras	31	27	7	24	3	92	3	31	2.25	5
Plejada	52	28	45	42	55	222	28	55	3.36	23
Reduta	24	49	50	44	51	218	24	51	3.71	29
RGT Bilanz	30	23	20	14	33	120	14	33	2.28	6
RGT Kilimanjaro	2	22	18	4	4	50	2	22	2.45	7
RGT Metronom	10	45	46	34	34	169	10	46	2.14	4
RGT Provision	13	16	5	23	1	58	1	23	4.32	41
RGT Ritter	3	53	23	38	32	149	3	53	2.98	18
RGT Specialist	21	7	8	21	10	67	7	21	4.26	40
Rivero	47	10	3	20	24	104	3	47	2.97	17
Sfera	9	51	32	18	41	151	9	51	4.38	43
SU Mangold	18	55	37	48	26	184	18	55	4.61	47
SU Petronia	7	43	53	52	30	185	7	53	5.38	55
SU Tarroca	20	54	42	30	39	185	20	54	5.11	52
SU Viedma	23	46	34	45	29	177	23	46	3.94	37
SY Cellist	34	1	30	25	23	113	1	34	3.83	33
SY Dubaj	28	34	4	5	13	84	4	34	2.62	11
SY Orofino	27	9	47	51	45	179	9	51	3.36	22
SY Yukon	16	17	2	6	5	46	2	17	2.78	15
Symetria	39	39	24	13	8	123	8	39	5.09	51
Titanus	45	15	29	53	35	177	15	53	2.52	9
Tytanika	29	38	26	47	42	182	26	47	5.13	53
Venecja	36	19	6	3	17	81	3	36	2.57	10

The strongest positive correlation was observed between the Zeleny sedimentation test and the Hagberg falling number, while a negative correlation was found between protein content and thousand-grain weight (Figure 1). We also observe a negative correlation between protein content and yield (−0.25) as well as protein content and thousand-grain weight (−0.35).

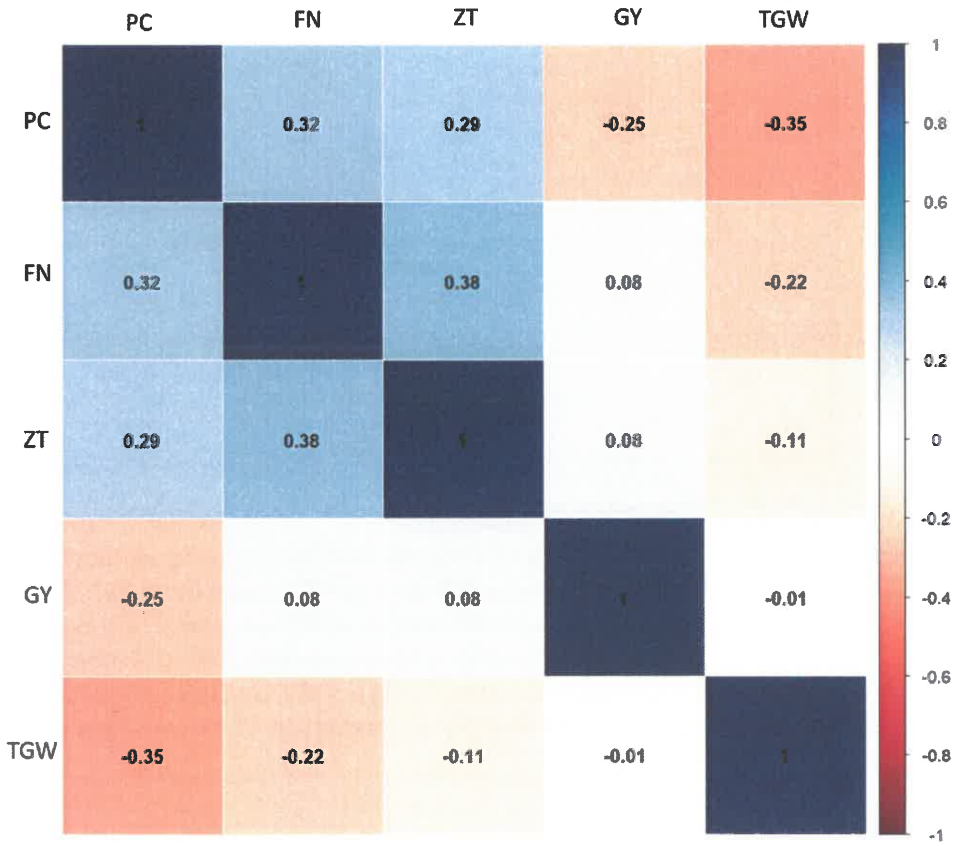

Figure 1. A correlation analysis for all study traits across genotypes and study environments. Protein content, PC; falling number, FN; Zeleny test, ZT; grain yield, GY; thousand-grain weight, TGW.

In the CCA analysis (Figure 2), we observed relationships between the mean values of the studied traits in locations and the chemical and physical properties of soils in those locations (presented in Table S1). We observed a correlation between yield in the location and the available water capacity class (AWCC) according to the FAO Harmonized World Soil Database and Soil Organic Carbon Stock. For TGW, there is a relationship with the clay fraction. Traits related to grain quality, such as protein content, falling number, and Zeleny test, exhibited a similar pattern dependent on soil nutrient availability class, sand fraction, and phosphorus content.

Figure 3 presents the results of CCA for the mean values of study traits and evaluation of cultivars' resistance (from Table S2). We observe a strong correlation between the mean values for protein content and resistance to lodging and Septoria leaf blight. The mean thousand-grain weight was dependent on chaff septoria. Unfortunately, for grain yield, falling number, and Zeleny test, it is not possible to identify variables characterizing cultivars that have an impact on the values of these traits.

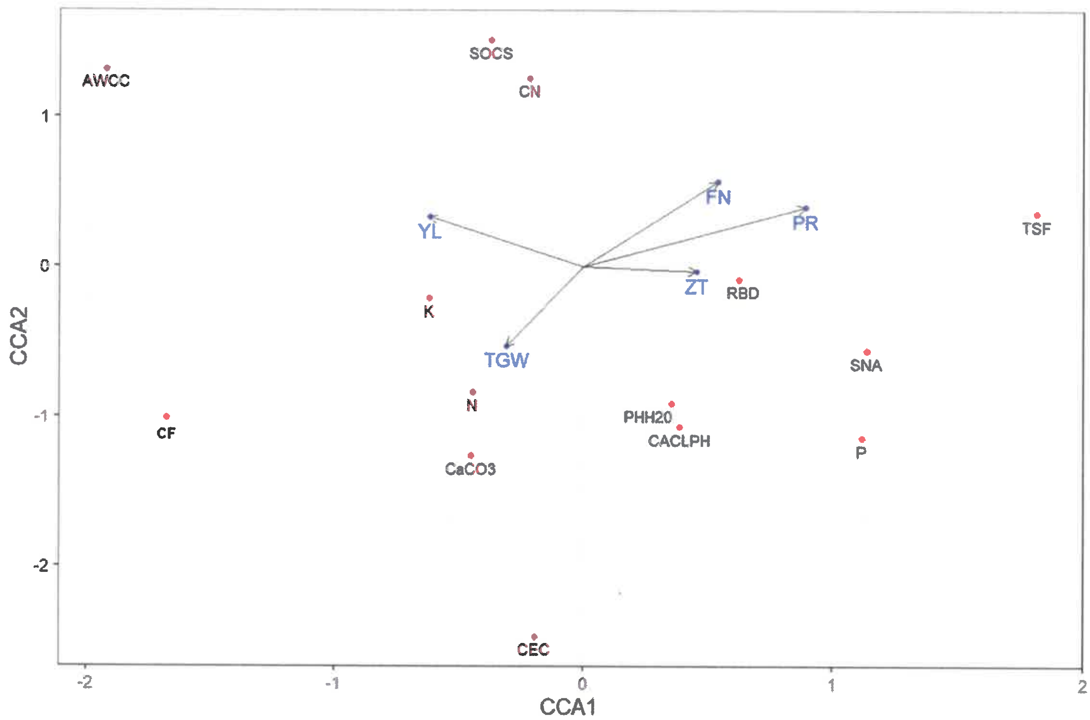

Figure 2. Biplot CCA for trial locations containing means of the study traits and soil characterizing locations. Reference bulk density, RBD; sand fraction, TSF; clay fraction, CF; soil nutrient availability class, SNA; available water capacity class, AWCC; soil organic carbon stock, SOCS; calcium carbonates, $CaCO_3$; cation exchange capacity, CEC; C:N, CN; potassium content, K; nitrogen content, N; phosphorus content, P; pH in CaCl, CACLPH; pH in H_2O, PHH20; protein content, PR falling number, FN; Zeleny test, ZT; grain yield, YL thousand-grain weight, TGW.

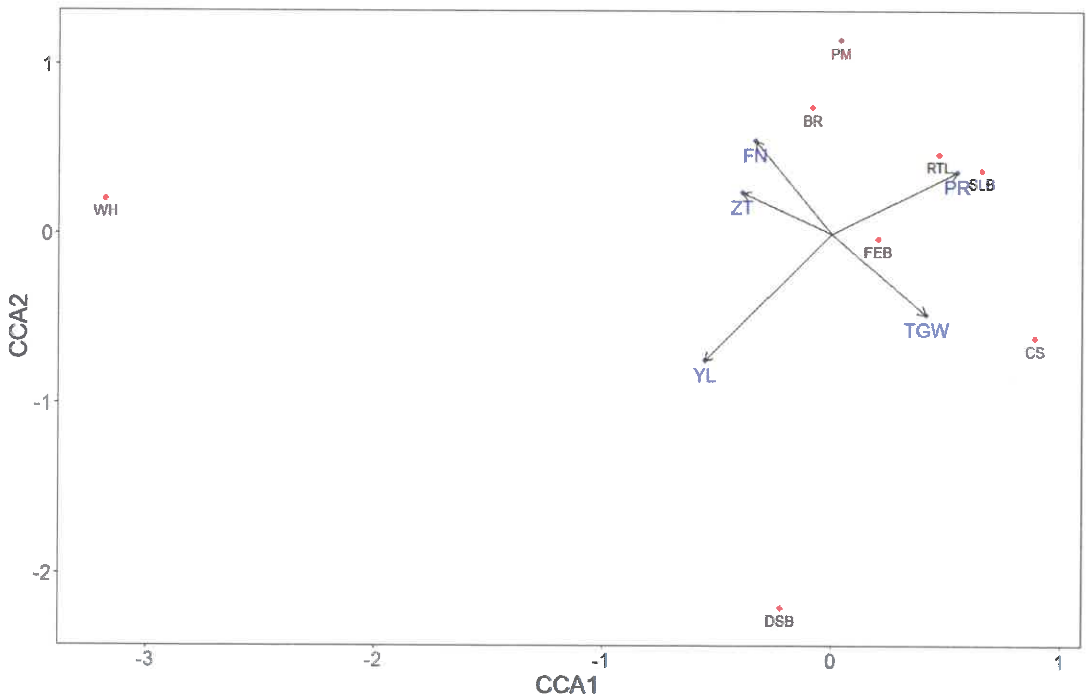

Figure 3. Biplot CCA for cultivar means of the study traits and additional traits characterizing these cultivars. Winter hardiness, WH; resistance to lodging, RTL; powdery mildew, PM; brown rust, BR; Septoria leaf blight, SLB; chaff Septoria, CS; diseases of the stem base, DSB; Fusarium ear blight, FEB; protein content, PR falling number, FN; Zeleny test, ZT; grain yield, YL; thousand-grain weight, TGW.

Figure 4 presents the results of CCA for cultivars' Shukla stability variances of study traits and additional traits characterizing cultivars. We observed a strong correlation between yield stability and resistance to chaff Septoria, powdery mildew, and brown rust. For traits related to grain quality such as protein content, falling number, and Zeleny test, we observed a positive correlation, confirming the results of Pearson correlation analysis presented in Figure 1. The stability of thousand-grain weight was dependent on resistance to lodging and diseases of the stem base. The stability of protein content and the stability of Zeleny sedimentation values were dependent on Fusarium ear blight and winter hardiness.

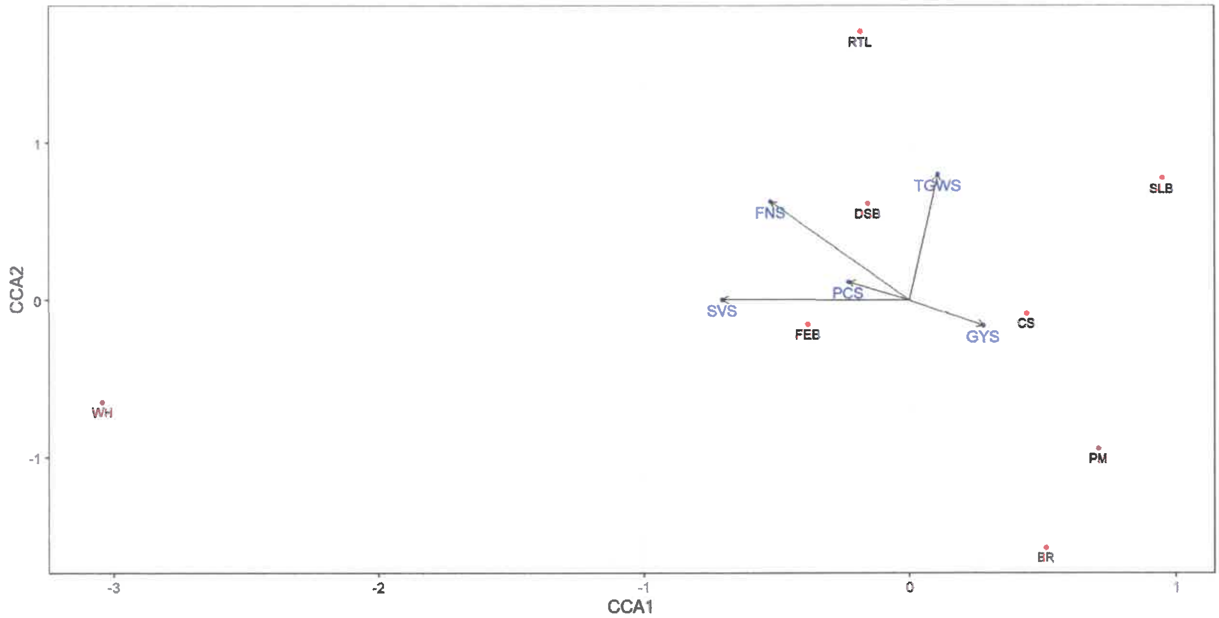

Figure 4. Biplot CCA for cultivars' Shukla stability variance of study traits and additional traits characterizing these cultivars. Winter hardiness, WH; resistance to lodging, RTL; powdery mildew, PM; brown rust, BR; Septoria leaf blight, SLB; chaff Septoria, CS; diseases of the stem base, DSB; Fusarium ear blight, FEB; protein content Shukla stability PCS; falling number Shukla stability, FNS; Zeleny test Shukla stability, SVS; grain yield Shukla stability, GYS; thousand-grain weight Shukla stability, TGWS.

4. Discussion

Assessing the stability of varieties is an important issue related to both genetic and agronomic progress in a changing climate [16,17]. It allows for the identification of genotypes or cultivars adapted to specific climatic and soil conditions, as well as production requirements. Stability is commonly used in recommending cultivars for cultivation by farmers, with tests conducted by state institutions or producer associations. These studies pinpoint specific genotypes recommended for cultivation in a given region [18]. Due to the high turnover of cultivars in the market and the fact that such recommendations are tailored to local conditions, they may not be of interest to a wider audience of scientists, including plant breeders [19]. However, understanding the relationships and dependencies of stability on genotype properties allows for generalization and inference, leading to an understanding of the causes of stability. As mentioned in the Introduction, there is currently a lack of research in this area. In our study, we proposed using a multivariate method, canonical correspondence analysis (CCA), to search for causal relationships.

A comprehensive assessment of cultivar stability should not focus solely on individual traits. For many traits, especially in the case of grains, it should encompass grain quality characteristics, or even baking quality traits. We also proposed the sum of Shukla's variance rankings for each of the studied traits, which would serve as a synthesis of stability evaluations for individual traits. This approach allows for the selection of cultivars that are most stable across multiple traits simultaneously. However, this approach is straightforward and has several drawbacks. For instance, it may classify a cultivar as multivariate stable even if it ranks unfavorably for one of the traits in the stability ranking (high Shukla variance value). This limitation may become apparent, especially in datasets where a large number of traits are considered simultaneously. Therefore, in addition to the sum itself, we also provide the minimum and maximum values of the Shukla variance ranking for each cultivar. Olivoto et al. [20] proposed a multivariate model based on factor analysis, which allows for the assessment of stability using a single parameter value for multiple considered traits, referred to as MTSI. For our dataset of winter wheat cultivars, we observe a low level of agreement between the sum of Shukla variance rankings and the MTSI parameter. Many studies have been conducted comparing the agreement of assessments between different stability parameters, but they mainly focused on individual traits. These previous studies indicate that the level of agreement between parameters depends on the species, trait, and climatic conditions of the conducted trials [21].

Identified genotypes that are stable for all simultaneously important traits, whether through the Shukla variance ranking sum or the MTSI parameter, constitute valuable parental forms for breeding programs. In our set of cultivars, such genotypes of interest to breeders or other researchers include, Bataja and SY Yukon for the Shukla variance ranking sum and Medalistka and KWS Spencer for the MTSI. The application of CCA analysis to the mean values of the varieties showed a strong relationship between the protein content of the varieties and resistance to lodging and Septoria leaf blight [22,23]. Unfortunately, for the yield, the CCA analysis did not allow for the identification of any of the applied variables characterizing the varieties. This is probably due to the limited set of additional cultivar characteristics used.

The utilization of the CCA method facilitated the identification of traits that characterize cultivars and play a vital role in shaping the stability of key traits in the dataset of winter wheat. It was demonstrated that the stability of grain yield was contingent upon resistance to chaff Septoria, powdery mildew, and brown rust, factors closely associated with weather conditions [24,25]. The greater resistance of cultivars to these diseases resulted in reduced yield variability due to environmental conditions, consequently leading to greater yield stability. If plant breeders aim to enhance genotype stability regarding yield, they should focus on selecting cultivars resistant to these three fungal diseases. However, for grain quality traits, we observe that winter hardiness had a significant impact on their stability. A high level of plant healthiness post-winter for a cultivar allows for stable values of these traits across various environmental conditions. Varieties with low winter hardiness will exhibit significant variability depending on prevailing winter conditions, and the values of these traits will be more strongly influenced by wintering conditions, whether favorable or not. Having information about the cultivar traits that are important for their stability increases the efficiency of breeding work, both phenotype-based and genotype-based. It allows for the selection of these traits and/or their markers to focus on and pay special attention to during selection [26,27]. This will significantly improve efficiency and optimize the costs of genotype-based breeding [28].

Unfortunately, for the presented dataset, different variables characterizing varieties were related to the mean values of traits, while others were related to the Shukla stability cultivar. This further complicates the selection of traits that breeders should focus on. Ideally, the same traits characterizing the cultivar would have an impact on both the mean values of traits and their stability assessment.

5. Conclusions

In conclusion, the evaluation of cultivar stability should not solely focus on identifying varieties or recommending cultivars with a high degree of stability but should always be complemented by seeking relationships and causes of this stability, including the use of other traits characterizing cultivars or environments. We have demonstrated that yield stability was strongly dependent on the degree of resistance to the following fungal diseases:

chaff Septoria, powdery mildew, and brown rust. However, traits related to the grain quality (e.g., protein contents, filling numbers) of winter wheat grain were dependent on winter hardiness. This will certainly contribute to breeding progress, especially the selection of multi-traits stable genotypes of winter wheat in temperate climates. Information about traits strongly associated with shaping the mean values and stability of the traits under study will ensure food security in a changing climate. The application of the CCA method proved to be a useful tool for exploring the relationships between the stability of grain traits and cultivar characteristics.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy14040779/s1, Table S1. Characteristics of winter wheat cultivars based on official registration test. Table S2. Soil characteristics of study location.

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1.1.3 Full Text of the Published Article 3

Title: Influence of Crop Management on Stability of Rye Yield and Some Grain Quality Traits

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ORIGINAL ARTICLE

Agronomy, Soils, and Environmental Quality

Influence of crop management on stability rye yield and some grain quality traits

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Abstract

The study explored the performance of hybrid and population rye (*Secale cereale*) cultivars under two different crop management intensities in Poland: moderate-intensity and high-intensity management. The focus was grain yield, grain quality, yield components, and variety stability in two growing seasons (2018/2019 and 2019/2020) at three locations. Hybrid cultivars consistently yielded higher grain yields (9.81 t ha^{-1}) than population cultivars (7.90 t ha^{-1}), with increase of 24.9%. However, hybrid cultivars had lower protein content (8.94%) than population cultivars (9.77%). Spike number was the most influential factor on yield, followed by 1000-grain weight and grains per spike, regardless of cultivar type. Hybrid cultivars displayed a lower degree of stability as assessed using the ranking sum of the Shukla variance and the multi-trait stability index. Hybrid cultivars were strongly dependent on resistance to fungal diseases, including *Septoria* (*Mycosphaerella graminicola*), and increased stability under moderate-intensity management. Resistance to soil acidification became more important for cultivar stability under high-intensity management.

1 | INTRODUCTION

Climate change may severely affect the yield stability and damage the yield and quality of field crops due to the prevailing impacts of environmental stresses (Müller et al., 2018; Trębicki et al., 2015). Evaluation of cereal crops' yield and grain quality stability under various climatic changes is a highly relevant topic.

Rye (*Secale cereale*), originating from Turkey to Transcaucasia, arrived in northern Europe as a weed. Thanks to its winter hardiness and lower nutrient needs, it became the dominant cereal in the early Middle Ages (Behre, 1992). Rye was originally grown from France to Siberia. Currently, 86% of the world's rye is produced in Europe, with Germany, Poland, and Denmark leading production (FAOSTAT, 2022). Rye has both population and hybrid cultivars. Rye's population varieties are self-incompatible, while hybrid varieties originate from self-fertile parental lines. Early hybrids had a superior grain yield compared to population cultivars but were more susceptible to ergot than population cultivars. Hybrid breeding began in the 1970s at the University of Hohenheim, Germany, with the world's first three hybrids released in 1985 (Geiger & Miedaner, 2009). Hybrid breeding revolutionized rye farming, offering a 20% higher grain yield advantage over population rye in a 30-year span (Laidig et al., 2017). Today, hybrid rye dominates German cultivation (Besondere Ernte- und Qualitätsermittlung, 2021), occupying 80% of the land. It's also prevalent in other major production nations and available in Austria, the United States, and Canada.

Abbreviations: CART, classification and regression trees; HIM, high input crop management; MIM, moderate input crop management; MTSI, multi-trait stability index.

The cultivation of rye played a significant role in shaping Europe's history and position as a world power. Its ability to thrive in challenging conditions made it an important food and industrial resource and contributed to the region's economic growth and development (Mitterauer, 2010). Today, rye is still an important crop in many parts of Europe, particularly in a belt that stretches from the North German Plain through Poland, Ukraine, Belarus, Scandinavia, and the Baltics into central and northern Russia and Canada. This region has a cool, wet climate that is well-suited to the cultivation of rye, and the crop is a key component of grain production systems in these areas. Rye grain not only provides health benefits, such as high fiber content and a good source of B complex vitamins, but it also possesses other important features that render it a valuable crop for sustainable food production (Kučerová, 2009).

In recent years, the popularity of hybrid rye cultivars has increased due to their ability to generate higher yields compared to population cultivars. A comparison of 19 cultivars in Denmark revealed a 10%–20% increase in yield due to hybrid rye cultivars (Hansen et al., 2004). Analyzing value for cultivation or use trials conducted in Germany from 1985 to 2016, hybrids showed significant breeding progress versus population cultivars. The overall yield trend for hybrids exhibited a yearly increase of 1.17% compared to 1985 (Miedaner & Laidig, 2019). However, in the case of rye, where both population and hybrid cultivars can be cultivated, the yield variation may differ. The determination of grain yield through its components may also vary between these two types of cultivars, and it can be modified by crop management (Lehmann et al., 2013). To date, there is a lack of literature on research regarding differences in the variability of winter rye yield and its formation by components between population and hybrid cultivars. Understanding the differences in yield formation by its components will allow for more efficient breeding in terms of this trait and NO_3^-enable more effective cultivar recommendations to farmers. Much recent attention has been given to yield stability analysis since the increment of climatic changes is also connected with the decline in crop yield stability (Driscoll et al., 2022; Müller et al., 2018; Najafi et al., 2018; Ray et al., 2019). However, most studies have focused on assessing yield stability or individual utility traits. Nevertheless, it also becomes important to explore a comprehensive approach based on multiple traits simultaneously, encompassing both yield and qualities related to grain. Unfortunately, there is a lack of such comprehensive stability assessments, especially for winter rye. Additionally, previous studies have concentrated solely on evaluating cultivars' stability, without delving into the search for its determinants and causes. This research will enable the identification of the relationship between cultivars' characteristics and their multiple stability traits.

Core Ideas

- Hybrid rye cultivars have higher grain yields compared to population cultivars but lower protein content.
- There were no major differences in the influence of yield component conditions between the two cultivar types.
- Hybrid cultivars show a lower degree of grain yield stability than population rye cultivars.
- Strongly affecting the stability of rye is resistance to fungal diseases and aluminum activity in the soil.

This study aimed to (1) evaluate cultivar's grain quality traits and stability for winter rye using different statistical parameters (classic parameter and multi-trait stability index [MTSI]), (2) assess the relationship between rye grain quality stability and cultivar characteristics (e.g., resistance to diseases and lodging, plant height, reaction to soil aluminum), and (3) compare the contribution of yield components to grain yield variation between population cultivars and hybrid cultivars.

2 | MATERIALS AND METHODS

2.1 | Field experiment

Grain yield, its components, and selected grain quality traits were obtained from a two-factorial trial conducted in two growing seasons, 2018–2019 and 2019–2020, in three Poland locations: Choryń (52.03° N, 16.77° E), Laski (51.80° N, 21.15° E), and Sobiejuchy (52.91° N, 17.72° E). The experiments are located in the main Polish rye-producing regions on soils typically intended for rye cultivation with loamy sand soil texture. According to the World Reference Base for Soil Resources, the soils are classified as follows: Choryń—Retisols, Laski—Cambisols, and Sobiejuchy—Luvisols. These soils are characterized by a very high abundance of phosphorus, potassium, and magnesium, and their pH ranges from neutral to alkaline, indicating that liming treatments are unnecessary. The average monthly temperatures ranged from 14.2°C in Choryń to 15.7°C in Laski in September, and from 9.7°C in Laski to 10.5°C in Sobiejuchy in October. In both September and October, average monthly temperatures exceeded the average of the multi-year period (1991–2020). The 2018/2019 season was characterized by a very long autumn growing season, and average winter temperatures did not fall below 0°C. The autumn and winter months were particularly warm. Autumn stunting of vegetation in this season did not occur. In addition, the 2019/2020 growing season was rich in precipitation. Total precipitation in Choryń was 707 mm in 2019/2020, where the multi-year average is 539 mm, or 168 mm less. High precipitation in 2020 fell in the months of May (105 mm) and June (111 mm) in Choryń, where the monthly total precipitation was 52 and 54 mm, respectively, more than the 1991–2020 multi-year average. In Choryń, February was exceptionally abundant in precipitation (151 mm), which was 121 mm more than the multi-year average, allowing plants to use their post-winter water reserves from early spring. A favorable distribution of precipitation was also recorded in Sobiejuchy and Laski. The 2018/2019 growing season was cooler; September, November, and December in the 2018/2019 season recorded lower monthly temperatures compared to the same months in 2019/2020, by 1.9°C, 1.5°C, and 1.3°C, respectively. As a result, autumn vegetation in this season shortened by a month. The winter months were also colder, January (by 3.8°C) and February (by 2.6°C), which also resulted in a delayed start of spring vegetation compared to the 2019/2020 season. In Sobiejuchy, only in May higher total precipitation was observed—158% of the multi-year average. All other months had lower precipitation totals versus the multi-year average. In Sobiejuchy, April was particularly dry, with only 8 mm, or 20 mm less than the multi-year average. In Choryń and Laski, conditions were also dry, with extremely dry conditions recorded during the growing season in April and June, with only May being a month with optimal total precipitation. In Choryń, there was the lowest total precipitation in the 2018/2019 season, with 334 mm, or 62% of the multi-year average.

In each trial, 11 population winter rye cultivars and five hybrid cultivars from different origins were tested. Study cultivars were developed in a temperate climate in central Europe (Table S1). Most were developed after 2010, although there are three cultivars developed in the 1980s. However, they are still cultivated and constitute valuable parent forms for further breeding. The second factor in the study trial was two levels of management intensity: moderate input crop management (MIM) and high input crop management (HIM) were implemented. The MIM level included standard nitrogen (N) fertilization adopted to the condition of each locality, about 90 kg N ha^{-1}, and fungicide (triconazole + prochloraz) to prepare seeds for sowing and protection against weeds. At a higher level of agricultural technology (HIM), nitrogen fertilization was increased by 30–40 kg N ha^{-1}, depending on location. In addition, a growth regulator and two fungicide treatments were also used. The details of the field conditions for the trial location, including planting date, seeding density, and fungicides used, are presented in Table S2. In Laski and Choryń, the forecrop was winter rape in both seasons, and in Sobiejuchy, the forecrop was triticale, but before the forecrop, there were peas. Each experiment was conducted according to a split-block design with two replicates. The crop management levels were assigned in the whole plot, and cultivars were assigned in the subplot. The individual plot area was 10 m^2.

The yield and yield components, including the number of spikes, the average number of grains per spike, and 1000-grain weight, were measured during the harvest and based on 1 m^2 sample taken from the middle of the field. The selected quality traits, such as test weight, grain protein content, and starch content, were determined by near-infrared spectroscopy using an InfratecTM 111 1241 Grain Analyzer (FOSS) with calibration based on appropriate AACC methods (AACC International, 2015).

2.2 | Statistical methods

In the proposed statistical analysis methods, the combination of the growing season and location was treated as the environmental factor. The analysis of grain yield, its components, and some grain quality traits (test weight, grain protein content, and starch content) was performed using a single-stage approach for a linear mixed model (LMM). The one-stage analysis was performed based on LMM as follows:

$$y_{ijknr} = \mu + z_i + m_j + zm_{ij} + g_k + gz_{ki} + gm_{kj} + gmz_{kij} + r_{jih} + b_{jihn} + e_{ijhkn} \quad (1)$$

where y_{ijknr} is the value of the study trait, μ is the overall mean, z_i is the random effect of the ith environment, m_j is the fixed effect of the jth crop management, zm_{ij} is the random interaction effects of the ith environment and jth crop management, g_k is the fixed effect of the kth cultivar, gz_{ki} is the random interaction effect of the kth cultivar and ith environment, gm_{kj} is the fixed interaction effect of the kth cultivar and jth crop management level, gmz_{kij} is the random interaction effect of the kth cultivar, jth crop management, and ith environment, $r_{i(h)}$ is the random effect of the hth replication nested in ith environment, bi_{hn} is the random effect of the nth block nested in the hth replication at the in ith environment, e_{ijkl} is the random error associated with the trait observation y_{ijkl}.

After applying a linear mixed-effects model, the rye cultivars were divided into two groups (types): population cultivars and hybrid cultivars. The significance of mean differences in the investigated traits between these groups of cultivars was compared using a linear contrast with Sidak's procedure (Šidák, 1967).

Path coefficient analysis was used to determine the impact on the grain yield of rye and its multiplicative yield component. In these analyses, we evaluated only the direct effects of the number of spikes, the average grains per spike, and 1000-grain weight on grain yield. Path coefficient analyses were conducted based on adjusted means obtained from model

(1) calculated for the traits regarding all the combinations between environments (adjusted means for combination cultivars and environment), separately for crop management and type of cultivars. These adjusted means were calculated using the algorithm described by Welham et al. (2010). The path analysis was conducted separately for the type of cultivars (population, hybrid) and two crop management (MIM, HIM).

Shukla's stability variance (Shukla, 1972) was used to evaluate the cultivar stability of each study trait. This parameter evaluates stability for single traits. For each trait, a ranking (in ascending order) was determined based on Shukla's stability variance, which was later summed up for each cultivar. The cultivars with a low sum of Shukla's stability variance can be considered the most stable in terms of all considered characteristics. We also used an MTSI to evaluate stability (Olivoto et al., 2019). This method is based on an exploratory factor analysis. The interpretation of this indicator is based on Shukla's stability variance on the principle that the smaller the value, the more favorable the stability. The lower the MTSI value of the parameter, the more stable the variety is in terms of multi-traits simultaneously. Both indicators were assessed separately for both levels of crop management and were evaluated across the combination of years and experimental sites.

The classification and regression trees (CART) method was used to assess the relationship between the rye stability of study traits and the dataset with cultivar characteristics. This will allow identifying the factors affecting the yield stability, yield components, and some grain quality traits. The cultivar's characteristics used in this analysis came from official testing conducted by the Polish Research Centre for Cultivar Testing (COBORU). This cultivars dataset includes an assessment of resistance to fungal diseases, to lodging, and grain sprouting in spikes on a 9-point scale (9 being the most favorable condition and 1 being the least favorable condition), and quantitative traits including plant height, number of days to heading, and fully ripe. The characteristics also included the year of registration, type of cultivars (population, hybrid), and selected baking characteristics, for example, flour yield and maximum viscosity of starch gruel. The full dataset used to assess the influence of rye stability of study traits was presented in Table S1.

All statistical analyses were performed using R 4.2.1 software (R Core Team, 2024). The Shukla's stability variance and MTSI were obtained using the metan package (Olivoto & Lúcio, 2020). The CART approach was conducted using the rpart package.

3 | RESULTS

The means of grain yield ranged from 6.92 to 9.82 t ha^{-1} for MIM crop management and 7.64 to 10.90 t ha^{-1} for HIM (Table 1). The mean grain yield for the tested *hybrid* varieties was significantly higher than the yield of the population varieties for both MIM (+1.69 t ha^{-1}, +22.5%) and HIM (+2.14 t ha^{-1}, +25.7%) (MIM: p-value < 0.0001; HIM: p-value < 0.0001, Table 2). For 1000-grain weight, the highest means were observed for population cultivars in both crop managements (26.9 g for MIM and 26.8 g for HIM). The mean 1000-grain weight did not differ statistically significantly in both study crop managements (MIM: p-value 0.5997; HIM: p-value 0.5651). In terms of protein content, the highest mean in crop management was observed for population cultivars in HIM (9.10%) and in MIM (10.44%). On average, a significantly higher protein content is observed for population varieties than for hybrid cultivars; this effect is observed in both MIM (+0.58% protein, +6.8%) and HIM (+1.09% protein, +11.7%) (MIM: p-value < 0.0001; HIM: p-value < 0.0001).

The contribution of yield components to rye grain yield variation was evaluated using the path analysis (Figure 1). The influence of study yield components on the yield was very similar for both crop management and in both cultivar types. The number of spikes had the strongest influence on yield, and this component explained about 50% of yield variability. The second was 1000-grain weight, which explained, regardless of the applied crop management and type of variety, about 35% of rye yield variation. Rye yield was least affected by the number of grains per spike by 15%. All path coefficients in both crop managements and in both types of cultivar were significant. The relationships between the yield components (correlation coefficient) depended on the type of cultivar used. For population cultivars, we observe only a statistically significant positive correlation between the number of grains per spike and 1000-grain weight in both crop managements (0.288 for MIM and 0.296 for HIM). Other correlations between the yield components were not statistically significant. The relationships between the components of hybrid cultivars depended on crop management. For MIM crop management, we observe a significant negative correlation between the number of grains per spike and 1000-grain weight. While for HIM, the only significant correlation was the relationship between the number of spikes and the number of grains per spike (−0.323).

In MIM crop management, population cultivar Rubin was the most stable regarding grain yield according to the Shukla stability variance (Table 1). The stability ranking of study traits of the cultivars is shown in Table S3. Moreover, in accordance with this stability parameter, the lowest stability cultivar was hybrid (Turkus, even with a higher mean yield than population cultivars). The higher grain yield of hybrid cultivar (Serafino) possesses the 13th stability ranking. According to the Shukla variance in HIM crop management similar to MIM crop management, population cultivars were the most stable cultivars in terms of grain yield, and the most unstable was the hybrid cultivar (Binntto).

TABLE 1 Mean value and Shukla stability variances of rye grain yield, its components, and selected grain quality traits in moderate input crop management (MIM) (a) and high input crop management (HIM) (b) crop management at three locations in Poland, 2018/2019 and 2019/2020.

Cultivars	Grain yield (t ha^{-1}) Mean	Grain yield (t ha^{-1}) Shukla	1000-grain weight (g) Mean	1000-grain weight (g) Shukla	Grain protein content (%) Mean	Grain protein content (%) Shukla	Grain density (kg hL^{-1}) Mean	Grain density (kg hL^{-1}) Shukla	Starch content (%) Mean	Starch content (%) Shukla	No. of spikes per head Mean	No. of spikes per head Shukla	Grain weight per spike (g) Mean	Grain weight per spike (g) Shukla
Moderate input crop management (MIM)														
Agat	7.34b	3.53	26.7ab	0.35	8.91b	0.22	72.4a	0.48	55.0ab	0.24	555e	3396	26.7ab	0.35
Amber	7.86c	2.33	27.0b	2.98	9.23cd	0.23	73.4ab	0.83	55.7b	0.41	545d	2519	27.0b	2.98
Amilo	6.92a	3.80	26.4a	0.98	9.00bc	0.01	75.0c	0.22	54.4a	0.13	491a	1023	26.4ab	0.98
Antoninskie	7.45bc	2.19	27.4b	1.07	9.15c	0.14	73.3a	0.29	55.3b	0.26	491a	579	27.4c	1.07
Binntto[a]	9.67e	5.75	27.7cb	1.53	8.53a	1.17	73.9b	2.07	55.3b	2.08	605f	1053	27.7c	1.53
Diament	7.22b	0.63	26.6ab	1.21	9.14c	0.07	73.7ab	0.70	55.3b	0.07	487a	932	26.6ab	1.21
Dolaro[a]	9.53e	14.37	27.6b	0.64	8.41a	0.09	75.0c	0.99	55.7b	0.09	624g	4285	27.6c	0.64
Granat	8.02d	0.39	26.9ab	0.11	9.23cd	0.07	73.8b	0.17	54.8a	0.29	558e	1043	26.9b	0.11
Hadron	7.47bc	5.22	27.8cb	0.83	9.31d	0.30	73.6ab	0.41	55.6b	0.31	500b	2719	27.8c	0.83
Opal	7.21b	0.83	25.3a	0.86	8.94b	0.04	72.5a	1.10	55.4b	0.22	524c	875	25.3a	0.86
Rubin	7.88cd	0.22	27.0b	0.79	8.94b	0.01	74.0b	0.57	55.8b	0.31	547d	1357	27.0b	0.79
Serafino[a]	9.82e	13.53	26.6ab	3.01	8.37a	0.33	75.0c	2.09	55.7b	0.79	620g	2079	26.6ab	3.01
Skand	7.62c	1.52	26.8ab	0.72	8.94b	0.07	74.7c	0.48	55.5b	0.17	534d	1010	26.8ab	0.72
Tur[a]	7.72c	14.81	24.5a	2.53	8.78ab	0.73	73.0a	0.53	54.8a	0.68	518c	5834	24.5a	2.53
Turkus	7.54bc	8.61	28.0c	1.54	9.30d	0.07	73.8b	1.75	55.5b	0.17	520c	1342	28.0c	1.54
High input crop management (HIM)														
Agat	8.31b	0.421	26.0ab	0.418	10.4c	0.02	71.6b	1.73	53.6a	0.02	610d	551	26.0ab	0.42
Amber	8.43b	4.678	27.3b	0.525	10.4c	0.29	72.6b	3.16	54.5b	0.32	588c	3400	27.3b	0.53
Amilo	7.94ab	3.204	27.4b	2.65	10.2c	0.85	73.9bc	0.08	53.7a	2.18	547b	1781	27.4bc	2.65
Antoninskie	7.64a	1.939	27.2b	2.19	10.7c	0.52	72.4b	0.40	53.9a	0.34	513a	2376	27.2b	2.19
Binntto[a]	10.68d	14.681	27.1b	4.87	9.27ab	0.23	72.2b	1.50	54.6b	0.50	705 g	4621	27.1b	4.87
Diament	8.03ab	1.412	27.0b	3.12	10.6c	0.10	66.4a	222	53.9a	0.11	516a	1662	27b	3.12
Dolaro[a]	10.90e	11.886	27.2b	2.75	9.3ab	0.25	74.4c	2.37	54.6b	0.46	664e	2585	27.2b	2.75
Granat	8.45b	2.841	25.5ab	1.84	10.5c	0.01	72.6b	0.14	53.4a	0.06	588c	2346	25.5a	1.84
Hadron	8.43b	1.878	27.7b	0.466	10.4c	0.58	72.3b	3.41	54.2ab	1.02	586c	549	27.7c	0.47
Opal	8.01ab	1.47	24.2a	1.52	10.4c	0.16	70.9b	0.74	53.4a	0.33	578bc	1251	24.2a	1.52
Rubin	8.47b	1.775	26.7b	0.405	10.6c	0.21	72.6b	3.68	53.8a	0.50	565b	2201	26.7b	0.41
Serafino[a]	10.81e	5.617	25.3ab	0.147	9.16a	0.30	74.1bc	2.90	54.8c	0.86	680f	405	25.3a	0.15
Skand	8.52b	10.583	26.8b	3.86	10.3c	0.08	73.9bc	2.78	54.2ab	0.52	538b	4995	26.8b	3.86
Tur[a]	9.35c	4.861	25.9ab	2.09	9.66b	0.71	71.8b	1.23	54.2ab	0.51	562b	2640	25.9ab	2.09
Turkus	9.1c	0.734	28.6c	3.99	10.3c	0.14	73.8bc	0.36	54.1ab	0.20	569b	562	28.6d	3.99

Note: Lowercase letters indicate the significance of mean differences for cultivars.
[a]Hybrid cultivar.

TABLE 2 Comparison of rye population and hybrid cultivars across crop management system for grain yield, gain quality, and yield components at three locations in Poland, averaged for 2018/2019 and 2019/2020.

Mean		Grain yield ($t\ ha^{-1}$)	1000-grain weight (g)	Grain protein content (%)	Grain density ($kg\ hL^{-1}$)	Starch content (%)	No. of spikes per head	Grain weight per spike (g)
Moderate input crop management (MIM)	Population cultivars	7.50	26.9	9.10	73.7	55.3	523	26.9
	Hybrid cultivars	9.19	26.6	8.52	74.2	55.4	592	26.6
	p value	<0.0001	0.5997	<0.0001	0.2607	0.7643	0.0039	0.5997
High input crop management (HIM)	Population cultivars	8.30	26.8	10.44	72.1	53.9	563	26.8
	Hybrid cultivars	10.44	26.4	9.35	73.1	54.6	653	26.4
	p value	<0.0001	0.5652	<0.0001	0.3811	0.0041	0.0024	0.5652
Population cultivars		7.90	26.8	9.77	72.9	54.6	543	26.8
Hybrid cultivars		9.81	26.5	8.94	73.7	55.0	622	26.5
p value		<0.0001	0.6632	0.0032	0.2819	0.8803	<0.0001	0.6615
Moderate input crop management (MIM)		7.95	26.82	8.95	73.8	55.3	541	26.8
High input crop management (HIM)		8.87	26.66	10.15	72.4	54.1	587	26.7
p value		<0.0001	0.6811	<0.0001	0.3091	0.8221	0.0021	0.6221

We compared compatibility cultivars order between MIM and HIM crop management for Shukla stability variance for grain yield. They are in a completely different order. Spearman's rank correlation coefficient can be used to measure its compatibility; in this case, it was 0.21 ($p = 0.4131$).

Regarding protein content, the lowest values of Shukla variance were in population cultivars. The greatest value of Shukla variance was in hybrid cultivars, which indicated more instability of hybrid as compared to population cultivars. At the same time, consideration of Shukla variance and mean protein content revealed that population cultivars ranked least and higher in protein content than hybrid cultivars. All population cultivars showed lower Shukla variance of grain density, starch content, number of spikes, and grain weight per spike except Turkus, which displayed the highest stability (ranked first in stability ranking). While all hybrid cultivars except Binntto and Turkus (population cultivars) showed higher Shukla variance and less stability than other cultivars. Overall, for MIM crop management, the sum of ranking Shukla stability variance across all study traits hybrid cultivars was less stable than population cultivars.

In the HIM crop management, we observed differences in stability between population and hybrid cultivars. Population cultivars generally exhibited lower Shukla variance, indicating higher stability. However, hybrid cultivars are less stable, which may be due to the greater sensitivity of this type of cultivars to weather conditions.

A comparison of the order of cultivars for the sum ranking of cultivars based on Shukla stability variance across all study traits and between the crop managements is presented in Figure 2. The greatest decrease/increase was observed for the Skand population cultivars, which for MIM was second in terms of stability, while for HIM, it was last. The concordance of cultivar order for sum of rankings for all features of Shukla stability variance between MIN and HIM crop managements measured by the Spearman correlation was 0.19, but this coefficient was not significant.

Table S4 represents the MTSI of yield, its components, and grain quality traits. In this experiment, the two top-performing cultivars for MTSI in MIM crop management using a 15% selection pressure were selected. The improvement in traits is expressed as selection differentials. In both crop managements, populations performed well versus hybrids. The concordance of cultivar order for sum of rankings for MTSI between MIM and HIM crop management measured by the Spearman correlation was −0.20, but this coefficient was not significant.

Comparing the order of cultivars for MIM crop management for stability assessments between the sum of ranks of Shukla variance and MSTI, the agreement was relatively high, and the value of the Spearman correlation was 0.63 ($p = 0.0023$). On the other hand, for HIM crop management,

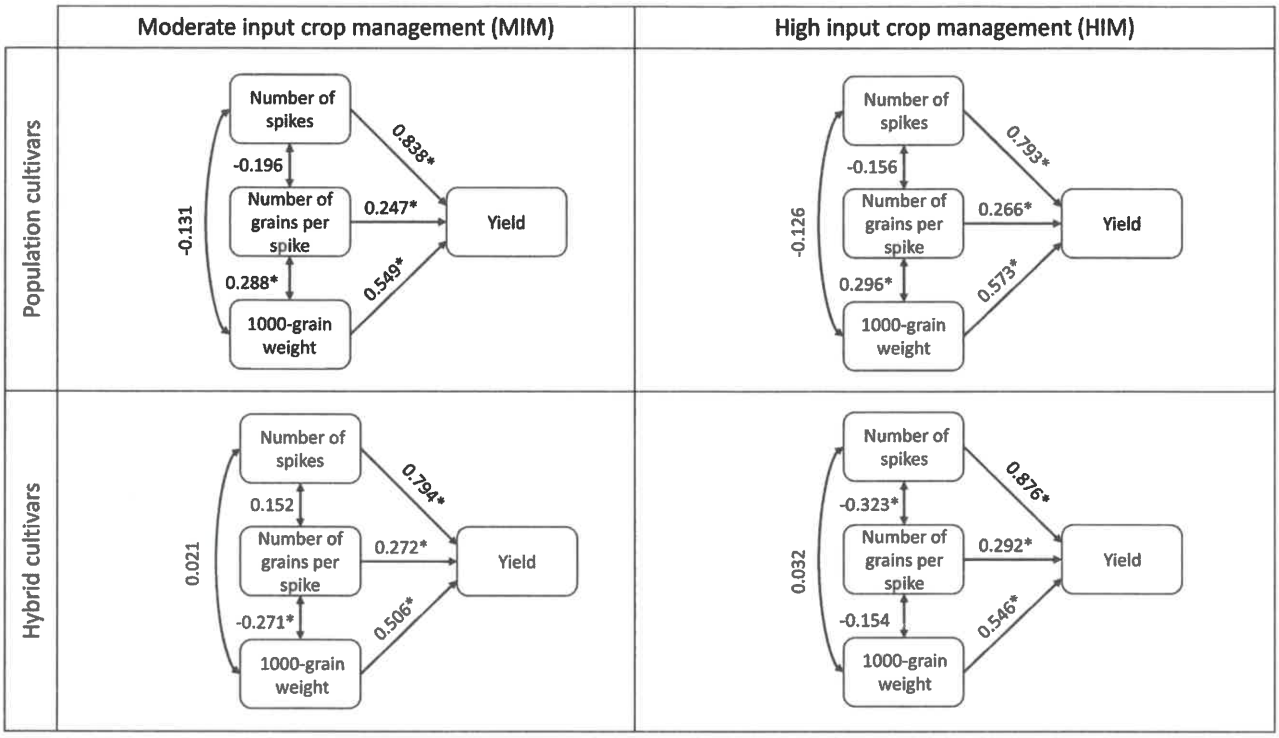

FIGURE 1 Path analysis diagrams show the direct influence (single-headed arrow) on rye grain yield, its components, and the correlation (double-headed arrow) between yield components in two crop managements and type of cultivars among three locations in Poland (2018/2019, 2019/2020). *Significant value of path coefficient or correlation coefficient at $\alpha = 0.05$.

the value for agreement of the order of cultivars between stability parameters was 0.50 ($p = 0.0167$).

To determine the most important characteristics of winter rye cultivars based on an official registration study in affecting the sum of ranking Shukla stability variance, or MTSI value, a regression tree was fitted using the CART method. These results for MIM and HIM crop management are presented in Figure 3. The residency of septoria leaf blotch was the most important predictor in explaining the sum of ranking Shukla stability variance in both study crop management. The value of residency for septoria leaf blotch approximately >7 in a 9-point scale (9 being the most favorable condition and 1 being the least favorable condition) resulted in the smaller means the sum of ranking Shukla stability variance (47 in MIM, 51 in HIM), then that is less resistant to this disease—<7 (81 in MIM, 75 in HIM). The MIM crop management group of highest residence for septoria leaf blotch was further divided by the resistance to stem-based diseases. Cultivars characterized by values ≥7.4 have a lower mean value of the sum of ranking Shukla stability variance. On the other hand, for HIM, the second important variable is time to fully ripe, and the most stable were those cultivars that had less than 200 days to this development phase.

The explanation of the value of MTSI by characteristics of winter rye cultivars based on official registration using the CART method was dependent on crop management. For lower intensity crop management MIM, the variable MTSI variability the most was residence on stem rust. Cultivars with a value ≥7.7 on a 9-point scale resulted in smaller means of the MTSI. Then, the subset with greater residence on stem rust was further divided by resistance to stem-based diseases. When it was ≥7.7, the cultivars had a lower value of MTSI than those with a small resistance value for stem-based diseases. When examining MTSI value in HIM crop management, the most contributing variable was a reaction to aluminum. When it was higher than five on a nine-point scale, cultivars had more stability across considerate traits (lower mean value of MTSI).

4 | DISCUSSION

In our experiment, we confirmed a significant increase in yield for hybrid cultivars, representing a consistent boost of ~24.2% versus population cultivars. Remarkably, this yield increase was consistent across both MIM and HIM crop management systems. These findings align with previous

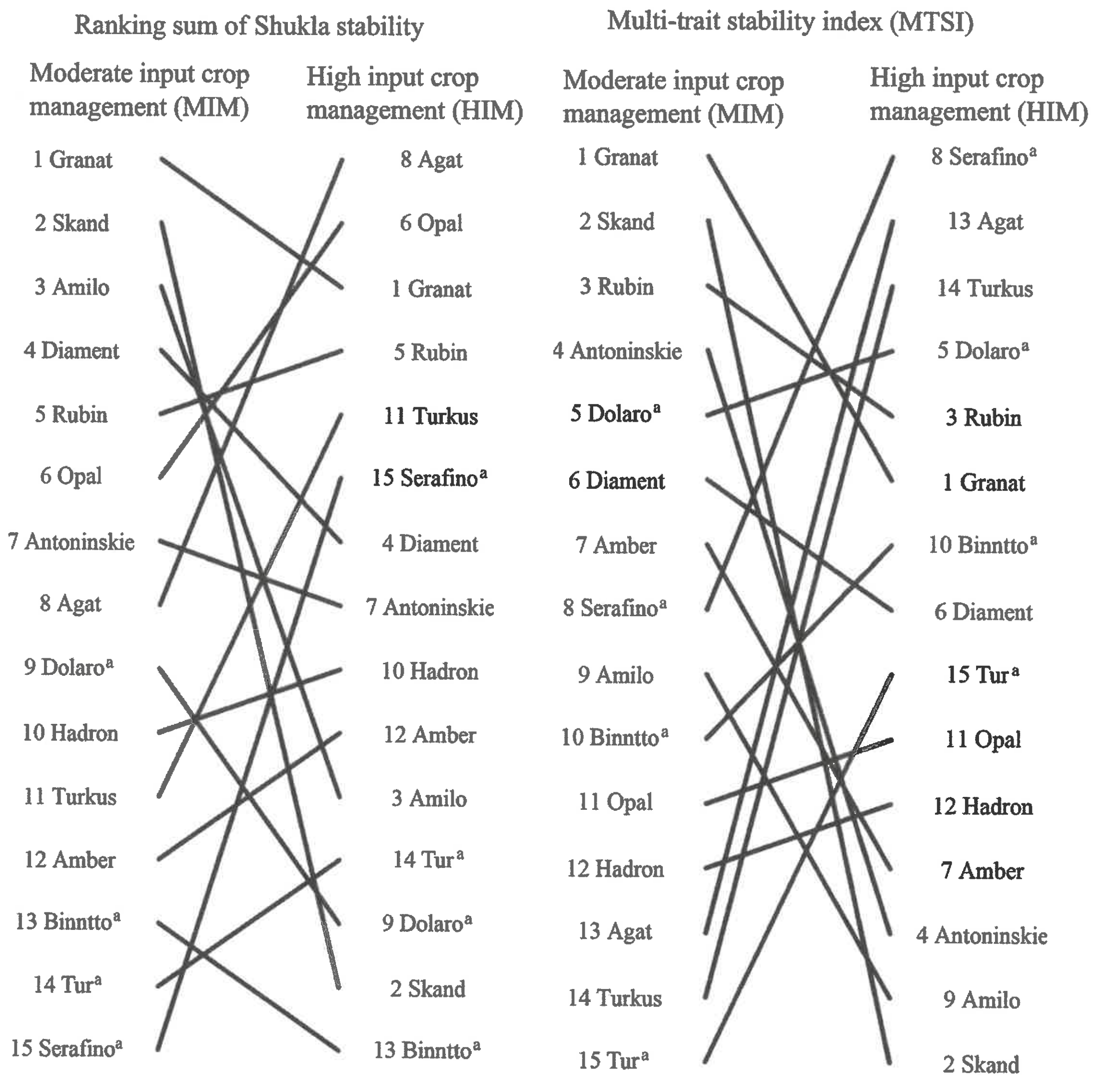

FIGURE 2 The comparison of rye cultivar's order of the values for ranking sum of Shukla stability variance and multi-trait stability index (MTSI) parameter across study traits in moderate input crop management (MIM) and high input crop management (HIM) for three locations in Poland (2018/2019, 2019/2020). [a]Hybrid cultivar.

Germany studies, where official registration trials reported an 18.1% increase in rye yield for hybrid cultivars (Laidig et al., 2017). Similarly, hybrid cultivars have demonstrated yield advantages in various cereals, including wheat, where yield increases of ~5.5% were observed in southeast Germany (Prey et al., 2019). Notably, research by Kučerová (2009) in the Czech Republic on the influence of location and year on rye performance revealed hybrid Picasso outperformed open-pollinated population cultivars Dankowskie Nowe and Selgo, displaying superior attributes like 1000-grain weight, specific weight, kernel size, and grain yield.

The grain protein content for hybrid cultivars was lower than population cultivars. The size of this difference depended on crop management. For MIM, it was 3%, and for HIM, it was 6.5%. This decrease in protein content indirectly shows the well-known negative correlation between yield and protein content, especially for HIM crop management, where we observed an even higher yield for hybrid cultivars. Increasing nitrogen fertilization did not contribute to minimizing the decrease in the grain protein content. With rye being the most commonly used grain for bread making in Europe, there is a growing need to enhance its nutritional and bioactive properties by comprehending genetic variability and the impact of agronomic management practices. The adoption of rye cultivation plays a vital role in promoting integrated pest management, decreasing inputs, and enhancing overall dietary nutrition. These efforts are crucial for enhancing global food security on a broader scale.

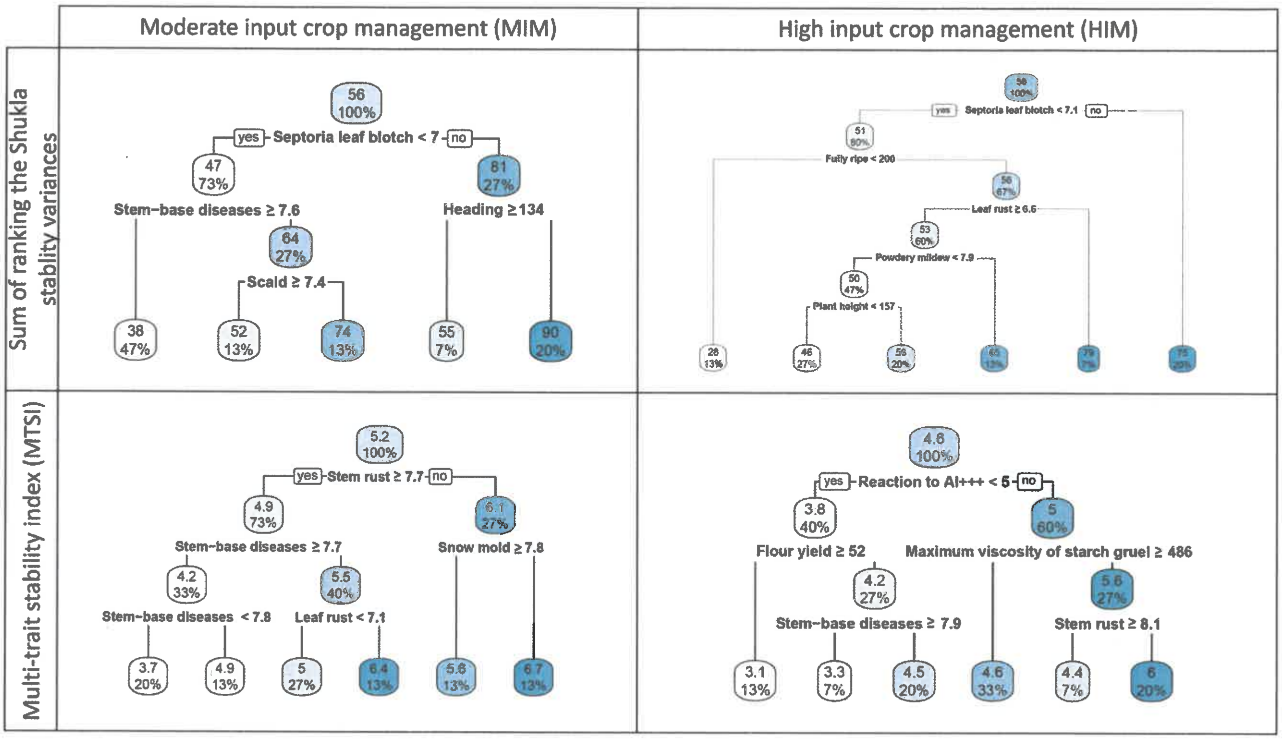

FIGURE 3 Regression tree based on the classification and regression trees (CART) method predicting the value of the sum of ranking Shukla stability variance and multi-trait stability index (MTSI) from characteristics of winter rye cultivars grown at three locations in Poland (2018/2019, 2019/2020). In the box, the first line presents the mean value of stability parameters, and the second line shows the percentage of cultivars included in each group.

Moreover, it would be important to know the mechanism of the higher yielding potential of hybrid cultivars, particularly the ways of yield formation by its components. Knowledge about the differences in the importance of yield components for hybrid and population cultivars will allow for even more effective breeding and genotype selection. However, our research shows that there are no major differences in the influence of three yield components on yield conditions between the two types of rye cultivars. Also, increasing the degree of intensity of crop management does not cause a strong differentiation influencing the yield and its components. Regardless of the cultivars type and crop management used, we observe the strongest effect of the number of spikes, followed by the 1000-grain weight, and the smallest impact of the number of grains per spike. This arrangement of the influence of yield components is typical for cereals, observed in a temperate climate (Chmielewski & Köhn, 2000; Zając et al., 2014). On the other hand, for hybrid varieties, when growing with more intensive crop management, HIM shows a completely different interdependence between the study's three yield components versus other combinations of variety type and crop management. This shows the phenomenon of compensation between the yield components, allowing for more effective use of increased doses of nitrogen fertilization or modifying the relationship between the components with unlimited access to nitrogen (Makary et al., 2020; Sadras & Slafer, 2012; Slafer et al., 2014; Xiong et al., 2018).

A higher yield of hybrid cultivars than indicated in the above discussion paragraphs is common for many species of cereals but also other crops (e.g., rapeseed). However, our research expands knowledge about the extent to which the yield is determined by its components. It turns out that for both types of cultivars, spikes number was the most important. This effect was the same for MIM and HIM crop management. Assessment of the importance of individual yield components of hybrid and population cultivars against the background of various crops significantly complements the knowledge. The stability of varieties was assessed separately for individual traits and the multi-trait approach using the ranking sum of the Shukla variance or the MTSI measure. Evaluation of grain yield stability using Shukla stability variance showed hybrid cultivars were characterized by a low degree of stability. All four tested hybrid cultivars took the last five places in the ranking of across-study cultivars. Increasing the grain yield simultaneously increases the range of values of this trait, which in turn affects variability. So, it would probably be more correct to assess cultivars and compare stability for individual traits within each group of varieties, separately for population cultivars and hybrid cultivars.

Nowadays, both breeders and farmers are interested not only in the assessment of yield stability but also in other important utility characteristics. And to select those genotypes that are stable in many traits at the same time. For this purpose, we proposed the sum of Shukla stability variance rankings across the considered traits. It is a relatively simple parameter that does not require complicated statistical methods and software. Olivoto et al. (2019) proposed a multi-trait method for assessing the stability of MTSI based on factor analysis. This is similar to the previously known methods of assessing the interaction between environmental and genotype, for example, additive main effect and multiplicative interaction method or the genotype and genotype–environment interaction biplot method. For the less intensive MIM crop management, we observe a relatively high agreement between the sum of rankings Shukla stability variance and MTSI. The first two cultivars were the same in terms of multi-trait stability in both methods. On the other hand, for HIM, the consistency of the order of the varieties was much lower. This may be because with less intensive methods of cultivation, which are not optimal for rye production, especially hybrid varieties, the variability of all study traits was not great. Hence, the assessment differences in stability between the cultivars using the two approaches were not great. With the use of very intensive HIM crop management, the varieties present their full genetic expression and full potential, so the differentiation of traits between them was much greater. Also, the stability assessment methods based on two completely different approaches and methods strongly differentiated the order of cultivars.

When assessing multi-trait stability using two methods in MIM crop management, hybrid cultivars were characterized by lower stability compared to population cultivars. Under these conditions of cultivation with average fertilization and no disease protection (no fungicides), population cultivars were more stable in terms of all considered features. Population cultivars in Poland to this day account for the majority of crops of this species, as in Canada (Wilde et al., 2017). The situation is completely different in Germany (Hackauf et al., 2022; Laidig et al., 2017), where hybrid cultivars significantly dominate. In Poland, land with poorer properties is allocated for rye cultivation, but the adoption of expensive hybrid rye cultivation technology would not be economically justified. On the other hand, for more intensive HIM crop management, hybrid cultivars were much better in terms of multi-trait stability. Even one of the hybrid cultivars ranked first for the MSTI parameter.

Using the regression tree generated by the CART method, it was possible to explain the stability assessment performed using other characteristics describing the cultivars. Identification of such features affecting yield stability allows for more effective breeding work, including the selection of genotypes and recommendation of cultivars for cultivation. It turns out that with less intensive crop management, resistance to fungal diseases is very important, especially septoria leaf blotch, stem rust, and stem-based diseases. Therefore, breeders who focus their breeding cultivars for cultivation in less intensive agriculture, where the use of fungicides is limited or even prohibited, as in organic farming, the intensification of resistance breeding should be increased. On the other hand, for the more intensive crop management, the multi-trait stability, especially measured by the MTSI parameter, was influenced the most by resistance to aluminum and, thus, soil acidification. Rye is a species that tolerates soil acidification; this is important because rye is mainly grown in Poland on acidic soils. In order to obtain a stable and good-quality crop, cultivars should be more resistant to acidification at a high level of production intensity to take full advantage of it.

5 | CONCLUSION

Our study provides new insights into the potential quality and yield performance of hybrid and population cultivars under two crop managements. Hybrid cultivars exhibited higher yields than population cultivars, with an increase of about 15% observed in both MIM and HIM crop management. The study found no major differences in the influence of yield components on yield conditions between the two types of rye cultivars. The number of spikes had the strongest effect on yield, independent of the level of crop management. Hybrid grain protein content was lower than for population cultivars, with a decrease of 6.4% and 10.6% for MIM and HIM crop management, respectively. The stability of varieties was assessed separately for individual traits and a multi-trait approach using the ranking sum of the Shukla variance or the MTSI measure. This study proposes the sum of Shukla stability variance rankings across the considered traits as a simple parameter to assess the stability of genotypes in many traits simultaneously. Hybrid rye cultivars were less stable than population cultivars, possibly due to the greater sensitivity of this type of cultivar to environmental conditions, especially weather. An important factor in ensuring cultivar stability is resistance to fungal diseases, especially in MIM. In more intensive crop management, HIM, resistance to soil acidification begins to play a key role.

AUTHOR CONTRIBUTIONS

A. Z. Ghafoor: Conceptualization; formal analysis; resources; visualization; writing—original draft; writing—review and editing. **M. Wijata**: Writing—review and editing. **J. Rozbicki**: Conceptualization; methodology; project administration; writing—review and editing. **R. Krysztofik**: Investigation. **K. Banaszak**: Investigation. **H. Karim**: Writing—review and editing. **A. Derejko**: Writing—review and editing. **M. Studnicki**: Conceptualization; software; supervision; writing—original draft; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Appendix 2

2.1 Declarations and statements of co-authors

2.1.1 Statements of co-authors of Article 1

Title: Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars

Authors: Abu Zar Ghafoor, Alicja Ceglińska, Hassan Karim, Magdalena Wijata, Grzegorz Sobczyński, Adriana Derejko, Marcin Studnicki, Jan Rozbicki, Grażyna Cacak-Pietrzak

Journal: Agriculture (MDPI)

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Niniejszym oświadczam, że w pracy Ghafoor, A. Z., Céglińska, A., Karim, H., Wijata, M., Sobczyński, G., Derejko, A., Studnicki, M., Rozbicki, J., & Cacak-Pietrzak, G. (2024). Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars. *Agriculture*, *14*(12), 2131 doi: 10.3390/agriculture14122131 mój indywidualny udział w jej powstaniu polegał na przygotowanie szczegółowej koncepcji badań, przygotowanie zbiorów danych, przeprowadzenia analizy statystycznej, napisanie oraz edycja manuskryptu zarówno pierwszej wersji jak i ostatecznej. Mój udział w przygotowanie tej pracy wynosił 70%.

Co-authorship declaration

I hereby declare that in the work Ghafoor, A. Z., Céglińska, A., Karim, H., Wijata, M., Sobczyński, G., Derejko, A., Studnicki, M., Rozbicki, J., & Cacak-Pietrzak, G. (2024). Influence of Genotype, Environment, and Crop Management on the Yield and Bread-Making Quality in Spring Wheat Cultivars. *Agriculture*, *14*(12), 2131. doi: 10.3390/agriculture14122131 my individual contribution to its creation consisted in preparing a detailed research concept, preparing data sets, conducting statistical analysis, writing and editing the manuscript both the first and final version. My contribution to the preparation of this work was 70%.

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Co-authorship declaration

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2.1.2 Statements of co-authors of Article 2

Title: Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates

Authors: Abu Zar Ghafoor, Adriana Derejko, Marcin Studnicki

Journal: Agronomy (MDPI)

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I hereby declare that in the work Ghafoor, A. Z., Derejko, A., & Studnicki, M. (2024). Identification of Plant and Soil Characteristics Affecting Stability of Winter Wheat Cultivar in Temperate Climates. Agronomy, 14(4), 779. https://doi.org/10.3390/agronomy14040779 my individual contribution to its creation consisted in preparing a detailed research concept, preparing data sets, conducting statistical analysis, preparing graphs, writing and editing the manuscript of both the first and final version. My contribution to the preparation of this work was 85%.

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2.1.3 Statements of co-authors of Article 3

Title: Influence of Crop Management on Stability of Rye Yield and Some Grain Quality Traits

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Journal: Agronomy Journal (Wiley)

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Ghafoor, A. Z., Wijata, M., Rozbicki, J., Krysztofik, R., Banaszak, K., Karim, H., Derejko, A., & Studnicki, M. (2024). Influence of crop management on stability rye yield and some grain quality traits. *Agronomy Journal*, 116, 2263–2274. https://doi.org/10.1002/agj2.21647 mój indywidualny udział w jej powstaniu polegał na edycja manuskryptu oraz pełnienie funkcji autora korespondencyjnego. Mój udział w przygotowanie tej pracy wynosił 5%.

Co-authorship declaration

I hereby declare that in the work Ghafoor, A. Z., Wijata, M., Rozbicki, J., Krysztofik, R., Banaszak, K., Karim, H., Derejko, A., & Studnicki, M. (2024). Influence of crop management on stability rye yield and some grain quality traits. Agronomy Journal, 116, 2263–2274. https://doi.org/10.1002/agj2.21647 my individual contribution to its creation consisted in editing the manuscript and serving as the corresponding author. My contribution to the preparation of this work was 5%.

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