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Wpływ nawożenia dolistnego mikroelementami na plonowanie i jakość ziarna jęczmienia jarego

Rozprawa doktorska

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Streszczenie

Celem pracy była ocena wpływu dolistnego stosowania wybranych mikroelementów: miedzi (Cu), manganu (Mn), molibdenu (Mo) i cynku (Zn) na przebieg procesów fizjologicznych, plonowanie oraz wartość technologiczną ziarna trzech odmian browarnych jęczmienia jarego (Baryłka, KWS Irina i RGT Planet). Rozprawę doktorską stanowi cykl trzech publikacji naukowych opartych na wynikach doświadczenia polowego przeprowadzonego w latach 2019–2021 w południowo-wschodniej Polsce.

W badaniach oceniano wskaźniki architektury łanu, zawartość chlorofilu w liściach, parametry wymiany gazowej i fluorescencji chlorofilu, biometrię roślin, plon i elementy struktury plonu, a także cechy fizyczne i skład chemiczny ziarna oraz wybrane wskaźniki jakości otrzymanego słodu jęczmiennego. Przyjęty układ badań umożliwił powiązanie odpowiedzi roślin na poziomie fizjologicznym z efektem produkcyjnym oraz oceną cech istotnych z punktu widzenia przemysłu słodowniczego. Takie ujęcie pozwoliło zbadać zarówno wpływ poszczególnych mikroelementów, jak i stopień, w jakim obserwowane zmiany były determinowane przez genotyp i warunki środowiskowe.

W przeprowadzonym doświadczeniu zastosowanie każdego z badanych nawozów mikroelementowych wyraźnie poprawiło plonowanie roślin oraz wpłynęło pozytywnie na stosunek plonu ziarna do plonu biologicznego. Spośród badanych odmian najlepszym efektem produkcyjnym cechowała się odmiana RGT Planet, której średni plon ziarna z trzech sezonów wegetacyjnych wyniósł 5,81 t ha⁻¹.

Najwyższe wartości parametrów architektury łanu (LAI i MTA) odnotowano na poletkach, na których zastosowano molibden. W badaniach wykazano, że dolistna aplikacja badanych nawozów korzystnie modyfikowała funkcjonowanie aparatu fotosyntetycznego roślin jęczmienia. Rośliny, opryskiwane mikroelementami, charakteryzowały się wyższą zawartością chlorofilu w liściach. Obserwowano również korzystne zmiany w parametrach wymiany gazowej i fluorescencji chlorofilu. Najwyższe wartości stężenia międzykomórkowego CO₂ (C_i) i wskaźnika fotosyntezy netto (P_N) wykazano po zastosowaniu miedzi, natomiast współczynnik transpiracji (E) był najwyższy w wyniku aplikacji cynku. Analiza fluorescencji chlorofilu wskazała na szczególnie istotne znaczenie molibdenu i cynku w kształtowaniu reakcji fizjologicznych roślin. Przy nawożeniu preparatami zawierającymi

Mo i Zn odnotowano najwyższe wartości wszystkich analizowanych parametrów fluorescencji chlorofilu.

Uzyskane wyniki potwierdziły istnienie dodatnich zależności pomiędzy wybranymi wskaźnikami fizjologicznymi a plonem ziarna, co wskazuje, że poprawa sprawności fizjologicznej roślin stanowi ważny aspekt kształtowania efektu plonotwórczego. Dolistne nawożenie mikroelementami wpływało również na wybrane cechy biometryczne roślin i elementy struktury plonu, a zakres odpowiedzi zależał od zastosowanego pierwiastka, odmiany oraz warunków pogodowych w okresie wegetacji.

Rośliny z obiektów, na których zastosowano nawozy mikroelementowe, były niższe w porównaniu z roślinami z poletek kontrolnych i cechowały się większą krzewistością produkcyjną. Spośród testowanych genotypów odmiana RGT Planet najczęściej wyróżniała się korzystnymi wartościami mierzonych cech. U tej odmiany w trzyletnim cyklu badawczym odnotowano najdłuższe kłosa (średnio 7,26 cm), największą krzewistość produkcyjną (3,77), obsadę kłosów (720 szt. m⁻²) oraz największą liczbę i masę ziaren z kłosa (odpowiednio 18,4 i 0,74 g). Szczególnie korzystne oddziaływanie na masę 1000 ziaren wykazało zastosowanie manganu i molibdenu. Po zastosowaniu preparatów zawierających te pierwiastki średnia wartość MTZ wyniosła 49,5 g. Wśród badanych odmian Baryłka i RGT Planet cechowały się lepszymi właściwościami fizycznymi ziarna w porównaniu z odmianą KWS Irina.

W pracy wykazano, że zabiegi dolistne modyfikowały skład chemiczny ziarna, jednak był on w większym stopniu determinowany przez genotyp oraz warunki pogodowe w okresie wegetacji roślin. Zastosowanie nawozu na bazie molibdenu spowodowało istotny wzrost zawartości białka – ważnego wskaźnika przydatności ziarna do produkcji słodu – jednak uzyskana wartość (10,5% s.m.) spełniała normy stawiane przez przemysł przetwórczy. Każdy z testowanych nawozów wpłynął na obniżenie zawartości tłuszczu w ziarnie. Modyfikacje składu chemicznego nie przełożyły się jednak na istotną poprawę badanych parametrów jakości słodu.

Wyniki badań pozwalają stwierdzić, że dolistne stosowanie Cu, Mn, Mo i Zn może być użytecznym elementem agrotechniki jęczmienia browarnego, poprawiającym sprawność fizjologiczną roślin i zwiększającym plonowanie. Potwierdza to pierwszą hipotezę badawczą, zakładającą korzystny wpływ nawożenia dolistnego mikroelementami na przebieg procesów fizjologicznych i kształtowanie plonu ziarna. Natomiast cechy jakościowe surowca i wyprodukowanego słodu były w znacznie większym stopniu determinowane przez genotyp

oraz zmienność warunków środowiskowych w latach badań. Przeprowadzone analizy nie potwierdziły w pełni hipotezy zakładającej poprawę przydatności technologicznej ziarna w wyniku stosowania badanych mikroelementów. Uzyskane wyniki potwierdzają, że skuteczność dolistnego dokarmiania mikroelementami należy rozpatrywać łącznie w aspekcie fizjologicznym, produkcyjnym i technologicznym.

Słowa kluczowe: jakość słodu; jęczmień browarny; mikroelementy; nawożenie dolistne; parametry fizjologiczne; plon ziarna; skład chemiczny ziarna

Summary

The aim of the study was to evaluate the effect of foliar application of selected micronutrients: copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn) on physiological processes, yield, and the technological value of grain of three spring malting barley cultivars (Baryłka, KWS Irina and RGT Planet). The doctoral dissertation consists of a series of three scientific publications based on the results of a field experiment conducted in 2019–2021 in south-eastern Poland.

The study evaluated canopy architecture indices, chlorophyll content in leaves, gas exchange parameters and chlorophyll fluorescence, plant biometrics, grain yield and yield components, as well as physical traits and chemical composition of grain and selected quality indicators of the obtained barley malt. The adopted experimental design made it possible to link plant responses at the physiological level with production effects and the evaluation of traits important from the perspective of the malting industry. This approach allowed the assessment of both the effects of individual micronutrients and the extent to which the observed changes were determined by genotype and environmental conditions.

In the experiment, the application of each micronutrient fertilizer significantly enhanced crop productivity and improved the harvest index. Among the studied cultivars, RGT Planet achieved the highest grain yield, with a mean of 5.81 t ha⁻¹ over three growing seasons.

The highest values of canopy architecture parameters (LAI and MTA) were recorded in plots where molybdenum was applied. The study demonstrated that foliar application of the tested fertilizers positively modified the functioning of the photosynthetic apparatus of barley plants. Plants treated with micronutrients were characterized by higher chlorophyll content in leaves. Beneficial changes were also observed in gas exchange parameters and chlorophyll fluorescence. The highest values of intercellular CO₂ concentration (C_i) and net photosynthesis rate (P_N) were recorded following copper application, whereas the transpiration rate (E) was highest after zinc application. Analysis of chlorophyll fluorescence highlighted the crucial role of molybdenum and zinc in plant physiological responses. The highest values of all analyzed chlorophyll fluorescence parameters were recorded after fertilization with products containing Mo and Zn.

The obtained results confirmed the existence of positive relationships between selected physiological indicators and grain yield, showing that improvement in the physiological efficiency of plants is an important factor in determining crop performance. Foliar micronutrient fertilization also influenced selected plant biometric traits and yield components, and the range of responses depended on the applied element, cultivar and weather conditions during the growing season.

Plants grown under micronutrient fertilization were shorter than those in control plots and had a higher number of productive tillers. Among the tested genotypes, the RGT Planet cultivar most frequently exhibited the favorable values of the analyzed traits. In the three-year research period, this cultivar had the longest spikes (on average 7.26 cm), the highest number of productive tillers (3.77), spike density (720 spikes m⁻²), and the number and weight of grains per spike (18.4 and 0.74 g, respectively). Manganese and molybdenum showed particularly beneficial effects on the 1000 grain weight (TGW). Following the use of preparations containing these elements, the average TGW value was 49.5 g. Among the studied cultivars, Baryłka and RGT Planet were characterized by better physical grain properties compared to the KWS Irina cultivar.

The study indicated that foliar treatments modified the chemical composition of the grain. However, it was primarily influenced by genotype and weather conditions during the growing season. The application of molybdenum-based fertilizer resulted in a significant increase in protein content – an important indicator of grain suitability for malt production – although the obtained value (10.5% d.m.) still met the standards required by the processing industry. Each of the tested fertilizers reduced the fat content in the grain. Nevertheless, these changes in chemical composition did not lead to a significant improvement in the analyzed malt quality parameters.

The conducted study showed that foliar application of Cu, Mn, Mo and Zn may constitute a useful element of malting barley agronomy, improving plant physiological efficiency and increasing yield. This confirms the first research hypothesis that foliar fertilization with micronutrients positively affects physiological processes and grain yield formation. However, the quality traits of the raw material and the produced malt were to a much greater extent determined by genotype and variability of environmental conditions during the study years. The research did not fully confirm the hypothesis assuming an improvement in the technological suitability of grain as an effect of the application of the

tested micronutrients. The obtained results confirm that the effectiveness of foliar micronutrient fertilization should be considered jointly in physiological, production and technological aspects.

Keywords: malt quality; malting barley; micronutrients; foliar fertilization; physiological parameters; grain yield; grain chemical composition

Wstęp i przegląd literatury

Jęczmień (*Hordeum vulgare* L.) należy do rodziny wiechlinowatych (*Poaceae*) i jest jednym z najdłużej uprawianych zbóż na świecie oraz gatunkiem istotnym dla bezpieczeństwa żywnościowego. Pod względem areалу zajmuje piąte miejsce wśród upraw rolniczych i stanowi ważny element europejskiego rolnictwa. W 2024 roku na świecie jęczmień uprawiano na powierzchni 44 milionów hektarów, a plony ziarna wyniosły 142 miliony ton. Największymi producentami ziarna tego gatunku są Rosja, Australia i Niemcy (FAO 2025). Jęczmień obok pszenicy należy do najdłużej uprawianych zbóż. Najstarsze ślady jego udomowienia pochodzą sprzed 7 tys. lat p.n.e z Bliskiego Wschodu z rejonu Żyznego Półksiężycza (Szempliński i in. 2020). Uprawiany jest w szerokim zakresie środowisk, zarówno w rolnictwie wysokonakładowym, jak i w systemach ekstensywnych. W uprawie występują formy jare i ozime (Newton i in. 2011, Langridge 2018). Około 65–70% wyprodukowanego ziarna przeznacza się na paszę dla zwierząt, a 33% jest wykorzystywane przez przemysł piwowarski do produkcji słodu. Słód jęczmienny jest głównym źródłem cukrów fermentacyjnych wykorzystywanych przez drożdże w tradycyjnym procesie warzenia piwa. Tylko 2–5% ziarna jest przeznaczane bezpośrednio do konsumpcji (Newton i in. 2011, Sullivan i in. 2013, Dawson i in. 2015, Kok i in. 2019, Zeng i in. 2020). W przemyśle spożywczym z ziarna jęczmienia pozyskuje się głównie kaszę pęczak i perłową. Dzięki zawartości cennych związków bioaktywnych produkty jęczmienne w diecie człowieka wpływają na obniżenie ryzyka występowania chorób cywilizacyjnych (Idehen i in. 2017, Gong 2019, Geng 2022).

Istnieją dwa typy botaniczne jęczmienia: dwurzędowy i sześciorzędowy. W Europie, Australii i Ameryce Południowej tradycyjnie do celów browarniczych wykorzystywane są odmiany dwurzędowe, podczas gdy jęczmień browarny sześciorzędowy jest popularniejszy w Ameryce Północnej (Elbasyoni i in. 2020, Miralles i in. 2021). Ziarno jęczmienia dwurzędowego jest bardziej pulchne i ma większy udział bielma skrobiowego w porównaniu z sześciorzędowym. W konsekwencji słód jęczmienny produkowany z jęczmienia dwurzędowego ma niższy stosunek białka do skrobi, co skutkuje wyższą wydajnością ekstraktu fermentacyjnego (Kok i in. 2019).

Dostępność wody i składników odżywczych ma kluczowe znaczenie dla wielkości i jakości plonu. Wraz ze wzrostem liczby ludności na świecie wzrasta zapotrzebowanie na

ziarno zbóż, które jest surowcem strategicznym i stanowi podstawę wyżywienia ludzi. W badaniach agrotechnicznych istotne jest pogłębienie wiedzy na temat procesów warunkujących rozwój, wzrost oraz plonowanie roślin zbożowych (Serrago i in. 2023, Meng i in. 2023). Dotychczasowe prace badawcze dotyczące nawożenia jęczmienia skupiały się przede wszystkim na ocenie znaczenia makroelementów w kształtowaniu wielkości plonu. Spośród nich najwięcej uwagi poświęcono azotowi, uznanemu za kluczowy i najbardziej plonotwórczy składnik (Desalegn i in. 2017, Kassie i Tesfaye 2019, Bobrenko i in. 2021, Tehulie i Eskezia 2021). W literaturze naukowej dostępne są nieliczne aktualne doniesienia na temat dolistnego stosowania mikroelementów w postaci nawozów jednoskładnikowych w uprawie jęczmienia jarego. Zohdi Aghdam i Jalili (2025) porównali wpływ dolistnej i doglebowej aplikacji żelaza, cynku i manganu na plon i jakość ziarna jęczmienia, natomiast Tobiasz-Salach i Augustyńska-Prejsnar (2020) zbadały efekt opryskiwania roślin miedzią i manganem. Dhillon i in. (2023) ocenili wpływ nawożenia cynkiem na plonowanie i jakość ziarna jęczmienia browarnego. W badaniach przeprowadzonych z użyciem miedzi i cynku, Anjum i in. (2017) wykazali, że łączne zastosowanie tych dwóch pierwiastków poprawiło plon i składniki plonu jęczmienia. Doniesienia naukowe dotyczące stosowania mikroelementów skupiają się również na aplikowaniu nawozów wieloskładnikowych (Boshev i in. 2016).

Rośliny wyższe do prawidłowego rozwoju potrzebują sześciu mikroelementów: miedzi, manganu, cynku, żelaza, boru i molibdenu. Pierwiastki te, mimo że są wymagane w niewielkich ilościach, odgrywają kluczową rolę w procesach metabolicznych komórek. Jako składniki strukturalne lub aktywatory enzymów uczestniczą w licznych reakcjach biochemicznych, kluczowych zarówno dla procesu fotosyntezy i tworzenia plonu, jak i dla oddychania zachodzącego podczas kielkowania ziarna w trakcie słodowania (Welch i in. 1995, Michałojć i in. 2003, Ram i in. 2017, Rahman i in. 2020, Bashir i in. 2021). Niedobór miedzi i manganu ogranicza funkcjonowanie kluczowych enzymów odpowiedzialnych za usuwanie reaktywnych form tlenu, kielkowanie nasion i fotosyntezę (Stoltz i Wallenhammar 2014, Schmidt i Husted 2019, Gupta i in. 2024). Ponadto miedź wpływa na lignifikację ścian komórkowych oraz prawidłowy rozwój organów generatywnych (Printz i in. 2016, Rahmati Ishka i Vatamaniuk 2020). Roślinne enzymy molibdenowe biorą udział w redukcji i asymilacji azotu oraz metabolizmie siarczanów. Nawożenie molibdenem poprzez opryskiwanie dolistne może skutecznie uzupełniać wewnętrzne niedobory molibdenu i wspierać aktywność enzymów zależnych od tego pierwiastka (Kaiser i in. 2005, Rana i in. 2020, Oliveira

i in. 2022). Cynk jest katalitycznym i strukturalnym kofaktorem białkowym w setkach enzymów. Największą klasą białek wiążących cynk w organizmach jest domena palca cynkowego (Rudani i in. 2018, Cabot i in. 2019, Stanton i in. 2022). Chociaż znaczenie wymienionych pierwiastków jest dobrze udokumentowane, znacznie mniej wiadomo na temat ich dolistnej aplikacji w warunkach polowych, szczególnie w odniesieniu do wpływu na parametry fizjologiczne roślin oraz jakość produkowanego ziarna.

Problem niedoboru mikroelementów dostępnych dla roślin ulega nasileniu m.in. w wyniku procesów wymywania, wapnowania gleb kwaśnych oraz uprawy roślin o wysokich wymaganiach odżywczych. Dodatkowo pogłębiany jest przez wysokie zapotrzebowanie nowoczesnych odmian (Tripathi 2015, Jatav i in. 2020). Dokarmianie roślin mikroelementami stosowane jest w celu maksymalizacji plonów, a także jako metoda biofortyfikacji roślin (Alshaal i El-Ramady 2017, Szeremet i in. 2022). Popularną formą dostarczania roślinom mikroelementów jest opryskiwanie dolistne, które na szerszą skalę zaczęło być stosowane w latach 50. XX wieku (Boynton 1954, Laane 2018). Polega ono na aplikowaniu składników odżywczych, biostymulatorów i innych korzystnych substancji do nadziemnych części roślin. Można je stosować w kontrolowanych ilościach i w określonym czasie wzrostu roślin (Niu i in. 2021). Nawożenie dolistne umożliwia szybkie zaopatrzenie roślin w składniki odżywcze zarówno w przypadku ich niedoboru w glebie, jak i w sytuacjach utrudnionego pobierania przez system korzeniowy, np. podczas suszy (Patil i Chetan 2018, Januszkiewicz i in. 2023). Metoda ta pozwala również ograniczyć straty, które występują przy nawożeniu doglebowym w wyniku wypłukiwania lub immobilizacji. Dawki nawozów stosowane dolistnie mogą być niższe w porównaniu z nawożeniem doglebowym. Przekłada się to na korzyści ekonomiczne oraz ogranicza negatywny wpływ rolnictwa na środowisko. Dodatkowo dolistna aplikacja nawozów może być łączona z zabiegami ochrony roślin, co umożliwia redukcję liczby zabiegów agrotechnicznych i obniżenie nakładów ponoszonych na produkcję.

Stosowanie mikroelementów zwiększa metabolizm antyoksydacyjny u roślin i pomaga złagodzić stresy środowiskowe (Vatansever i in. 2017, Ahmed i in. 2020, Tavanti i in. 2021). Jednak zbyt wysokie dawki mikroelementów mogą być toksyczne dla roślin (Chrysargyris i in. 2022, Cruz i in. 2022). Obecnie strategia dokarmiania dolistnego jest wykorzystywana w rolnictwie jako forma uzupełniającego odżywiania roślin, zwłaszcza w uprawach o wysokim potencjale plonowania (Niu i in. 2021, Oliveira i in. 2022, Januszkiewicz i in. 2023). Stosowanie preparatów na bazie mikroelementów praktykuje się

głównie w uprawie zbóż (Rawashdeh i Florin 2015, Vasundhara 2021), roślin oleistych (Arabhanvi i in. 2021) i warzyw (Kumar i in. 2016, Sidhu i in. 2019). Reakcja rośliny uprawnej na dolistne dostarczanie składników odżywczych jest zróżnicowana w zależności od gatunku, a także odmiany uprawnej w obrębie tego samego gatunku (Kannan 2010, Fernández i in. 2013, Januszkiewicz i in. 2023).

Obecnym celem hodowli jęczmienia jest optymalizacja plonowania, przy jednoczesnej poprawie przydatności przetwórczej. Identyfikacja odmian jęczmienia browarnego o pożądanych parametrach ziarna ma kluczowe znaczenie dla poprawy wydajności produkcji i jakości słodu. Badania z zakresu praktyki agrotechnicznej są istotne dla zwiększenia przydatności ziarna do celów browarniczych (Fox i Bettenhausen 2023, Gebeyaw 2021). Stosowana agrotechnika ma istotny wpływ na jakość ziarna, w szczególności na jego wielkość oraz skład chemiczny, które w dużym stopniu decydują o przydatności surowca do produkcji piwa (Khokonova 2018). Doniesienia naukowe wskazują, że niedobory mikroelementów mogą prowadzić do pogorszenia cech istotnych dla słodowania. Jednak większość tych badań dotyczy nawożenia doglebowego lub stosowania preparatów wieloskładnikowych, co utrudnia ocenę wpływu poszczególnych pierwiastków. Niewiele badań koncentruje się na dolistnym stosowaniu nawozów jednoskładnikowych i ich wpływie zarówno na plon, skład chemiczny ziarna, jak i parametry otrzymanego słodu. Wcześniejsze badania dotyczące zależności pomiędzy nawożeniem, a jakością jęczmienia browarnego skupione były przede wszystkim na wpływie nawożenia azotem na skład chemiczny ziarna (Błażewicz i in. 2018, Terefe i in. 2018, Kassie i Tesfaye 2019, Tadesse i in. 2021). W związku z tym istnieje luka badawcza dotycząca zakresu, w jakim poszczególne mikroelementy stosowane na organy nadziemne roślin mogą modyfikować jakość ziarna jęczmienia browarnego i jego przydatność do słodowania. Wypełnienie jej jest kluczowe dla oceny, czy ukierunkowane zabiegi dolistne mogą być skutecznym narzędziem agrotechnicznym w celu poprawy efektywności produkcji słodu. Dolistna aplikacja składników odżywczych może wpływać na plonowanie oraz skład chemiczny ziarna jęczmienia, ale cechy te są przede wszystkim warunkowane czynnikami genetycznymi (Kozłowska i in. 2012, Boshev i in. 2016, Tobiasz-Salach i in. 2018).

W literaturze brakuje kompleksowych badań oceniających wpływ dolistnego nawożenia mikroelementami na fizjologię, plonowanie i jakość jęczmienia browarnego w doświadczeniach polowych. W szczególności ograniczone są informacje dotyczące wpływu

tych zabiegów na parametry fluorescencji chlorofilu i wymiany gazowej, które stanowią istotny wskaźnik stanu fizjologicznego roślin. Ponadto brak jest danych łączących wpływ mikroelementów na wielkość plonu, skład chemiczny oraz właściwości technologiczne ziarna, co ogranicza możliwość opracowania efektywnych zaleceń agrotechnicznych. Przeprowadzone badania mają znaczenie zarówno poznawcze, pozwalając lepiej zrozumieć mechanizmy działania mikroelementów w jęczmieniu, jak i praktyczne, stanowiąc podstawę do formułowania zaleceń poprawiających efektywność produkcji oraz jakość surowca browarniczego.

Rozprawę doktorską stanowi cykl trzech powiązanych tematycznie artykułów naukowych, opublikowanych w międzynarodowych czasopismach. Publikacje te tworzą zbiór prac stanowiący kompleksową ocenę wpływu dolistnego stosowania mikroelementów na wzrost, rozwój, plonowanie oraz jakość technologiczną jęczmienia browarnego (*Hordeum vulgare* L.). Wybrane artykuły badawcze powstały na podstawie doświadczenia polowego, które prowadzone było w trzech sezonach wegetacyjnych.

Pierwszy artykuł pt. *Influence of foliar application of microelements on yield and yield components of spring malting barley* (Agriculture, 2024) koncentruje się na ocenie wpływu dolistnej aplikacji mikroelementów na plon oraz jego składowe. Publikacja omawia znaczenie mikroelementów w kształtowaniu wielkości i struktury plonu jęczmienia browarnego. Uzyskane wyniki wskazują na istotne zależności pomiędzy nawożeniem dolistnym, a efektem produkcyjnym.

Drugi artykuł pt. *Effect of foliar application of microelements on chlorophyll content, canopy architecture indicators, and physiological parameters of Hordeum vulgare L. plants* (PeerJ, 2025) stanowi rozwinięcie badań nad plonowaniem poprzez uwzględnienie aspektów fizjologicznych roślin. W tej pracy przeanalizowano wpływ mikroelementów na parametry architektury łanu, zawartość chlorofilu w liściach oraz wybrane wskaźniki fizjologiczne roślin jęczmienia. Otrzymane wyniki umożliwiają lepsze poznanie roli dolistnej aplikacji mikropierwiastków w przebiegu procesów fizjologicznych w roślinach uprawnych.

Trzeci artykuł pt. *Impact of foliar application of copper, manganese, molybdenum, and zinc on the chemical composition and malting quality of barley cultivars* (Agronomy, 2025) skupia się na ocenie wpływu wybranych mikroelementów na skład chemiczny ziarna oraz parametry jakościowe istotne z punktu widzenia przemysłu słodowniczego. Uwzględnienie

tego aspektu jest kluczowe, ponieważ w przypadku jęczmienia browarnego na równi z wielkością plonu istotna jest jakość technologiczna ziarna.

Przedstawione publikacje stanowią spójną całość, która jest szczegółowym opracowaniem problematyki wpływu dolistnego nawożenia mikroelementami na:

- efekty produkcyjne uprawy,
- procesy fizjologiczne zachodzące w roślinach,
- skład chemiczny ziarna,
- jakość słodowniczą ziarna jęczmienia browarnego.

Przedstawione artykuły umożliwiają prześledzenie pełnego ciągu zależności: od odpowiedzi fizjologicznej roślin, przez efekt plonotwórczy, aż do oceny jakości surowca dla przemysłu słodowniczego. Łącznie publikacje te tworzą spójny cykl badawczy obejmujący poziom fizjologiczny, produkcyjny oraz technologiczny uprawy.

1. Cel badań i hipotezy badawcze

Przedstawiony cykl publikacji skoncentrowany jest na problemie badawczym, którym była kompleksowa ocena znaczenia dolistnego stosowania wybranych mikroelementów w uprawie jęczmienia jarego browarnego. Poszczególne prace obejmowały kolejno analizę wpływu badanych zabiegów na elementy struktury plonu i plon ziarna, parametry fizjologiczne roślin w trakcie wegetacji oraz skład chemiczny ziarna, a także jego przydatność słodowniczą. Celem badań była ocena wpływu dolistnej aplikacji miedzi (Cu), manganu (Mn), molibdenu (Mo) i cynku (Zn) na przebieg procesów fizjologicznych, kształtowanie elementów struktury plonu, wielkość plonu oraz wartość technologiczną ziarna trzech odmian browarnych jęczmienia jarego (Baryłka, KWS Irina, RGT Planet) uprawianych w warunkach polowych.

Realizacja głównego celu badań obejmowała następujące cele szczegółowe:

- określenie wpływu dolistnej aplikacji Cu, Mn, Mo i Zn na plon ziarna i jego elementy struktury;
- zbadanie oddziaływania stosowanych mikroelementów na wskaźniki architektury łanu, zawartość chlorofilu w liściach, parametry wymiany gazowej oraz fluorescencję chlorofilu w roślinach jęczmienia;
- ustalenie efektu dolistnego stosowania mikroelementów w kształtowaniu cech fizycznych i składu chemicznego ziarna;
- ocenę wpływu stosowanych zabiegów na wybrane wskaźniki jakości słodu;
- określenie reakcji badanych odmian jęczmienia na zastosowane mikroelementy w zmiennych warunkach środowiskowych w poszczególnych latach badań.

Założono hipotezy badawcze:

H1: Nawożenie dolistne mikroelementami wpływa korzystnie na przebieg procesów fizjologicznych i plonowanie roślin.

H2: Dolistna aplikacja wybranych mikroelementów poprawia wartość technologiczną ziarna.

2. Metodyka badań

2.1 Doświadczenie polowe

Podstawę metodyczną rozprawy stanowiło ścisłe doświadczenie polowe przeprowadzone w latach 2019–2021 w miejscowości Reczpol, w południowo-wschodniej Polsce ($49^{\circ}47'03''\text{N}$, $22^{\circ}34'37''\text{E}$). W badaniach zastosowano układ split-block z czterema powtórzeniami. Powierzchnia pojedynczego poletka do zbioru wynosiła 15 m^2 .

Zastosowano następujące czynniki doświadczenia: (I) odmiana jęczmienia jarego dwurzędowego w typie browarnym (Baryłka, KWS Irina oraz RGT Planet); (II) dolistne nawożenie jednoskładnikowymi nawozami mikroelementowymi, obejmujące: obiekt kontrolny (bez nawożenia), zastosowanie miedzi (Cu), manganu (Mn), molibdenu (Mo) i cynku (Zn).

Źródłem mikroelementów były nawozy z serii Mikrovit® (Intermag Sp. z o.o.), stosowane dolistnie w postaci roztworów wodnych. W doświadczeniu zastosowano: MIKROVIT® MIEDŹ zawierający 75 g Cu l^{-1} w formie siarczanu miedzi (CuSO_4) w dawce 2 l ha^{-1} , MIKROVIT® MANGAN zawierający 160 g Mn l^{-1} w formie siarczanu manganu i azotanu manganu w dawce 2 l ha^{-1} , MIKROVIT® MOLIBDEN zawierający 33 g Mo l^{-1} w formie molibdenianu amonu ($(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$) w dawce 1 l ha^{-1} oraz MIKROVIT® CYNK zawierający 112 g Zn l^{-1} w formie siarczanu cynku (ZnSO_4) w dawce 2 l ha^{-1} . Oprysk wykonano jednokrotnie w fazie strzelania w źdźbło (BBCH 30–32) (Lancashire i in. 1991), w warunkach bezwietrznych, przy użyciu opryskiwacza ciśnieniowego. Dawki nawozów ustalono zgodnie z zaleceniami producenta dla upraw zbóż.

We wszystkich latach badań stosowano nawożenie mineralne w dawkach $50\text{ kg ha}^{-1}\text{ N}$, $60\text{ kg ha}^{-1}\text{ P}_2\text{O}_5$ i $90\text{ kg ha}^{-1}\text{ K}_2\text{O}$. Wiosną, przed siewem, aplikowano nawóz Polifoska® 6 w dawce 300 kg ha^{-1} oraz saletrę amonową (32% N) w dawce 100 kg ha^{-1} . W celu zabezpieczenia podstawowego zaopatrzenia roślin w mikroelementy w fazie krzewienia (BBCH 25–27) na wszystkich obiektach zastosowano wieloskładnikowy preparat dolistny Opti Zboża (Chemirrol Sp. z o.o.) w dawce 3 kg ha^{-1} . Preparat ten zawierał w g kg^{-1} : N – 140, P_2O_5 – 160, K_2O – 160, MgO – 30, SO_3 – 180, Cu – 3, Fe – 1,5, Mn – 5, Mo – 0,4 i Zn – 1,5.

Certyfikowany materiał siewny badanych odmian pochodził od firm hodowlanych. Siew wykonywano w pierwszej dekadzie kwietnia: 6 kwietnia 2019 r., 2 kwietnia 2020 r. oraz 8 kwietnia 2021 r. Norma wysiewu wynosiła 165 kg ha^{-1} , rozstawa rzędów 12 cm , a głębokość

siewu 3 cm. Przedplonem jęczmienia w każdym roku badań był rzepak ozimy (*Brassica napus* L.). Agrotechnikę stosowano zgodnie z intensywną technologią uprawy jęczmienia jarego, z pełną ochroną roślin przed chwastami, chorobami i szkodnikami. Materiał siewny zaprawiano preparatem Funaben Plus 02WS w dawce 150 g na 100 kg ziarna. W fazie BBCH 25–29 stosowano herbicydy Mocarz 75WG w dawce 0,2 kg ha⁻¹ oraz Herbistar 200EC w dawce 0,5 l ha⁻¹, w fazie BBCH 31–34 regulator wzrostu Moddus 250EC w dawce 0,4 l ha⁻¹ i fungicyd Fandango 200EC w dawce 1,0 l ha⁻¹, a w fazie BBCH 51–55 fungicyd Kier 450S w dawce 1,0 l ha⁻¹. W 2019 r. dodatkowo zastosowano insektycyd Delmetros 100SC w dawce 0,05 l ha⁻¹.

Przed zbiorem określano liczbę kłosów na 1 m². Zbiór ziarna przeprowadzano w fazie pełnej dojrzałości (BBCH 89), w trzeciej dekadzie lipca: 22 lipca 2019 r., 30 lipca 2020 r. oraz 25 lipca 2021 r. Plon ziarna oceniano oddzielnie dla każdego poletka.

2.2 Charakterystyka warunków klimatyczno-glebowych

2.2.1 Warunki glebowe

Przed założeniem doświadczenia wykonano analizę właściwości fizykochemicznych gleby w akredytowanym laboratorium Stacji Chemiczno-Rolniczej w Rzeszowie. Doświadczenie założono na glebie typu Fluvic Cambisol (CMfv). Odczyn gleby oznaczano potencjometrycznie według PN-ISO 10390, zawartość węgla organicznego metodą Tiurina według PN-ISO 14235, zawartość przyswajalnego fosforu i potasu metodą Egnera-Riehma według PN-R-04023 i PN-R-04022+AZ1, a magnezu metodą Schachtschabela według PN-R-04020+AZ1. Ilość miedzi, manganu, cynku i żelaza oznaczano po mineralizacji w HCl metodą płomieniowej spektrometrii absorpcyjnej zgodnie z odpowiednimi normami branżowymi. Gleba miała odczyn lekko kwaśny; pH w 1 mol dm⁻³ KCl wynosiło 6,0 w 2019 r. oraz 5,8 w latach 2020 i 2021, a zawartość węgla organicznego mieściła się w zakresie 1,1–1,3%.

2.2.2 Warunki pogodowe

Charakterystykę warunków pogodowych opracowano na podstawie danych otrzymanych ze Stacji Meteorologicznej w Zadąbrowiu (50°19'09"N, 21°48'19"E). Na ich podstawie obliczono średnie miesięczne temperatury powietrza oraz sumy opadów atmosferycznych w okresie wegetacji jęczmienia. Warunki wodno-termiczne scharakteryzowano z wykorzystaniem współczynnika hydrotermicznego Sielanianowa (*k*) według wzoru:

$$k = \frac{P}{\Sigma t \cdot 0,1}$$

gdzie:

P – suma opadów miesięcznych (mm),

Σt – suma średnich dobowych temperatur powietrza (°C) w danym miesiącu.

Otrzymane wartości interpretowano według klasyfikacji Skowery (2014), różnicującej warunki od skrajnie suchych do skrajnie wilgotnych.

2.3 Pomiary parametrów w czasie wegetacji roślin

W czasie wzrostu roślin oceniono wpływ dolistnej aplikacji badanych mikroelementów na architekturę łanu, zawartość chlorofilu i przebieg procesów fizjologicznych w roślinach. W każdym roku pomiary wykonywano dwukrotnie w okresie wegetacji w fazach BBCH 43–45 oraz BBCH 50–52. Wyniki przedstawiano jako średnie z dwóch terminów pomiarów.

2.3.1 Wskaźniki architektury łanu

Wskaźniki architektury łanu, tj. indeks powierzchni liści (LAI) oraz średni kąt nachylenia liścia (MTA), oznaczano z wykorzystaniem aparatu LAI-2000 (LI-COR). Na każdym poletku wykonywano jeden pomiar nad łanem i cztery pomiary w łanie.

2.3.2 Indeks zawartości chlorofilu

Kumulację chlorofilu w liściach oceniano na podstawie indeksu zawartości chlorofilu (CCI), określanego przy użyciu przenośnego chlorofilometru CCM-200plus (Opti-Sciences). Na każdym poletku wykonywano pięć pomiarów na liściach podflagowych losowo wybranych roślin.

2.3.3 Wymiana gazowa

Wartości parametrów wymiany gazowej określono przy użyciu systemu LCpro-SD (ADC Bioscientific Ltd.). Oceniano międzykomórkowe stężenie CO_2 (C_i), współczynnik transpiracji (E), przewodnictwo szparkowe (g_s) oraz szybkość fotosyntezy netto (P_N). Pomiary wykonywano na trzech losowo wybranych liściach podflagowych z każdego poletka. Natężenie światła w komorze pomiarowej wynosiło $350 \mu\text{mol m}^{-2} \text{s}^{-1}$, temperatura około 22°C , a wilgotność względna powietrza około 60%.

2.3.4 Fluorescencja chlorofilu

Parametry fluorescencji chlorofilu zbadano za pomocą fluorometru Pocket PEA (Hansatech Instruments), wyposażonego w zaciski zacieniające. Liście adaptowano do ciemności przez 30 minut. Sygnał fluorescencji rejestrowano w czerwonym świetle aktywnym o maksymalnej długości fali 627 nm, emitowanym przez 1 s z maksymalną intensywnością 3500 μmol (photon) $\text{PAR m}^{-2} \text{s}^{-1}$. Na każdym poletku wykonywano pomiary na pięciu losowo wybranych liściach podflagowych. Oceniano maksymalną wydajność fotochemiczną PSII (F_v/F_m), potencjalną wydajność fotochemiczną (F_v/F_o), udział aktywnych centrów reakcji PSII (RC/ABS) oraz wskaźnik wydajności fotosyntetycznej (PI).

2.4 Analizy laboratoryjne

Po zbiorze, ziarno z poszczególnych poletek oczyszczano, dosuszano w warunkach laboratoryjnych do uzyskania stabilnej wilgotności przechowalniczej, a następnie kondycjonowano w temperaturze pokojowej.

2.4.1 Plon ziarna i indeks żniwny

Plon ziarna z każdego poletka przeliczano na 1 ha przy standardowej wilgotności 14%. Równocześnie zważono biomasę części nadziemnych roślin, co pozwoliło obliczyć indeks żniwny (HI) jako stosunek plonu ziarna do plonu biomasy nadziemnej.

2.4.2 Elementy struktury plonu

Przed zbiorem z każdego poletka pobierano losowo po 20 reprezentatywnych roślin. W pobranym materiale oznaczano wysokość roślin, długość kłosa, liczbę pędów produkcyjnych na roślinie, masę ziarna z kłosa oraz liczbę ziaren z kłosa. Uzyskane wyniki wykorzystano do oceny wpływu badanych czynników na kształtowanie elementów struktury plonu jęczmienia jarego browarnego.

2.4.3 Cechy fizyczne ziarna

Masę 1000 ziaren (MTZ) określono przy użyciu licznika ziaren firmy Sadkiewicz Instruments. Gęstość ziarna (masę hektolitra) oznaczano przy użyciu wilgotnościomierza i gęstościomierza do ziarna Dрамиński GMDM, typ WZW2 (Dрамиński Inc.). Oznaczenie

wykonywano w trzech powtórzeniach, a wynik przyjmowano jako średnią z pomiarów. Wyrównanie ziarna oceniano przez przesiewanie próbki o masie 100 g przez sita Vogla na mechanicznym sortowniku SŻK Sadkiewicz przez 3 minuty. Wynik wyrażano jako udział masy ziarna zatrzymanego na sitach o średnicy 2,5 i 2,8 mm w całkowitej masie próbki.

2.4.4 Skład chemiczny ziarna

W celu analizy składu chemicznego ziarno rozdrabniano w młynie nożowym Knifetec 1095 (Foss Tecator), uzyskując jednorodny materiał analityczny. Zawartość wody oznaczano metodą referencyjną zgodnie z normą PN-EN ISO 712, przy zachowaniu zgodności z zasadami stosowanymi w ocenie surowca browarniczego według Analytica EBC. Zawartość białka ogólnego obliczano na podstawie azotu całkowitego oznaczonego metodą Kjeldahla zgodnie z normą PN-EN ISO 20483, stosując współczynnik przeliczeniowy 6,25. Tłuszcz surowy oznaczano metodą ekstrakcyjną zgodnie z PN-EN ISO 11085, włókno surowe zgodnie z PN-EN ISO 6865, natomiast popiół całkowity oznaczano wagowo po spopieleniu próbki zgodnie z PN-EN ISO 2171. Każde oznaczenie wykonywano w trzech powtórzeniach, a wyniki wyrażano w przeliczeniu na suchą masę.

W celu oznaczenia składu pierwiastkowego próbki poddawano mineralizacji na mokro w układzie otwartym, na bloku grzejnym Tecator, z zastosowaniem mieszaniny $\text{HNO}_3\text{:HClO}_4\text{:H}_2\text{SO}_4$ w stosunku objętościowym 20:5:1, aż do uzyskania klarownych roztworów. Zawartość Ca, Cu, Fe, K, Mg, Mn i Zn oznaczano metodą płomieniowej atomowej spektrometrii absorpcyjnej na spektrofotometrze Hitachi Z 2000, z rozpylaniem powietrze-acetylen i korekcją tła wykorzystującą efekt polaryzacji Zeemana. Parametry pomiarowe dostosowano do wymagań normy ISO 6869, stosując linie analityczne 422,6 nm dla Ca, 324,8 nm dla Cu, 248,3 nm dla Fe, 766,5 nm dla K, 285,2 nm dla Mg, 279,5 nm dla Mn oraz 213,8 nm dla Zn. Kalibrację przeprowadzano z użyciem zewnętrznych roztworów wzorcowych przygotowanych w tym samym środowisku kwaśnym co próbki, a w każdej serii pomiarowej uwzględniano próbę ślepą.

2.4.5 Ekstraktywność teoretyczna

Ekstraktywność teoretyczną ziarna jęczmienia (E) obliczono według wzoru Bishopa, opracowanego dla jęczmienia dwurzędowego (Błażewicz i in. 2007):

$$E = 84,5 - 0,75B + 0,1MTZ$$

gdzie:

E – ekstraktywność teoretyczna ziarna (% s.m.),

B – zawartość białka w ziarnie (% s.m.),

MTZ – masa 1000 ziaren (g),

84,5 – stała charakterystyczna dla jęczmienia dwurzędowego.

Do obliczeń wykorzystano otrzymane w badaniach wyniki zawartości białka w ziarnie oraz masy 1000 ziaren.

2.4.6 Produkcja słodu i analiza parametrów jakościowych

Proces słodowania ziarna przeprowadzono w skali laboratoryjnej według standardowego schematu mikrosłodowania jęczmienia stosowanego w badaniach (MEBAK 2016). Słodowanie wykonywano w trzech równoległych powtórzeniach, a każda próbka obejmowała 425 g ziarna w przeliczeniu na suchą masę. Etap moczenia i kiełkowania prowadzono w mikrosłodowni w temperaturze $14 \pm 1^{\circ}\text{C}$ i przy wilgotności względnej powietrza powyżej 95%. Ziarno moczone w wodzie o temperaturze około 14°C do uzyskania docelowego stopnia uwodnienia wynoszącego 45%. Całkowity czas moczenia wynosił około 72 godzin; wodę wymieniano co 24 godziny, a materiał regularnie napowietrzano. Schemat moczenia obejmował: w pierwszej dobie 4 godziny pod wodą i około 20 godzin na powietrzu, w drugiej dobie do 2 godzin pod wodą i pozostały czas na powietrzu, natomiast w trzeciej dobie ziarno spryskiwano wodą do osiągnięcia 45% wilgotności, po czym pozostawiano je na powietrzu do rozpoczęcia kiełkowania. Po zakończeniu moczenia ziarno kiełkowano przez 5 dni w tych samych warunkach temperatury i wilgotności, codziennie kontrolując masę materiału i delikatnie mieszając ziarno w celu zapewnienia równomiernego dostępu tlenu oraz zapobiegania zlepieniu.

Po zakończeniu kiełkowania zielony sól suszono konwekcyjnie w suszarce jednositowej z nadmuchem ciepłego powietrza. Suszenie prowadzono przez 23 godziny według programu: 16 godzin w temperaturze 50°C , następnie 1 godzinę w temperaturze 60°C , 1 godzinę w temperaturze 70°C oraz 5 godzin w temperaturze 80°C . Po schłodzeniu sól odkiełkowano przez utarcie na sicie i oddzielenie wysuszonych kiełków

korzeniowych. Otrzymany sód przechowywano w szczelnie zamkniętych pojemnikach do czasu wykonania analiz jakościowych.

Analizę jakości sodu wykonywano na śrucie przygotowanej bezpośrednio przed oznaczeniami przez zmielenie sodu w młynie nożowym Knifetec 1095 (Foss Tecator). Pobieranie prób i przygotowanie materiału prowadzono zgodnie z zasadami Analytica EBC (1997). Oznaczano wilgotność sodu metodą utraty masy, zawartość białka ogólnego obliczaną z azotu całkowitego oznaczonego metodą Kjeldahla, ekstraktywność sodu na podstawie laboratoryjnej brzezki uzyskanej w teście zaciera kongresowego, liczbę Kolbacha jako stosunek azotu rozpuszczalnego w brzezce do azotu całkowitego w sódzie oraz siłę diastatyczną metodą spektrofotometryczną. Wyniki ekstraktywności wyrażano jako procent ekstraktu w suchej masie sodu, a siłę diastatyczną w jednostkach Windisch–Kolbach. Wszystkie oznaczenia wykonywano w trzech niezależnych powtórzeniach.

2.5 Metody statystyczne

Wyniki opracowano statystycznie z wykorzystaniem pakietu Statistica. Dla danych dotyczących cech agronomicznych, cech fizycznych ziarna, składu chemicznego oraz parametrów jakości sodu zastosowano analizę wariancji odpowiednią dla układu split-block. W części obejmującej parametry fizjologiczne wyniki trzyletniego doświadczenia opracowano dodatkowo z zastosowaniem modelu hierarchicznego typu cross-classified, co umożliwiło uwzględnienie sezonowej zmienności warunków meteorologicznych i interakcji między badanymi czynnikami. Szczegółowa postać modelu była dostosowana do charakteru analizowanego zbioru danych i odpowiadała rozwiązaniom przyjętym w publikacjach składowych.

Przed wykonaniem analiz weryfikowano normalność rozkładu reszt testem Shapiro–Wilka oraz jednorodność wariancji testem Levene’a. Istotność różnic pomiędzy średnimi oceniano testem HSD Tukeya przy poziomie istotności $p \leq 0,05$. Zależności pomiędzy badanymi cechami określano za pomocą współczynników korelacji Pearsona. W analizie zależności między plonem ziarna, a parametrami fizjologicznymi dane agregowano do średnich dla kombinacji rok $\times$ odmiana $\times$ nawożenie, co dawało 45 jednostek porównawczych wykorzystywanych w analizie korelacyjnej.

3. Wyniki badań

3.1 Wpływ warunków pogodowych na wartości analizowanych cech

W trakcie trzyletniego doświadczenia polowego (2019–2021) wykazano jednoznacznie, że rok wegetacji istotnie różnicował wszystkie badane cechy jęczmienia. Najkorzystniejsze warunki plonowania wystąpiły w 2021. W tym roku uzyskano plon ziarna wyższy odpowiednio o 20,0% i 31,0% oraz lepsze wyrównanie ziarna - o 4,9% i 9,0% w porównaniu do lat 2019 i 2020 (Publikacja 1, Tab. 7).

Rok wegetacji istotnie wpływał na cechy biometryczne roślin oraz komponenty struktury plonu. Rośliny uprawiane w sezonie 2020 były wyższe odpowiednio o 14,0 cm i 4,2 cm w porównaniu z latami 2019 i 2021. Natomiast w 2021 r. odnotowano najdłuższe kłosa (7,25 cm) oraz największą krzewistość produkcyjną (3,90), a także uzyskano najwyższą obsadę kłosów (767 szt. m⁻²), największą masę ziarna z kłosa (0,86 g) oraz masę 1000 ziaren (50,5 g) (Publikacja 1, Tab. 5 i 6). Układ warunków pogodowych w okresie wegetacji jęczmienia jarego w 2021 roku był sprzyjający. Kwiecień, miesiąc kielkowania nasion i wschodów roślin, według współczynnika hydrotermicznego, był miesiącem wyjątkowo wilgotnym (Publikacja 1, Tab. 4). Skutkowało to szybkimi i równomiernymi wschodami roślin. Wysoka wilgotność wpłynęła korzystnie na prawidłowy rozwój roślin również w maju i czerwcu. Najniższy plon ziarna uzyskano w 2020 roku. W tym roku kwiecień był miesiącem suchym, co negatywnie wpłynęło na wzrost roślin. Według Szemplińskiego i in. (2020) na plony jęczmienia jarego największy wpływ mają opady deszczu w okresie od siewu do krzewienia.

W ostatnim roku realizacji doświadczenia polowego odnotowano najwyższy wskaźnik powierzchni liści (LAI) – 5,72 m²·m⁻². W tym sezonie wegetacyjnym rośliny gromadziły najwięcej chlorofilu w liściach oraz miały najwyższe wartości parametrów wymiany gazowej (Publikacja 2, Tab. 2 i 3). Wskaźniki fluorescencji chlorofilu - F_v/F_m i F_v/F_o były najwyższe w 2019 r., natomiast RC/ABS i PI w 2021 r. (Publikacja 2, Tab. 4).

Badania wykazały, że układ warunków pogodowych istotnie modyfikował skład mineralny ziarna badanych odmian. W porównaniu do wyników uzyskanych w kolejnych latach badań, w 2019 roku odnotowano istotnie wyższą zawartość miedzi i cynku. Ziarno zebrane w 2021 roku cechowało się najwyższym poziomem żelaza i potasu (Publikacja 3, Tab. 2). W 2019 r. ziarno zawierało istotnie więcej białka, włókna i popiołu, natomiast zawartość

tych składników była najniższa w 2020 roku. Wyższy udział tłuszczu odnotowano w latach 2020 i 2021 w porównaniu z rokiem 2019 (Publikacja 3, Tab. 3).

W doświadczeniu stwierdzono również istotne różnicowanie parametrów jakościowych słodu w zależności od roku produkcji ziarna. Słód otrzymany z surowca wyprodukowanego w 2019 roku charakteryzował się najwyższą zawartością białka (11,3%) i wilgotnością (3,99%) oraz najniższą ekstraktywnością (82,2% s.m.) i siłą diastatyczną (271 °WK). W 2020 roku odnotowano najniższą wilgotność (3,80%) oraz zawartość białka (10,4%), a także najwyższą liczbę Kolbacha (42,8%). Natomiast w 2021 roku uzyskano najwyższe wartości ekstraktywności (82,8%) oraz siły diastatycznej (288 °WK) (Publikacja 3, Tab. 4).

3.2 Wpływ czynników doświadczalnych na plonowanie jęczmienia

W pracy analizowano wpływ czynników doświadczalnych na główny efekt produkcyjny uprawy zbóż, jakim jest plon ziarna. Otrzymane wyniki wykazały, że plonowanie roślin jęczmienia było istotnie różnicowane zarówno w zależności od zastosowanego nawożenia dolistnego mikroelementami, jak i od odmiany oraz roku wegetacji. Średni plon ziarna w doświadczeniu wyniósł 5,60 t ha⁻¹, a najwyższe wartości (niezależnie od odmiany) uzyskano w wyniku dolistnej aplikacji Mo (5,74 t ha⁻¹). Wśród badanych odmian najlepszym plonowaniem charakteryzowała się odmiana RGT Planet, szczególnie po zastosowaniu molibdenu, gdzie plon przekraczał 6,0 t ha⁻¹. Niezależnie od odmiany, dolistne stosowanie każdego z badanych mikroelementów skutkowało istotnym wzrostem plonu ziarna oraz indeksu żniwnego w porównaniu z obiektem kontrolnym (Publikacja 1, Tab. 7).

Analiza statystyczna wykazała istotną interakcję nawożenie x odmiana w odniesieniu do wielkości plonu, co wskazuje, że reakcja roślin na mikroelementy była różnicowana i zależała od właściwości genetycznych badanych odmian. Ponadto, stwierdzono istotne różnice pomiędzy odmianami – odmiana RGT Planet plonowała lepiej niż Baryłka i KWS Irina, niezależnie od wariantu nawożenia (Publikacja 1, Tab. 7).

3.3 Kształtowanie architektury łanu

W trakcie wegetacji roślin przeprowadzono ocenę wpływu nawożenia i odmiany na architekturę łanu jęczmienia. Określono indeks powierzchni liści (LAI) oraz średni kąt nachylenia liścia (MTA). Średnia wartość LAI w doświadczeniu wyniosła 5,08 m² m⁻². U każdej z badanych odmian najwyższe wartości odnotowano po zastosowaniu Mo (Publikacja 2, Tab. 2). U odmiany RGT Planet na poletkach, gdzie zastosowano Zn LAI był niższy o 6,3%

w porównaniu do kontroli. Analiza średnich dla odmian wykazała, że KWS Irina charakteryzowała się istotnie wyższą wartością LAI spośród badanych odmian (Publikacja 2, Tab. 2). Zastosowanie każdego z badanych nawozów mikroelementowych (niezależnie od odmiany) spowodowało wzrost wskaźnika LAI w porównaniu z kontrolą, a najwyższe wartości odnotowano w wyniku aplikacji Mo (wzrost o 7,6%) (Publikacja 2, Tab. 2).

Wartość MTA była najwyższa u odmiany KWS Irina po zastosowaniu Mo i wyniosła 53°. U odmian Baryłka i RGT Planet najwyższe wartości MTA zmierzono na poletkach nawożonych Cu (odpowiednio 46,4° i 48,4°). Odmiana KWS Irina miała średnio o 3,4°, a odmiana RGT Planet o 2,9 wyższe MTA w porównaniu do odmiany Baryłka (Publikacja 2, Tab. 2).

3.4 Przebieg procesów fizjologicznych w roślinach

W ramach badań oceniono wpływ czynników doświadczenia na procesy fizjologiczne zachodzące w roślinach – zawartość chlorofilu, wymianę gazową oraz fluorescencję chlorofilu. Indeks zawartości chlorofilu w liściach (CCI) wyniósł średnio 40,6. U odmian Baryłka i KWS Irina najwyższe wartości CCI (wzrost odpowiednio o 14,4% i 6,4% w porównaniu do kontroli) odnotowano w wyniku aplikacji Cu, natomiast u odmiany RGT Planet najwyższą wartość uzyskano na poletkach opryskiwanych Zn (wzrost o 13,0%) (Publikacja 2, Tab. 2). Zastosowanie każdego z nawozów mikroelementowych, wpłynęło na istotny wzrost średnich wartości CCI w porównaniu do kontroli. Najwięcej chlorofilu w liściach zgromadziły rośliny opryskiwane Cu - o 8,9% więcej w porównaniu do kontroli (Publikacja 2, Tab. 2).

Wyniki badań wykazały, że odmiana i nawożenie determinowały wartości parametrów wymiany gazowej roślin. U każdej z badanych odmian, wartości stężenia międzykomórkowego CO₂ (C_i) były najwyższe na poletkach nawożonych Cu i Zn (Publikacja 2, Tab. 3). Współczynnik transpiracji (E) był najwyższy u odmiany RGT Planet po zastosowaniu Zn (wzrost o 8,1% w porównaniu do kontroli). Wyższą wartość obserwowano również u odmiany KWS Irina przy nawożeniu Mn (Publikacja 2, Tab. 3). Odmiany KWS Irina i RGT Planet charakteryzowały się odpowiednio o 8,1% i 12,0% wyższą średnią wartością E w porównaniu do odmiany Baryłka. Aplikacja każdego z badanych mikroelementów spowodowała istotny wzrost wskaźnika E w porównaniu do kontroli, a największy wzrost (o 13%) odnotowano po zastosowaniu Zn.

Zmierzone w doświadczeniu przewodnictwo szparkowe (g_s) wyniosło 0,54 mmol (H_2O) $m^{-2} s^{-1}$ (Publikacja 2, Tab. 3). Analiza statystyczna wykazała u odmiany KWS Irina istotnie wyższą wartość g_s w porównaniu do Baryłki i RGT Planet. Zastosowanie mikroelementów dolistnie (niezależnie od testowanej odmiany) spowodowało wzrost g_s w porównaniu z kontrolą, a najwyższe wartości odnotowano u roślin z obiektów nawożonych Mo i Zn (Publikacja 2, Tab. 3).

Szybkość fotosyntezy netto (P_N) wyniosła średnio 14,5 ($\mu mol (CO_2) m^{-2} s^{-1}$). Najwyższą wykazano u odmiany RGT Planet po zastosowaniu Cu (wzrost o 10,3% w porównaniu do kontroli). Średnia wartość P_N u odmiany RGT Planet była wyższa w porównaniu do Baryłki i KWS Irina odpowiednio o 14,1% i 6,2%. Dolistne nawożenie każdym z badanych mikroelementów spowodowało istotny wzrost P_N w porównaniu z kontrolą, a najlepszy efekt uzyskano u roślin opryskiwanych nawozem na bazie miedzi (wzrost o 12,8%) (Publikacja 2, Tab. 3).

Średnia maksymalna wydajność fotochemiczna PSII (F_v/F_m) wyniosła 0,82. Najwyższe wartości odnotowano u odmiany Baryłka po opryskaniu roślin nawozem cynkowym (0,84). Odmiana ta uzyskała istotnie wyższą średnią wartość tego wskaźnika spośród badanych odmian. Dolistne zastosowanie każdego z badanych mikroelementów spowodowało wzrost średniej wartości wskaźnika F_v/F_m o 3,8% w porównaniu do kontroli (Publikacja 2, Tab. 4).

Oceniany w badaniach udział aktywnych centrów reakcji PSII (RC/ABS) był także zależny od zastosowanych czynników doświadczalnych. Najwyższe wartości odnotowano u odmiany Baryłka na poletkach nawożonych Mn i Mo. U odmiany RGT Planet obserwowano istotny wzrost tego parametru fluorescencji chlorofilu po zastosowaniu Mo. Niezależnie od nawożenia, Baryłka charakteryzowała się wyższą średnią wartością RC/ABS o 10,8% w porównaniu z KWS Irina i o 9,2% w porównaniu z RGT Planet. Dolistne nawożenie mikroelementami roślin jęczmienia spowodowało istotny wzrost RC/ABS , a najwyższe wartości obserwowano po opryskiwaniu roślin Mo i Zn (wzrost odpowiednio o 14,4% i 11,5% w porównaniu z kontrolą) (Publikacja 2, Tab. 4).

Potencjalna wydajność fotochemiczna (F_v/F_o) była najwyższa u odmiany RGT Planet po zastosowaniu Mo i Zn, natomiast najniższa u odmiany KWS Irina w wariancie kontrolnym. Wartość parametru była zróżnicowana pomiędzy badanymi odmianami. U roślin odmian Baryłka i RGT Planet wykazano wyższe wartości F_v/F_o w porównaniu z odmianą KWS Irina (odpowiednio o 2,9% i 4,0%). Dolistne zastosowanie każdego z testowanych nawozów

mikroelementowych (niezależnie od odmiany) spowodowało istotny wzrost F_v/F_o w porównaniu z kontrolą. Najlepszy efekt obserwowano po zastosowaniu Zn (wzrost o 6,0%) (Publikacja 2, Tab. 4).

Najwyższe wartości wskaźnika wydajności fotosyntetycznej (PI) odnotowano u odmiany Baryłka po zastosowaniu Mn i Mo. Wzrost w porównaniu do kontroli wyniósł odpowiednio 27,6% i 27,7%. Odmiana Baryłka (niezależnie od nawożenia dolistnego) charakteryzowała się istotnie wyższym PI w porównaniu do odmian KWS Irina i RGT Planet (odpowiednio o 7,6% i 6,2%). Zastosowanie każdego z nawozów mikroelementowych spowodowało wzrost PI w porównaniu do kontroli (niezależnie od odmiany). Najlepszy efekt obserwowano po zastosowaniu Mo i Zn (odpowiednio o 19,0% i 18,6%) (Publikacja 2, Tab. 4).

3.5 Cechy biometryczne roślin oraz struktura plonu jęczmienia

Analizy przeprowadzone w doświadczeniu obejmowały wpływ odmiany i nawożenia na kształtowanie cech biometrycznych roślin oraz elementów struktury plonu jęczmienia jarego. W doświadczeniu wysokość roślin mieściła się w zakresie 57,1–70,9 cm. Po zastosowaniu każdego z badanych mikroelementów obserwowano istotne obniżenie wysokości roślin (Publikacja 1, Tab. 5). Dolistna aplikacja każdego z badanych mikroelementów spowodowała istotny wzrost średniej liczby produktywnych pędów na roślinę w porównaniu z kontrolą (Publikacja 1, Tab. 5). Wyniki eksperymentu wskazują na istotny wpływ genotypu na mierzone cechy biometryczne. Rośliny odmiany RGT Planet były najwyższe (średnio 68,7 cm), wykształciły najdłuższe kłosa (ponad 7 cm) i charakteryzowały się największą liczbą produktywnych pędów na roślinę (3,77) w porównaniu do pozostałych testowanych odmian. Nie stwierdzono interakcji pomiędzy nawożeniem, a odmianą w mierzonych parametrach (Publikacja 1, Tab. 5).

W doświadczeniu obsada kłosów wyniosła średnio 704 szt. m^{-2} . Najmniejszą liczbę kłosów odnotowano u odmiany Baryłka po zastosowaniu Mn (673 szt. m^{-2}), a największą u odmiany RGT Planet po nawożeniu Mo lub Zn (737 szt. m^{-2}). Dolistne zastosowanie każdego z badanych mikroelementów spowodowało wzrost mierzonego parametru w porównaniu z kontrolą, a najlepszy efekt uzyskano po zastosowaniu Mo i Zn. Stwierdzono istotne różnice między odmianami. Największą średnią obsadę kłosów (720 szt. m^{-2}) odnotowano u odmiany RGT Planet, natomiast najmniejszą u odmiany Baryłka 687 szt. m^{-2} (Publikacja 1, Tab. 6).

Masa ziarna z kłosa wahała się od 0,58 do 0,76 g. Rośliny odmiany RGT Planet charakteryzowały się o 12,1% wyższą masą ziarna z kłosa i produkcją większej liczby ziaren z kłosa w porównaniu do pozostałych odmian. Dolistne zastosowanie każdego z badanych mikroelementów (niezależnie od odmiany) istotnie zwiększyło masę ziarna z kłosa w porównaniu z kontrolą (Publikacja 1, Tab. 6). Wykazano interakcję czynników doświadczalnych w zakresie liczby ziaren z kłosa. U odmiany Baryłka liczba ziaren z kłosa była najwyższa na poletkach kontrolnych, u KWS Irina najwyższe wartości tego parametru odnotowano po zastosowaniu Mo, natomiast u RGT Planet po opryskiwaniu roślin Mn. Analiza statystyczna wykazała, że rośliny odmiany RGT Planet wykształciły więcej ziaren z kłosa w porównaniu do pozostałych badanych odmian, natomiast nie potwierdzono wpływu nawożenia na ten parametr struktury plonu (Publikacja 1, Tab. 6).

3.6 Ocena cech fizycznych ziarna

W przeprowadzonych badaniach oceniano właściwości fizyczne ziarna, które stanowią istotne wskaźniki jego przydatności do procesu słodowania. Wyniki badań masy 1000 ziaren (MTZ) wykazały interakcję nawożenie x odmiana. Najwyższe wartości (powyżej 50 g) odnotowano u odmiany RGT Planet po dolistnym zastosowaniu Mn i Zn. W przypadku odmiany KWS Irina nawożenie tymi mikroelementami spowodowało odwrotny efekt (obniżenie wartości odpowiednio o 0,4 i 0,5 g w porównaniu do kontroli). Analiza średnich dla odmian wykazała, że ziarno odmian Baryłka i RGT Planet cechowało się wyższą MTZ w porównaniu do ziarna odmiany KWS Irina. Niezależnie od odmiany, dolistne zastosowanie każdego z mikroelementów skutkowało wzrostem MTZ w porównaniu do kontroli, a najwyższe wartości obserwowano na poletkach nawożonych Mn i Mo (49,5 g) (Publikacja 1, Tab. 6).

Średnie wyrównanie ziarna wyniosło 92,1%. Przeprowadzona analiza statystyczna nie wykazała interakcji między nawożeniem, a odmianą, a także istotnego wpływu badanych nawozów. Stwierdzono jednak różnice genotypowe. Wyższym wyrównaniem ziarna charakteryzowały się odmiany Baryłka i RGT Planet w porównaniu z odmianą KWS Irina (Publikacja 1, Tab. 7).

Gęstość ziarna wyniosła średnio 64,3 kg hl⁻¹. Najwyższe wartości uzyskano dla odmian Baryłka i RGT Planet po opryskaniu roślin Cu (odpowiednio 67,8 kg hl⁻¹ i 64,3 kg hl⁻¹), natomiast u odmiany KWS Irina w wyniku zastosowania Mn (64,2 kg hl⁻¹). Parametr ten był

warunkowany przede wszystkim genotypowo. Odmiana Baryłka miała wyższą gęstość ziarna ($66,3 \text{ kg hl}^{-1}$) w porównaniu do odmian KWS Irina i RGT Planet, natomiast nawożenie (niezależnie od odmiany) nie miało istotnego wpływu na tę cechę (Publikacja 3, Tab. 1).

3.7 Charakterystyka składu chemicznego i zawartości pierwiastków w ziarnie

W pracy analizowano skład chemiczny ziarna uzyskanego z doświadczenia polowego. Średnia zawartość białka wyniosła $10,4\%$ s.m. Opryskiwanie roślin każdym z badanych nawozów mikroelementowych (niezależnie od odmiany) spowodowało wzrost zawartości tego składnika w porównaniu z kontrolą, a najwyższe wartości odnotowano w ziarnie roślin nawożonych Mo. Odmiana Baryłka cechowała się najwyższą zawartością białka spośród badanych odmian ($10,9\%$ s.m.), natomiast najniższą RGT Planet ($10,0\%$ s.m.) (Publikacja 3, Tab.3).

Zawartość tłuszczu w ziarnie wyniosła średnio $2,39\%$ s.m. U odmian Baryłka i KWS Irina największą zawartość tego składnika stwierdzono na obiektach kontrolnych, natomiast u odmiany RGT Planet najwyższy poziom wykazano po zastosowaniu Zn. Dolistne nawożenie mikroelementami (niezależnie od odmiany) spowodowało obniżenie zawartości tłuszczu w ziarnie w porównaniu z kontrolą. W doświadczeniu stwierdzono interakcję nawożenie x odmiana w odniesieniu do zawartości tego składnika (Publikacja 3, Tab. 3).

Najwięcej włókna u odmian Baryłka i KWS Irina zawierało ziarno z obiektów, na których zastosowano Cu i Zn, natomiast u odmiany RGT Planet najwyższe wartości odnotowano na kontroli. Ziarno odmiany Baryłka charakteryzowało się istotnie wyższą zawartością tego składnika w porównaniu z odmianami KWS Irina i RGT Planet (wzrost odpowiednio $0,25$ i $0,42\%$ s.m.), natomiast nie wykazano istotnego wpływu nawożenia (Publikacja 3, Tab. 3).

Ziarno jęczmienia zawierało średnio $2,74\%$ popiołu w s.m. Nie wykazano różnic w zawartości tego składnika w wyniku egzogennej aplikacji mikroelementów. Parametr ten był warunkowany przede wszystkim genotypowo. Największy udział popiołu odnotowano u odmiany Baryłka ($2,83\%$ s.m.), natomiast najniższy u odmiany RGT Planet ($2,67\%$ s.m.) (Publikacja 3, Tab. 3).

Analiza składu pierwiastkowego ziarna jęczmienia wykazała istotne różnice w reakcji poszczególnych odmian jęczmienia na dokarmianie dolistne. Wykazano interakcje czynników doświadczalnych w zakresie zawartości Ca, Fe, Mg i Mn (Publikacja 3, Tab. 2).

Wyniki średnich dla nawożenia (niezależnie od odmiany) wykazały, że na poletkach, gdzie zastosowano nawożenie Mn, ziarno kumulowało więcej wapnia w porównaniu do pozostałych wariantów doświadczenia. W badaniach wykazano, że opryskiwanie roślin nawozem na bazie Zn wpłynęło na istotne zwiększenie zawartości tego pierwiastka w jęczmieniu. Efektu wzrostu w ziarnie ilości mikroelementu zawartego w nawozie nie obserwowano w przypadku nawożenia Cu i Mn. Zawartość manganu w ziarnie była najwyższa w ziarnie pochodzącym z poletek kontrolnych (Publikacja 3, Tab. 2).

W doświadczeniu odnotowano silny wpływ genotypu na poziom gromadzenia analizowanych pierwiastków w ziarnie. Odmiana Baryłka charakteryzowała się najwyższą zawartością Cu, Fe, Mn i Zn, natomiast najwyższe wartości K i Mg stwierdzono u odmiany KWS Irina. Ziarno odmiany RGT Planet zawierało więcej Ca w porównaniu do pozostałych badanych odmian, natomiast odmiana KWS Irina cechowała się najwyższą kumulacją potasu (Publikacja 3, Tab. 2).

3.8 Analiza jakości słodu jęczmiennego

Przed słodowaniem ziarna na podstawie oznaczonej zawartości białka oraz wartości MTZ obliczono ekstraktywność teoretyczną ziarna (E), która wyniosła średnio 81,6% s.m. Analiza statystyczna wyników wykazała interakcję czynników doświadczalnych, a parametr ten był warunkowany głównie genotypowo. Najwyższe wartości odnotowano u odmiany RGT Planet w ziarnie zebranym z obiektów nawożonych Mn i Zn (82,0% s.m.), natomiast najniższą u odmiany Baryłka po zastosowaniu Cu, Mn i Mo (81,2% s.m.). Wyniki wykazały, że najlepszą ekstraktywnością teoretyczną (niezależnie od nawożenia) cechowała się odmiana RGT Planet (81,9 % s.m.), natomiast najniższą odmiana Baryłka (81,3% s.m.) (Publikacja 3, Tab. 1).

Końcowy etap analiz laboratoryjnych obejmował ocenę wpływu zastosowanych czynników doświadczalnych na wybrane parametry jakościowe słodu jęczmiennego. Stwierdzono istotną interakcję nawożenie x odmiana w kształtowaniu ekstraktywności, liczby Kolbacha oraz siły diastatycznej słodu. Najlepszą ekstraktywnością cechował się sód odmiany RGT Planet z ziarna otrzymanego z poletek nawożonych Mn i Zn, a najwyższe wartości liczby Kolbacha odnotowano w słodzie odmiany KWS Irina wyprodukowanym z ziarna roślin opryskiwanych Mn (43,5%). Odmiana ta charakteryzowała się również

najwyższą siłą diastatyczną (294 °WK) w wariacie z zastosowaniem Mo (Publikacja 3, Tab. 4).

Na podstawie uzyskanych wyników stwierdzono, że jakość słoju jęczmiennego kształtowana była przede wszystkim przez genotyp i rok uprawy jęczmienia, a nie poprzez dolistną aplikację testowanych mikroelementów. W słoju otrzymanym z ziarna nawożonego Mo i Zn odnotowano wyższą średnią ekstraktywność i siłę diastatyczną, jednak różnice te nie były statystycznie istotne. Słód wyprodukowany z ziarna odmiany Baryłka cechował się najwyższą wilgotnością (4,01%) i zawartością białka ogólnego (11,4% s.m.). Odmiana KWS Irina uzyskała najwyższe wartości liczby Kolbacha (średnio 42,9%) i siły diastatycznej (288 °WK). Najwyższą ekstraktywność (82,8% s.m.), najniższą wilgotność (3,92%), zawartość białka (10,5% s.m.) oraz liczbę Kolbacha (39,5%) odnotowano w słoju wyprodukowanym z ziarna odmiany RGT Planet (Publikacja 3, Tab. 4).

3.9 Ocena zależności pomiędzy architekturą łanu, parametrami fizjologicznymi roślin oraz elementami struktury plonu, a plonem ziarna jęczmienia

Przeprowadzone doświadczenie obejmowało analizę zależności pomiędzy wartościami wskaźników architektury łanu, parametrów fizjologicznych i cech struktury plonu ziarna, a jego wielkością przy pomocy współczynnika korelacji Pearson'a (r). Najwyższe dodatnie korelacje z plonem uzyskano dla wskaźnika transpiracji (E) ($r=0,81$), zawartości chlorofilu (CCI) ($r=0,69$), stężenia międzykomórkowego CO_2 (C_i) ($r=0,62$) oraz szybkości fotosyntezy netto (P_N) ($r=0,57$). Zależność pomiędzy MTA, a plonem ziarna była ujemna i nie osiągnęła poziomu istotności statystycznej ($r=-0,28$) (Publikacja 2, rys. 1).

Analiza cech struktury plonu wykazała silny dodatni związek pomiędzy plonem ziarna, a obsadą kłosów ($r=0,88$) (Publikacja 1, Tab. 8). Wysokie wartości współczynnika korelacji stwierdzono również pomiędzy plonem, a masą ziarna z kłosa ($r=0,66$), masą 1000 ziaren ($r=0,51$) oraz wyrównaniem ziarna ($r=0,65$) (Publikacja 1, Tab. 8). Odnotowano również istotną zależność pomiędzy wyrównaniem ziarna, a obsadą kłosów ($r=0,60$), masą ziarna z kłosa ($r=0,56$) oraz masą 1000 ziaren ($r=0,68$). Silna korelacja wystąpiła pomiędzy masą ziarna z kłosa, a indeksem żniwnym ($r=0,55$). Dodatnią zależność stwierdzono także pomiędzy liczbą, a masą ziarna z kłosa ($r = 0,51$) (Publikacja 1, Tab. 8).

4. Wnioski

1. Dolistna aplikacja miedzi, manganu, molibdenu i cynku w uprawie jęczmienia jarego browarnego wywierała korzystny wpływ na funkcjonowanie aparatu fotosyntetycznego roślin i efektywność plonowania, natomiast jej oddziaływanie na wartość technologiczną ziarna i jakość słoðu było ograniczone oraz silnie zależne od odmiany i warunków pogodowych w latach badań.
2. Nawożenie roślin mikroelementami znacznie zwiększyło plonowanie jęczmienia jarego, przy czym najsilniejsze działanie plonotwórcze odnotowano po zastosowaniu molibdenu i cynku. W wyniku nawożenia tymi mikroelementami plon ziarna w doświadczeniu wzrósł odpowiednio 0,44 i 0,41 t ha⁻¹ w porównaniu do kontroli.
3. Aplikacja mikroelementów korzystnie wpływała na wybrane cechy struktury plonu jęczmienia, zwiększając obsadę kłosów, masę ziarna z kłosa oraz masę 1000 ziaren. Nie stwierdzono natomiast istotnego wpływu zabiegu na liczbę ziaren w kłosie.
4. Testowane nawozy aplikowane dolistnie poprawiały aktywność fizjologiczną roślin, wpływając dodatnio na zawartość chlorofilu w liściach i intensywność fotosyntezy. Parametry wymiany gazowej - C_i i E były najwyższe po zastosowaniu cynku, natomiast wskaźnik P_N był najwyższy w wyniku dolistnej aplikacji miedzi.
5. Zastosowanie molibdenu i cynku spowodowało największe przyrosty wartości parametrów fluorescencji chlorofilu.
6. Nawożenie dolistne mikroelementami modyfikowało skład mineralny ziarna. Zastosowanie nawozu na bazie cynku znacząco zwiększyło zawartość tego pierwiastka w ziarnie, co wskazuje na skuteczność agronomicznej biofortyfikacji jęczmienia poprzez nawożenie dolistne. Takiej zależności nie wykazano w przypadku nawożenia miedzią i manganem.
7. Aplikacja nawozu zawierającego molibden przyczyniła się do istotnego zwiększenia zawartości białka w ziarnie jęczmienia w porównaniu do pozostałych wariantów nawożenia. Wynik ten wskazuje, że stosowanie molibdenu w uprawie jęczmienia browarnego wymaga ostrożności, zwłaszcza w warunkach sprzyjających nadmiernej akumulacji białka w ziarnie, ponieważ zbyt wysoki poziom tego składnika obniża przydatność technologiczną surowca dla przemysłu słodowniczego.

8. Wpływ mikroelementów na jakość słoju jęczmiennego ziarna był ograniczony i niejednoznaczny. Podstawowe parametry technologiczne warunkowane były przede wszystkim przez odmianę i układ warunków pogodowych w sezonie wegetacyjnym.
9. Najwyższym potencjałem plonotwórczym oraz najkorzystniejszymi cechami użytkowymi spośród badanych odmian charakteryzowała się odmiana RGT Planet. Odmiana ta wyróżniała się najwyższym plonem ziarna, korzystnymi elementami struktury plonu oraz wysoką ekstraktywnością ziarna i dobrymi parametrami jakościowymi słoju, co wskazuje na jej wysoką przydatność do produkcji browarnej.
10. Rezultaty trzyletniego doświadczenia polowego wykazały jednoznacznie, że rok wegetacji istotnie różnicował wszystkie badane cechy jęczmienia. Najkorzystniejsze warunki dla produkcji jęczmienia wystąpiły w 2021 r., w którym średni plon ziarna wyniósł 6,47 t ha⁻¹. W tym roku także cechy fizyczne, takie jak masa 1000 ziaren (50,5 g) oraz wyrównanie ziarna (96,8%) były najwyższe.
11. Dolistne stosowanie jednoskładnikowych nawozów mikroelementowych zawierających miedź, mangan, molibden i cynk w uprawie jęczmienia jarego browarnego korzystnie wpływa na funkcjonowanie aparatu fotosyntetycznego roślin oraz kształtowanie plonu ziarna, przy zachowaniu wymaganych parametrów jakościowych dla przemysłu słodowniczego. Efekty te są najbardziej widoczne na poziomie fizjologii roślin i produktywności, natomiast w mniejszym stopniu dotyczą składu chemicznego ziarna i cech słodowniczych. Wyniki badań mogą stanowić podstawę do doskonalenia zaleceń agrotechnicznych dotyczących dolistnego nawożenia mikroelementami w uprawie jęczmienia browarnego oraz przyczynić się do zwiększenia efektywności produkcji tego surowca. Równocześnie dobór właściwej odmiany stanowi kluczowy czynnik decydujący o jakości surowca technologicznego przeznaczonego dla przemysłu słodowniczego.

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Article

Influence of Foliar Application of Microelements on Yield and Yield Components of Spring Malting Barley

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Abstract: Barley is an economically important plant cultivated primarily for animal feed and in the brewing industry for the production of barley malt. Climate changes and an increase in grain demand result in a constant need to improve the volume and stability of cereal species yields and better use the potential of cultivars. In cereal production, an important aspect is the use of microelements, especially by foliar spraying. Microelements, as components or enzyme activators, play a significant role in plant growth and metabolic processes occurring in the cell. As a consequence, their availability is a factor determining plant development. The aim of this study was to determine the effect of foliar fertilization with selected microelements on the yield of two-row malting barley cultivars. In 2019–2021, a two-factor field experiment with barley was conducted in south-eastern Poland. The experimental factors were three spring barley cultivars (Baryłka, KWS Irina, and RGT Planet) of the brewing type and four single-component micronutrient fertilizers containing copper (Cu), manganese (Mn), molybdenum (Mo), and zinc (Zn). The foliar application of microelements resulted in improvements in selected elements of the yield structure and an increase in grain yield, and the effect depended on the fertilization applied. The highest grain yield was obtained from plots where fertilizer with Mo or Zn was used. Barley plants sprayed with Mo fertilizer developed the longest spikes and were characterized by the highest number of productive tillers per plant. The foliar application of Zn resulted in the formation of the highest number of spikes per unit area and grain uniformity. The RGT Planet cultivar was characterized by higher values of the measured parameters compared to Baryłka and KWS Irina.

Keywords: foliar fertilization; grain yield; *Hordeum vulgare* L.



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1. Introduction

Barley (*Hordeum vulgare* L.) belongs to the *Poaceae* family and is one of the longest-cultivated cereals in the world, important for food security. In terms of cultivated area, it is the fifth most popular crop and an important element of European agriculture. The largest barley grain producers are Russia, Australia, France, and Germany [1,2]. Barley is grown in high-production and low-input farming systems in a wide range of environments. Both spring and winter forms are available in cultivation [3–6]. Throughout the world, barley is grown primarily for animal feed and also for the production of barley malt used in brewing. About 2–5% of the grain is intended for direct human consumption. Numerous studies indicate that barley is one of the healthiest cereals in the human diet due to the high content of some important nutrients and beta-glucan [5,7,8]. There are two botanical types of barley: two-row and six-row genotypes. Traditionally, two-row malting barley has been grown in Europe [2].

Progressing climate change has a negative impact on the productivity of global agriculture; therefore, there is a need to expand the research on how to improve the yield of important crop species and better use the potential of cultivars. Nutrition and water availability are critical to the grain yield and quality of a cultivar in a variety of environments.

As the world population increases, the demand for cereal grains will increase; therefore, it is important to better understand the processes that determine the development, growth, and yield of cereal plants, including barley [2,9].

Previous research on barley fertilization has focused mainly on examining the role of macroelements in shaping the barley yield [10–13]. The most researched element in the cultivation of this species is nitrogen. Nitrogen is the most yield-producing ingredient in cereal fertilization, but it also significantly affects the suitability of grains for the brewing industry [12,14–22].

The availability of nutrients to plants depends on their contents in the soil, as well as on soil moisture, temperature, light, and climatic conditions [23]. An important aspect of grain agrotechnology is the use of microelements. It is known that all higher plants need six microelements, i.e., Mn, Fe, Cu, Zn, B, and Mo. Microelements are essential nutrients that are required in small amounts for the proper growth and development of plants [23,24]. They play a significant role in plant growth and metabolic processes in the cell. They are important components or activators of catalysts for many enzymatic processes, important both for yield formation (photosynthesis) and for grain germination in the malting process (respiration) [25–27]. Feeding plants with microelements can help maximize yields and is used as a method of plant biofortification [28]. In recent years, the occurrence of microelement deficiencies has become more and more frequent, and the rate of their reduction in the soil has been increased, among other factors, by leaching, liming acidic soils, growing plants with high nutritional requirements, and using marginal land for plant production. The problems of micronutrient deficiencies are also further enhanced by their high demand in modern crop cultivars [26,29,30].

A popular form of providing microelements to plants is foliar spraying, which became more widely used in the 1950s [31,32]. It involves applying nutrients, biostimulants, and other beneficial substances to the above-ground parts of plants, such as leaves and stems. The main advantage of foliar fertilization is the immediate absorption of the applied nutrients [28,33]. Using foliar fertilization, the losses that occur with soil fertilization due to the retardation and leaching of elements are avoided. Foliar doses can be lower than those applied to the soil, which is both economically and ecologically important. It is possible to combine foliar fertilization with plant protection treatments. This allows growers to reduce the number of treatments and financial expenditure on production. Fertilization with microelements helps alleviate abiotic stresses in plants [34]. Foliar application allows plants to be quickly supplied with nutrients in the case of both their deficiency in the soil and their difficult uptake, e.g., in the case of drought [33,35].

Foliar treatments with preparations containing microelements are used in the cultivation of many plant species, mainly in cereals [36,37], oil plants [38], and vegetables [39,40]. The response of a crop plant to the foliar supply of nutrients varies among different crop species, as well as among cultivars within the same species [41].

Due to the popularity of barley and the advantages of foliar fertilization, research on the impact of individual microelements on yield and their yield-producing characteristics should be expanded. There is a lack of information in the scientific literature regarding the effects of different microelements on malting barley. Among the microelements, copper, manganese, molybdenum, and zinc seem to be particularly important in cereal cultivation [37,42–44]. The aim of this study was to determine the effect of foliar fertilization with selected microelements on the yield of malting barley. A research hypothesis was established that states that foliar spraying with fertilizers containing microelements has a positive effect on yield components and causes an increase in grain yield.

2. Materials and Methods

2.1. Description of the Field Experiment

The field experiment was carried out in 2019–2021 in Reczpol (49°47′03″ N, 22°34′37″ E, south-eastern Poland). A two-factor experiment was set up using the split-block method with four repetitions. The experimental factors were as follows:

- I. Cultivars of spring two-rowed barley of the brewing type:
 - Baryłka (Hodowla Roślin Strzelce Sp. z o.o. Grupa IHAR, Strzelce, Poland);
 - KWS Irina (KWS Lochów Polska Sp. z o.o., Pruszy, Poland);
 - RGT Planet (R.A.G.T. Semences Polska Sp. z o.o., Toruń, Poland).
- II. Foliar fertilization with microelements:
 - Control—without fertilization;
 - Copper (Cu);
 - Manganese (Mn);
 - Molybdenum (Mo);
 - Zinc (Zn).

The dates of the treatments performed in barley cultivation are presented according to the BBCH scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) [45].

Mikrovit[®] single-component fertilizers from InterMag were used as the sources of microelements applied to the foliage. During the shooting phase, the foliar spraying of microelements in the form of aqueous solutions (BBCH 30–32) was carried out. The treatment was performed in windless weather using a pressure sprayer. Doses were determined according to the manufacturer's recommendations. The composition and doses used are presented in Table 1.

Table 1. Chemical compositions of the foliar fertilizers.

Fertilizer	Composition (g·L ^{−1})	Chemical Form	Dose (L·ha ^{−1})
MIKROVIT [®] MIEDŹ	75	Copper sulfate CuSO ₄	2
MIKROVIT [®] MANGAN	160	Manganese sulfate MnSO ₄ (65 g) and manganese nitrate Mn(NO ₃) ₂ (95 g)	2
MIKROVIT [®] MOLIBDEN	33	Ammonium molybdate (NH ₄) ₆ Mo ₇ O ₂₄	1
MIKROVIT [®] CYNK	112	Zinc sulfate ZnSO ₄	2

In the experiment, NPK fertilization was used each year at doses of 50 kg·ha^{−1} N, 60 kg·ha^{−1} P₂O₅, and 90 K₂O kg·ha^{−1}. In spring, before sowing, Polifoska[®] 6 fertilizer (6% N, 20% P₂O₅, 30% K₂O, 7% SO₃) was applied at a dose of 300 kg·ha^{−1} and Ammonium nitrate 32 at a dose of 100 kg·ha^{−1} (32% N). In order to ensure the basic requirements of plants in terms of microelements in the tillering phase (BBCH 25–27), the multi-ingredient foliar preparation Opti Zboża (Chemirrol) was used at a dose of 3 kg·ha^{−1}. The composition of the preparation in g·kg^{−1} was as follows: N—140; P₂O₅—160; K₂O—160; MgO—30; SO₃—180; Cu—3; Fe—1.5; Mn—5; Mo—0.4; Zn—1.5. In each year of the study, sowing was carried out in the first 10 days of April (6 April 2019, 2 April 2020, 8 April 2021). The certified seed material of the tested cultivars was obtained from breeding companies. The sowing rate was 165 kg·ha^{−1}. The seeds were sown at a 12 cm row spacing to a depth of 3 cm. The barley forecrop in each year of the study was winter oilseed rape. The area of a single harvest plot was 15 m². The dates and doses of the plant protection products and growth regulators used in barley cultivation are presented in Table 2. Before harvesting, the number of spikes per m² was determined. The grain was harvested at full maturity (BBCH 89). In the years of the research, the harvest date was in the last 10 days of July (22 July 2019, 30 July 2020, 25 July 2021).

2.2. Characteristics of Soil Conditions

The experiment was established on Fluvic Cambisol (CMfv). The soil pH was slightly acidic (Table 3). The soil analysis was performed in an accredited laboratory of the Chemical and Agricultural Station in Rzeszów. The soil was characterized by a low phosphorus con-

tent, a high or medium potassium content, and a high magnesium content. The manganese, zinc, and molybdenum contents were average in all years of the study. The copper content was low in 2019 and average in subsequent years. Iron was at an average level in 2019 and 2020 and at a high level in 2021 (Table 3).

Table 2. Dates and doses of preparations used in barley cultivation.

	Preparation		Dose	BBCH Phase
Fungicide	Funaben Plus 02WS	150	g per 100 kg of seed	-
	Fandango 200EC	1.0		31–34
	Kier 450S	1.0	L·ha ^{−1}	51–55
Herbicide	Mocarz 75WG	0.2	kg·ha ^{−1}	25–29
	Herbistar 200EC	0.5		25–29
Growth regulator	Moddus 250EC	0.4	L·ha ^{−1}	31–34
Insecticide	Delmetros 100SC	0.05		55 (only in 2019)

Table 3. The characteristics of the soil on which the field experiment was carried out.

Parameter	2019	Year 2020	2021
pH	6.0	5.8	5.8
in 1 mol·dm ^{−3} KCl			
Soil Organic Carbon (%)	1.3	1.1	1.1
Content of available forms mg·kg ^{−1} soil			
Phosphorus (P ₂ O ₅)	59	66	69
Potassium (K ₂ O)	220	160	188
Magnesium (Mg)	101	91	96
Copper (Cu)	2.2	2.4	3.7
Manganese (Mn)	164	396	225
Zinc (Zn)	5.0	10.3	20.0
Iron (Fe)	1080	1563	3824

2.3. Characteristics of Weather Conditions

Data on weather conditions are given according to measurements from the Meteorological Station located in Zadąbrowie (50.19'09" N, 21.48'19" E). On their basis, the average monthly temperatures and rainfall sums were calculated in the years of the field experiments. Precipitation and temperature values during the barley growing season are presented in Figure 1.

The water and thermal conditions during plant vegetation were characterized by calculating the hydrothermal coefficient of Sielianinow k . The average hydrothermal coefficients that characterize the weather patterns in particular years are presented in Table 4. The coefficient was calculated using the following formula:

$$k = \frac{P}{\Sigma t \cdot 0.1}$$

k —coefficient of Sielianinow;

P —total monthly precipitation (mm);

Σt —total of monthly daily temperatures (°C).

Hydrothermal conditions were characterized according to Skowera et al. [46] depending on the value of k :

$k \leq 0.4$ —extremely dry (ed);

$0.4 < k \leq 0.7$ —very dry (vd);

$0.7 < k \leq 1.0$ —dry (d);

$1.0 < k \leq 1.3$ —relatively dry (rd);

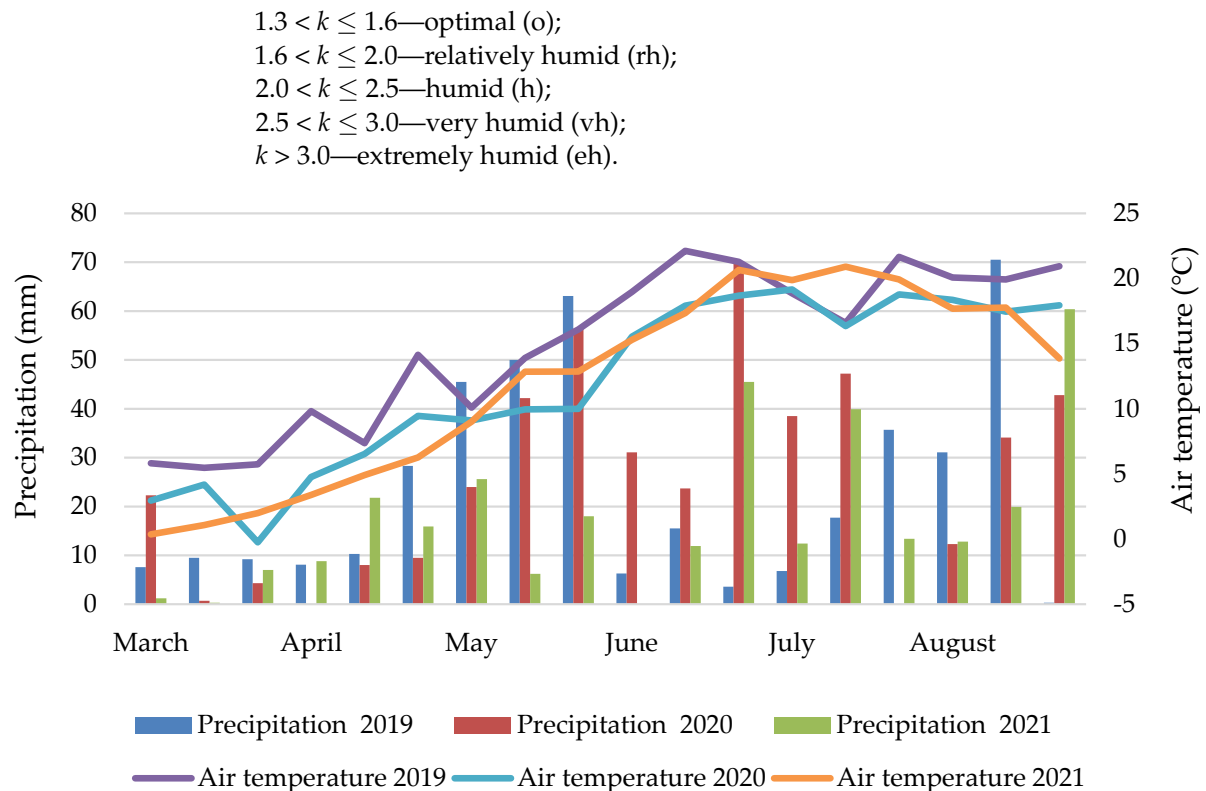


Figure 1. Weather conditions during the field experiment.

Table 4. Sielanianow coefficient (k) during barley vegetation.

Year	Month						Mean
	March	April	May	June	July	August	
2019	1.50 o	1.49 o	3.83 eh	0.41 vd	1.02 rd	1.62 rh	1.64 rh
2020	3.83 eh	0.84 d	4.09 eh	2.40 h	1.53 o	1.61 rh	2.38 h
2021	2.40 h	3.20 eh	1.39 o	1.08 rd	1.05 rd	1.83 rh	1.82 rh
Long-term * 1991–2020	3.81 eh	1.68 rh	1.83 rh	1.55 o	1.51 o	1.08 rd	1.91 rh

*—Calculated based on climatic standards for Rzeszów (50°02′01″ N, 22°00′17″ E) [47]; the Sielanianow coefficient (k) during the vegetation period in the years 2019–2021 (vd—very dry; d—dry; rd—relatively dry; o—optimal; rh—relatively humid; h—humid; eh—extremely humid).

The average values of the hydrothermal coefficient during barley vegetation in each year of the study indicate that these were years with quite high rainfall, with values close to the long-term average (Table 4). The wettest year was 2020. The most favorable weather conditions were recorded in March and April 2019, July 2020, and May 2021. The driest month was June 2019. Extremely humid conditions were recorded in May 2019, March and May 2020, and April 2021 (Table 4).

2.4. Laboratory Analyses of Yield

Before harvesting, 20 representative plants were randomly sampled from each plot to assess the biometric characteristics of plants and barley yield components, such as plant height (cm), spike length (cm), number of productive tillers per plant, grain weight per spike (g), and number of grains per spike. Thousand-grain weight (TGW) at 14% moisture content was determined using a grain counter (Sadkiewicz Instruments, Bydgoszcz, Poland) [48]. Grain yield (GY) per plot was calculated per hectare, taking into account 14% moisture content. The above-ground parts of the plants were weighed, and the ratio of grain yield to above-ground biomass yield, presented as the harvest index (HI), was calculated. Uniformity was assessed by sieving a 100 g grain sample through Vogel sieves on the SŽK

Sadkiewicz mechanical sorter for 3 min. The percentage ratio of the grain mass retained on sieves with diameters of 2.5 and 2.8 mm to the total mass of the sample was calculated [49].

2.5. Statistical Analysis

The data collected were statistically analyzed using the Statistica 13.1 (TIBCO Software Inc., Palo Alto, CA, USA) program. An analysis of variance (ANOVA) was performed for a two-factor split-block experiment. To determine and verify relationships, Tukey's post hoc test was performed at a significance level of 5%.

The relationships between the yield and its elements were determined on the basis of Pearson's simple correlation coefficients (r).

3. Results

3.1. Plant Height, Spike Length, and Productive Tillers

In the experiment, the height of the plants was in the range of 57.1–70.9 cm. Plants treated with foliar fertilizers were lower in height compared to control plots. After applying each of the microelements tested, a significant reduction in plant height was observed—on average by 6.7%—compared to the control (Table 5). The application of each of the tested microelements resulted in a significant increase in the number of productive tillers per plant compared to the control, but no significant differences in spike length were observed (Table 5).

The longest spikes, over 7 cm, were developed by plants after the application of molybdenum, and they were also characterized by a high number of productive tillers per plant. The results of the experiment indicate a significant impact of the cultivar used on the measured biometric characteristics. The plants of the RGT Planet cultivar were the tallest (average 68.7 cm), developed the longest spikes (over 7 cm), and were characterized by the highest number of productive tillers per plant (3.77) compared to the other two cultivars. There was no significant interaction between fertilization and the cultivar. Plants in the 2020 growing season were 14.0 cm and 4.2 cm higher, respectively, compared to 2019 and 2021. The longest spikes and the highest number of productive tillers per plant were recorded in 2021 (Table 5).

3.2. Yield Components of Barley

The values of the yield components differed significantly depending on the growing season. The highest number of spikes per m^2 , grain weight per spike, and TGW were obtained in 2021 (Table 6). In the experiment, the average number of spikes per m^2 was 704. The lowest was recorded in the Baryłka cultivar after Mn application (673), while the highest was in the RGT Planet cultivar after Mo or Zn fertilization (737). The foliar application of each of the applied microelements resulted in a significant increase in the measured parameter compared to the control. The best effect was obtained after the use of Mo or Zn: increases of 4.1% and 5.4%, respectively, were recorded. Significant differences between cultivars were found. RGT Planet had the highest number of spikes per m^2 (720), while Baryłka had the lowest (687) (Table 6).

Grain weight per spike ranged from 0.58 to 0.76 g. The highest values—above 0.70 g—were recorded after the use of all microelements tested in the RGT Planet cultivar, but the differences were not statistically significant. Compared to Baryłka and KWS Irina cultivars, RGT Planet was characterized by a 12% higher grain weight per spike and produced more grains per spike. The foliar application of each of the tested microelements significantly increased grain weight per spike compared to the control, regardless of the cultivar.

An interaction between fertilization and the cultivar in the number of grains per spike was demonstrated. The highest values were recorded in the RGT Planet cultivar after the application of Cu, Mn, or Zn. Regardless of the cultivars, plants produced more grains per spike after the application of Mn and Zn (18.1 and 18.0) than Cu and Mo, but these differences were not statistically significant.

Table 5. Biometric characteristics of plants depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Plant Height (cm)	Spike Length (cm)	Number of Productive Tillers per Plant
Baryłka	control	63.5 ± 3.2 ^{a-e}	6.73 ± 0.36 ^a	2.94 ± 0.31 ^a
	Cu	60.1 ± 9.7 ^{a-c}	6.66 ± 0.46 ^a	3.04 ± 0.42 ^a
	Mn	58.7 ± 10.5 ^{ab}	7.01 ± 1.31 ^a	3.57 ± 0.62 ^a
	Mo	60.5 ± 9.9 ^{a-d}	6.65 ± 0.35 ^a	3.51 ± 0.72 ^a
	Zn	59.1 ± 8.9 ^{ab}	6.59 ± 0.36 ^a	3.36 ± 0.51 ^a
KWS Irina	control	64.5 ± 7.6 ^{a-e}	6.83 ± 0.37 ^a	2.78 ± 0.26 ^a
	Cu	59.2 ± 7.1 ^{ab}	6.78 ± 0.62 ^a	3.50 ± 0.52 ^a
	Mn	57.1 ± 6.2 ^a	6.73 ± 0.42 ^a	3.70 ± 0.98 ^a
	Mo	57.2 ± 7.5 ^a	7.04 ± 0.27 ^a	3.92 ± 0.62 ^a
	Zn	57.9 ± 7.4 ^a	6.88 ± 0.39 ^a	3.76 ± 0.73 ^a
RGT Planet	control	70.9 ± 3.7 ^e	7.02 ± 0.48 ^a	3.41 ± 0.62 ^a
	Cu	68.6 ± 5.3 ^{de}	7.21 ± 0.23 ^a	3.90 ± 0.78 ^a
	Mn	67.9 ± 7.1 ^{c-e}	7.18 ± 0.35 ^a	4.03 ± 0.83 ^a
	Mo	66.3 ± 6.7 ^{b-e}	7.65 ± 2.03 ^a	3.71 ± 0.91 ^a
	Zn	69.6 ± 6.9 ^e	7.24 ± 0.50 ^a	3.81 ± 0.55 ^a
HSD _{p < 0.05} C × F		n.s. (0.9598)	n.s. (0.6871)	n.s. (0.4410)
Mean	Baryłka	60.4 ± 8.7 ^A	6.73 ± 0.67 ^A	3.28 ± 0.58 ^A
	KWS Irina	59.2 ± 7.4 ^A	6.85 ± 0.43 ^A	3.53 ± 0.76 ^B
	RGT Planet	68.7 ± 6.1 ^B	7.26 ± 0.97 ^B	3.77 ± 0.75 ^C
HSD _{p < 0.05} C		*** (0.0000)	** (0.0049)	*** (0.0004)
Mean	control	66.3 ± 6.0 ^B	6.86 ± 0.42 ^A	3.05 ± 0.50 ^A
	Cu	62.6 ± 8.5 ^A	6.89 ± 0.51 ^A	3.48 ± 0.68 ^B
	Mn	61.2 ± 9.3 ^A	6.97 ± 0.82 ^A	3.71 ± 0.82 ^B
	Mo	61.3 ± 8.8 ^A	7.11 ± 1.24 ^A	3.77 ± 0.76 ^B
	Zn	62.2 ± 9.2 ^A	6.90 ± 0.49 ^A	3.64 ± 0.62 ^B
HSD _{p < 0.05} F		*** (0.0003)	n.s. (0.5224)	*** (0.0009)
Year (Y)	2019	54.8 ± 7.8 ^A	6.87 ± 0.36 ^A	3.13 ± 0.42 ^A
	2020	68.8 ± 6.3 ^C	6.72 ± 0.70 ^A	3.56 ± 0.73 ^B
	2021	64.6 ± 4.2 ^B	7.25 ± 0.98 ^B	3.90 ± 0.76 ^C
HSD _{p < 0.05} Y		*** (0.0000)	*** (0.0002)	*** (0.0000)
Mean		62.7 ± 8.6	6.95 ± 0.76	3.53 ± 0.73

*** and ** indicate significant differences at $p < 0.001$ and $p < 0.01$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–e and A–C) are statistically different.

The average TGW of barley was 49.3 g. The highest values (above 50 g) were recorded in the RGT Planet cultivar after the foliar application of Mn and Zn. For the KWS Irina cultivar, fertilization with these microelements had the opposite effect. Decreases in TGW of 0.4 and 0.5 g, respectively, were observed. Baryłka and RGT Planet had 0.7 g higher TGW compared to KWS Irina. Regardless of the cultivar, the foliar application of each of the microelements tested resulted in an increase in TGW compared to the control, and the highest value was obtained in plants treated with Mn or Mo (49.5 g) (Table 6).

Table 6. Characteristics of the yield components depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Number of Spikes per m ²	Grain Weight per Spike (g)	Number of Grains per Spike	TGW (g)
Baryłka	Control	679 ± 58 ^a	0.68 ± 0.11 ^a	18.0 ± 1.2 ^{ab}	49.0 ± 1.8 ^{ab}
	Cu	678 ± 38 ^a	0.68 ± 0.18 ^a	16.8 ± 2.9 ^{ab}	49.6 ± 2.0 ^{bc}
	Mn	673 ± 61 ^a	0.67 ± 0.15 ^a	17.7 ± 1.5 ^{ab}	49.5 ± 1.4 ^b
	Mo	694 ± 75 ^a	0.64 ± 0.12 ^a	17.3 ± 1.4 ^{ab}	49.8 ± 2.1 ^{bc}
	Zn	713 ± 97 ^a	0.65 ± 0.11 ^a	17.3 ± 1.2 ^{ab}	49.5 ± 1.3 ^b
KWS Irina	Control	686 ± 76 ^a	0.58 ± 0.06 ^a	15.8 ± 2.3 ^a	48.6 ± 1.6 ^b
	Cu	688 ± 64 ^a	0.67 ± 0.20 ^a	17.7 ± 1.9 ^{ab}	49.8 ± 1.6 ^{bc}
	Mn	719 ± 56 ^a	0.68 ± 0.15 ^a	17.9 ± 1.2 ^{ab}	48.2 ± 2.1 ^{ab}
	Mo	711 ± 71 ^a	0.68 ± 0.17 ^a	18.1 ± 1.6 ^{ab}	49.2 ± 1.6 ^b
	Zn	719 ± 70 ^a	0.70 ± 0.17 ^a	18.0 ± 2.0 ^{ab}	48.1 ± 2.6 ^a
RGT Planet	Control	693 ± 52 ^a	0.67 ± 0.15 ^a	18.0 ± 1.8 ^{ab}	48.9 ± 2.0 ^{ab}
	Cu	722 ± 62 ^a	0.76 ± 0.11 ^a	18.6 ± 1.0 ^{bc}	48.4 ± 2.4 ^{ab}
	Mn	713 ± 51 ^a	0.76 ± 0.16 ^a	18.7 ± 1.5 ^{bc}	50.6 ± 1.9 ^c
	Mo	737 ± 81 ^a	0.73 ± 0.14 ^a	18.0 ± 1.3 ^{ab}	49.4 ± 2.9 ^b
	Zn	737 ± 89 ^a	0.76 ± 0.17 ^a	18.6 ± 1.8 ^{bc}	50.4 ± 2.1 ^c
HSD _{p < 0.05} C × F		n.s. (0.9748)	n.s. (0.8700)	* (0.0458)	** (0.0048)
Mean	Baryłka	687 ± 68 ^A	0.66 ± 0.13 ^A	17.4 ± 1.7 ^A	49.5 ± 1.7 ^B
	KWS Irina	705 ± 67 ^B	0.66 ± 0.16 ^A	17.5 ± 2.0 ^A	48.8 ± 2.0 ^A
	RGT Planet	720 ± 68 ^C	0.74 ± 0.15 ^B	18.4 ± 1.5 ^B	49.5 ± 2.4 ^B
HSD _{p < 0.05} C		*** (0.0006)	** (0.0057)	* (0.0145)	* (0.0220)
Mean	Control	686 ± 61 ^A	0.64 ± 0.12 ^A	17.3 ± 2.1 ^A	48.8 ± 1.8 ^A
	Cu	696 ± 58 ^{AB}	0.70 ± 0.17 ^B	17.7 ± 2.1 ^A	49.3 ± 2.1 ^{AB}
	Mn	701 ± 58 ^{A-C}	0.70 ± 0.16 ^B	18.1 ± 1.4 ^A	49.5 ± 2.0 ^B
	Mo	714 ± 76 ^{BC}	0.68 ± 0.14 ^{AB}	17.8 ± 1.4 ^A	49.5 ± 2.2 ^B
	Zn	723 ± 84 ^C	0.70 ± 0.16 ^B	18.0 ± 1.7 ^A	49.4 ± 2.2 ^{AB}
HSD _{p < 0.05} F		** (0.0013)	** (0.0049)	n.s. (0.3189)	* (0.0257)
Year (Y)	2019	697 ± 66 ^B	0.58 ± 0.07 ^A	18.4 ± 1.3 ^B	49.5 ± 1.7 ^B
	2020	648 ± 29 ^A	0.62 ± 0.07 ^B	16.6 ± 1.1 ^A	47.8 ± 2.0 ^A
	2021	767 ± 43 ^C	0.86 ± 0.12 ^C	18.3 ± 2.2 ^B	50.5 ± 1.5 ^C
HSD _{p < 0.05} Y		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean		704 ± 69	0.69 ± 0.15	17.8 ± 1.8	49.3 ± 2.1

***, **, and * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–c and A–C) are statistically different.

3.3. Grain Yield, Harvest Index, and Uniformity

In the conducted research, the average GY was 5.60 t·ha^{−1}. The Baryłka cultivar had the highest yield after the application of zinc (5.52 t·ha^{−1}), KWS Irina after the application of Mn (5.87 t·ha^{−1}), and RGT Planet after the application of Mo (6.05 t·ha^{−1}). Regardless of the cultivar, the foliar application of each of the microelements tested resulted in a

significant increase in GY compared to the control. The highest GY (above $5.70 \text{ t}\cdot\text{ha}^{-1}$) was obtained after the application of Mo and Zn. RGT Planet achieved higher yields of $0.42 \text{ t}\cdot\text{ha}^{-1}$ and $0.22 \text{ t}\cdot\text{ha}^{-1}$ compared to Baryłka and KWS Irina cultivars.

Analyzing the value of HI, no significant interactions were found between the cultivar and foliar fertilization with microelements. Only a slight increase in HI was observed in the RGT Planet cultivar after the application of Cu or Mn (0.54) (Table 7). The KWS Irina and RGT Planet cultivars (regardless of foliar fertilization) were characterized by a significantly higher HI compared to Baryłka. The foliar application of each of the microelements tested resulted in a significant increase in HI of 8.3% compared to the control.

Table 7. Values of grain yield, uniformity, and harvest index depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Grain Yield (GY) ($\text{t}\cdot\text{ha}^{-1}$)	Harvest Index (HI)	Uniformity (%)
Baryłka	Control	5.16 ± 0.97^a	0.49 ± 0.05^{ab}	92.7 ± 2.4^a
	Cu	5.45 ± 0.64^{ab}	0.51 ± 0.04^{ab}	91.0 ± 4.6^a
	Mn	5.31 ± 0.86^{ab}	0.53 ± 0.02^b	93.0 ± 4.4^a
	Mo	5.50 ± 0.80^{ab}	0.51 ± 0.04^{ab}	92.1 ± 3.7^a
	Zn	5.52 ± 0.95^{ab}	0.52 ± 0.04^b	93.5 ± 2.9^a
KWS Irina	Control	5.12 ± 0.90^a	0.45 ± 0.06^a	90.8 ± 5.9^a
	Cu	5.53 ± 0.66^{ab}	0.51 ± 0.03^{ab}	92.8 ± 3.6^a
	Mn	5.87 ± 0.57^d	0.50 ± 0.03^{ab}	90.4 ± 5.7^a
	Mo	5.68 ± 0.94^b	0.51 ± 0.05^{ab}	91.1 ± 5.5^a
	Zn	5.76 ± 0.90^c	0.51 ± 0.03^{ab}	90.8 ± 5.6^a
RGT Planet	Control	5.61 ± 0.62^b	0.50 ± 0.05^{ab}	93.0 ± 4.1^a
	Cu	5.81 ± 0.68^{cd}	0.54 ± 0.04^b	91.2 ± 4.5^a
	Mn	5.76 ± 0.90^c	0.54 ± 0.02^b	93.0 ± 4.7^a
	Mo	6.05 ± 0.92^e	0.53 ± 0.04^b	93.2 ± 4.1^a
	Zn	5.85 ± 1.03^{cd}	0.52 ± 0.03^b	93.2 ± 4.3^a
HSD _{p < 0.05} CxF		** (0.0096)	n.s. (0.6146)	n.s. (0.2931)
Mean	Baryłka	5.39 ± 0.83^A	0.51 ± 0.04^B	92.5 ± 3.7^B
	KWS Irina	5.59 ± 0.82^B	0.50 ± 0.05^A	91.2 ± 5.2^A
	RGT Planet	5.81 ± 0.78^C	0.53 ± 0.04^B	92.7 ± 4.3^B
HSD _{p < 0.05} C		*** (0.0000)	** (0.0020)	* (0.0291)
Mean	Control	5.30 ± 0.85^A	0.48 ± 0.05^A	92.2 ± 4.4^A
	Cu	5.59 ± 0.66^B	0.52 ± 0.04^B	91.7 ± 4.2^A
	Mn	5.65 ± 0.73^B	0.52 ± 0.03^B	92.2 ± 5.0^A
	Mo	5.74 ± 0.89^B	0.52 ± 0.04^B	92.1 ± 4.5^A
	Zn	5.71 ± 0.95^B	0.52 ± 0.03^B	92.5 ± 4.4^A
HSD _{p < 0.05} F		*** (0.0000)	*** (0.0000)	n.s. (0.7156)
Year (Y)	2019	5.39 ± 0.75^B	0.50 ± 0.04^A	91.9 ± 2.7^B
	2020	4.94 ± 0.35^A	0.50 ± 0.03^A	87.8 ± 3.3^A
	2021	6.47 ± 0.36^C	0.53 ± 0.05^B	96.8 ± 1.0^C
HSD _{p < 0.05} Y		*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean		5.60 ± 0.83	0.51 ± 0.04	92.1 ± 5.0

***, **, and * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–e and A–C) are statistically different.

In the three-year field research, the highest GY, HI, and uniformity were obtained in 2021. In this year, 1.53 t·ha⁻¹ and 1.08 t·ha⁻¹ more grain was obtained compared to 2019 and 2020, respectively, and the HI index was 0.03 higher. In 2020, the average uniformity was 87.3%, while in 2021, it was 9.5% higher (Table 7).

The analysis of the correlation coefficients showed a very high positive relationship between GY and the number of spikes per m^{-2} (0.88). A high correlation was observed between GY and grain weight per spike (0.66), TGW (0.51), and uniformity (0.65). A high correlation was also noted between uniformity and the number of spikes per m^{-2} (0.60), grain weight per spike (0.56), and TGW (0.68). HI was highly correlated with grain weight per spike (0.55). A high correlation was also observed between the number of grains per spike and grain weight per spike (0.51) (Table 8).

Table 8. Correlation coefficients (r) between the analyzed parameters.

[illegible]

4. Discussion

4.1. Influence of Weather Conditions

Climate and soil conditions are among the main factors influencing the growth and yield of crops. Morphological features and yield are also determined by the plant genotype, and the appropriate water resource is the basic factor determining the effectiveness of agricultural crops, including cereals [50–52]. Environmental conditions influence the development of features such as plant height, productive tillers, spike length, and TGW [53–55]. For all major field crops, yield components are produced during the entire crop cycle, from emergence to full maturity [56]. In our study, we noted significant differences in plant yield depending on the year of the field experiment. In three years of research, the best results for yield components were obtained in 2021. In this growing season, the plants had the longest spikes and the highest number of productive tillers. In addition, they developed the most spikes per m² and were characterized by the highest grain weight per spike, the highest TGW, and the highest GY. The weather during the barley growing season in 2021 was favorable. April, the month of seed germination and plant emergence, according to the hydrothermal coefficient, was an extremely humid month (Table 4). This resulted in the rapid and uniform emergence of plants. High humidity also had a positive effect on the proper development of plants in May and June. The lowest grain yield was obtained in 2020. In this year, April was a dry month, which negatively affected plant growth. According to Szempliński et al. [57], spring barley yields are most influenced by rainfall in the period from sowing to tillering.

Spring barley in the initial stages of development is highly sensitive to low temperatures. The optimal temperature for the crop during emergence is 5–7 °C and increases to about 8 °C in the leafing and heading phases. This temperature favors the productive tillering of barley plants [57]. In our own research, the average daily temperature in April 2021 was the most beneficial for spring barley (Figure 1).

According to the hydrothermal coefficient, May 2021 was a month with optimal temperature and humidity, while in 2019 and 2020, it was characterized by extremely high humidity (Table 4). Weather factors are particularly important during the shooting and heading periods due to the high sensitivity of barley to water deficiency in these phases, when the most important numerical and physiological components of the yield are determined [58–60]. In these development phases, the favorable conditions are a temperature from 17 to 19 °C and moderate rainfall, according to Pecio [61]. According to Szempliński et al. [57], the thermal optimum in the shooting phase of the barley stalk is 12–15 °C and is lower than that most often occurring in nature, and the optimal rainfall is 19–23 mm/10 days. Spring barley reaches these phases in the second half of May and June. In 2019, June was an extremely dry month, which limited plant heading and grain setting and, as a consequence, could have had a negative impact on the plant yield.

4.2. Influence of Experimental Factors

The main components determining the yield of cereal plants include the number of spikes per unit area, the number of grains per spike, and TGW [60,62–64]. According to Gozdowski and Mądry [65], the number of spikes per 1 m² is the yield component that most strongly influences the variability in barley yield. The highest correlation of this parameter with yield was also recorded in our study. In the conducted experiment, the best results were obtained after foliar spraying with Mo or Zn. Molybdenum occurs in the active center of plant enzymes that catalyze key stages of nitrogen, carbon, and sulfur metabolism [66]. Zinc affects the activity of hydrazase and carbonic anhydrase, the stabilization of ribosomal fractions, and cytochrome synthesis. This microelement activates plant enzymes that are involved in carbohydrate metabolism, protein synthesis, and the maintenance of the integrity of cell membranes [67]. The plants sprayed with Mo developed the longest spikes and were characterized by the highest number of productive tillers per plant. The foliar application of Zn resulted in the formation of the highest number of spikes per unit area and grain uniformity and also resulted in the highest yield increase. Similarly,

in the study by Moghdam et al. [68], who carried out the foliar application of Zn, B, and Cu to two wheat cultivars, it was shown that the type of element had a significant impact on productive tillers, the spike density, the harvest index, and grain yield but had no effect on TGW. After the use of Zn, a higher increase in value was observed compared to Cu. Differences were found between the tested barley cultivars. Similarly, in our experiment, after the application of Zn, a higher number of spikes per m² and grain yield were recorded compared to Cu, while the TGW value was similar.

Tillering, i.e., the production of lateral shoots, is an important agronomic attribute that determines the architecture of the canopy and the production of grass grains [69]. In the study by Anjum et al. [70], the use of microelements such as Cu and Zn had a positive effect on the number of productive tillers per plant and spike length. In the study by Noreen et al. [71], a significant increase in the spike length was demonstrated in barley as a result of the foliar application of Zn compared to the control. In the conducted research, the application of both Cu and Zn did not significantly increase the spike length compared to the control, but it significantly influenced the number of productive tillers per plant. Both Cu and Zn increased the measured parameter, and better results were obtained after the use of Zn. In our experiment, the foliar application of each microelement resulted in a reduction in plant height. These results are different from reports from other researchers who showed that spraying microelements can increase the barley plant height [70,72]. The conducted research showed that each of the tested cultivars responded to the applied foliar fertilization by increasing the number of grains per spike and TGW. Significant differences depending on the applied fertilization were observed in the RGT Planet cultivar (an increase in the number of grains per spike after the application of Cu, Mn, and Zn and TGW after the application of Mn and Zn).

Ishaq et al. [73] reported different responses of barley genotypes to Cu and Zn fertilization. Tobiasz-Salach et al. [74] researched the effect of foliar fertilization with Cu and Mn and showed an increase in spike density after the application of microelements, and the obtained effect depended on the cultivar. In our experiment, the RGT Planet cultivar showed the best effect among the tested cultivars. The plants of this cultivar were characterized by the highest values of biometric characteristics and yield components among the tested cultivars. As a rule, the higher the number of spikes per m², the smaller the grains. However, the RGT Planet cultivar had the highest number of spikes per m² and the highest number and weight of grains per spike. Also, the study by Ishaq et al. [73] conducted on four barley cultivars showed a significant impact of the cultivar on the spike density and TGW. Similarly, studies by other authors showed significant cultivar differences [75,76].

The amount of cereal grain yield is one of the basic factors influencing production efficiency. The application of each of the four tested microelements significantly influenced the increase in GY value. In the study by Liszewski and Błażewicz [77], the influence of Cu, Mn, and Fe on the yield of malting barley was compared. After applying foliar fertilization with microelements, a higher grain yield and improvements in yield components were observed compared to the control. Foliar Mn fertilization applied during malting barley cultivation resulted in statistically significant increases in grain yield of 0.37 t·ha⁻¹, and a similar value of 0.35 t·ha⁻¹ was obtained in our experiment. The use of micronutrients in the research by Anjum et al. [70] showed that the combined use of Cu and Zn improved the yield and the yield components of barley. In El-Magid's [78] study conducted under saline conditions, an increase in yield was observed due to the foliar application of microelements such as Mn and Zn. A significant increase in grain yield of 19.6% was recorded with Cu foliar spray in a study by Drissi et al. [79]. Barczak et al. [80] reported that Mn and Cu play a significant role in yield formation and cause the greatest increase in barley grain yield among microelements. This relationship was not demonstrated in our own research. The best yield-forming effects were achieved after spraying the plants with Mo or Zn. Similarly, in the study by Boorboori et al. [81], the analysis of the results showed that spraying with a Zn solution significantly increased grain yield. Mo fertilization through foliar sprays can effectively supplement internal molybdenum deficiencies and support the action of

molybdoenzymes [82]. For example, the experiment by Mahdavi [83] on barley showed that the foliar application of ammonium molybdate increased the production and development of stems and leaves and, consequently, the productive tillers of barley under drought stress. Five Mo enzymes in plants have been identified to catalyze key reactions in nitrogen assimilation, phytohormone synthesis, sulfite detoxification, and purine degradation [84].

The quality and usefulness of barley grain for brewing purposes are primarily influenced by the genetic characteristics of the cultivars, agronomic practices, and environmental factors. HI is the relationship between the harvested grain and the total biological yield. This parameter is widely used as an indicator of the efficiency of grain assimilation distribution and as a criterion for plant breeding to maximize yields. The value of the indicator is determined by environmental factors and varies between species. In cereals, HI values between 0.3 and 0.6 predominate [85–88]. The HI value can be modified by crop management [89]. Our experience has confirmed that agrotechnical treatments, such as foliar spraying with microelements, influence the increase in HI.

The quality requirements of malting barley are defined more precisely than those of feed and food barley [90,91]. In addition to grain yield, its quality parameters are important, such as protein content, bulk density, TGW, and uniformity [92]. The production of malt requires uniform, large grains. Uniformity is one of the basic parameters determining the usefulness of grain in the brewing industry and should be at least 90%. Plump grains give a higher efficiency of alcohol production, and only these grains are used for malting; therefore, a higher percentage of these grains is the main feature when assessing their usefulness [93–95]. Sharma and Verma [96] reported that features such as bulk density, the proportion of thick and thin grains, and husk content depend mainly on the cultivar and, to a lesser extent, on crop management. Gebeyaw [97] also observed significant differences depending on the cultivar. Similarly, in the conducted research, the value of this feature depended on the cultivar, but no significant increase in value was observed as a result of foliar fertilization with microelements. However, in the study by Dhillon et al. [98], the foliar application of Zn resulted in improved barley uniformity. A decrease in uniformity is caused by a situation in which the increase in productive tillering causes the plants to need to feed a larger number of grains. As a result, the content of plump grains is reduced [99,100]. In our study, we also noted a negative correlation between these parameters. In the experiment of Vahamidis et al. [101], with a decrease in grain yield, a decrease in the share of plump grains was observed. In this study, the potential of grains and spikes had a negative effect on both the grain yield and grain size.

5. Conclusions

This research assessed the impact of the foliar application of micronutrient fertilizers on the components and yield of spring barley brewing forms. The results confirmed the research hypothesis that foliar spraying with fertilizers containing microelements has a positive effect on the yield components and causes an increase in grain yield. Significant differences between cultivars were observed. The analysis showed that the foliar application of fertilizers containing elements such as Cu, Mn, Mo, or Zn in barley cultivation is justified in order to maximize the quantity and quality of the crop. Based on the conducted research, the use of foliar micronutrient fertilizers in malting barley cultivation can be recommended. The application of the fertilizers to the above-ground organs of plants did not interfere with the soil or the effective use of nutrients. This is an important economic and environmental aspect. It is important to expand the research on these issues, which will allow us to optimize spring barley production and increase grain production efficiency for the brewing industry.

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Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

Barbara Stadnik
(Imię i nazwisko autora)

Rzeszów, 23.03.2026r.
(miejscowość i data)

OŚWIADCZENIE

o merytorycznym wkładzie współautora

Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2024. Influence of foliar application of microelements on yield and yield components of spring malting barley. Agriculture, 14, 505*, mój wkład był wiodący i polegał na sformułowaniu celów i zadań badawczych, opracowaniu metodyki doświadczeń polowych i analiz laboratoryjnych, przeprowadzeniu doświadczeń polowych i wykonaniu analiz laboratoryjnych, zarządzaniu danymi, analizie statystycznej wyników badań, przygotowaniu oryginalnego szkicu artykułu, zredagowaniu pracy zgodnie z uwagami recenzentów oraz na wizualizacji danych w manuskrypcie.


(podpis osoby składającej oświadczenie)

Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

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Rzeszów, 23.03.2026r.
(miejscowość i data)

OŚWIADCZENIE

o merytorycznym wkładzie współautora

Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2024. Influence of foliar application of microelements on yield and yield components of spring malting barley. Agriculture, 14, 505* mój udział polegał na sformułowaniu celów i zadań badawczych, opracowaniu metodyki doświadczeń polowych oraz analiz laboratoryjnych, oraz nadzorze nad danymi, realizacją badań i publikacją artykułu naukowego.



(podpis osoby składającej oświadczenie)

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Rzeszów, 23.03.2026r.
(miejscowość i data)

OŚWIADCZENIE
o merytorycznym wkładzie współautora

Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2024. Influence of foliar application of microelements on yield and yield components of spring malting barley. Agriculture, 14, 505* mój udział polegał na analizie statystycznej wyników badań, zredagowaniu pracy zgodnie uwagami recenzentów oraz wizualizacji danych w manuskrypcie.


.....
(podpis osoby składającej oświadczenie)

Effect of foliar application of microelements on chlorophyll content, canopy architecture indicators, and physiological parameters of *Hordeum vulgare* L. plants

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ABSTRACT

Background: The availability of nutrients determines the proper development and yield of plants. Microelements play an important role primarily as cofactors of important enzymes in the metabolic and physiological processes of plants. Barley (*Hordeum vulgare* L.) is one of the most popular cereals in the world. It is used mainly as animal feed and as a raw material for the brewing industry.

Methods: A three-year field experiment was conducted to determine the effect of foliar spraying of plants with single-component fertilizers containing copper, manganese, molybdenum, and zinc on the physiological parameters of barley plants. In the experiment, three malting barley cultivars were tested: Baryłka, KWS Irina, RGT Planet. During the vegetation period of the plants after foliar fertilization, canopy architecture indices, chlorophyll content in leaves, and gas exchange and chlorophyll fluorescence parameters were measured.

Results: The foliar application of each of the microelements tested caused a significant increase in the chlorophyll content in the leaves and canopy architecture parameters (LAI and MTA) compared to the control. Furthermore, a significant increase in gas exchange parameters was also observed: intercellular CO₂ concentration (C_i), transpiration rate (E), stomatal conductance (g_s), net photosynthetic rate (P_N) and chlorophyll fluorescence parameters, maximum quantum yield of PSII photochemistry (F_v/F_m), fraction of active PSII reaction centers (RC/ABS), potential photochemical efficiency (F_v/F_0), and performance index (PI). The highest results of physiological parameters such as CCI, C_i , E , F_v/F_m , F_v/F_0 and PI were recorded after the application of zinc fertilizer. LAI and MTA were highest in plots with plants sprayed with molybdenum-based fertilizer. The foliar application of Cu caused the greatest increase in C_i and P_N . The experiment showed significant genotypic differences. The RGT Planet cultivar had a higher chlorophyll content, E and P_N parameters among the tested cultivars. The KWS Irina cultivar was characterized by the highest values of canopy architecture parameters and significantly lower values of CCI, F_v/F_m and F_v/F_0 compared to the Baryłka and RGT Planet.

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INTRODUCTION

The use of micronutrients is an important aspect in plant nutrition. All higher plants require six essential micronutrients such as manganese, iron, copper, zinc, boron, and molybdenum. These elements are essential components, required in small amounts for proper plant growth and development (Welch & Shuman, 1995; Ram et al., 2017; Kaur et al., 2023). Microelements are involved in various metabolic processes. The use of micronutrients increases antioxidant metabolism in plants and helps alleviate environmental stresses (Ahmed et al., 2020; Tavanti et al., 2021; Vatansever, Ozyigit & Filiz, 2017). However, too high doses of micronutrients can be toxic to plants (Gupta, 2010; Cruz et al., 2022). Optimizing plant nutrition with mineral compounds is a sustainable approach to improve plant health and yields. The supply of nutrients through foliar fertilization is a faster and more environmentally friendly method compared to soil fertilization. Nutrients can be applied in controlled amounts and at a specific time of plant growth (Niu et al., 2021). Furthermore, foliar fertilization is particularly effective in situations where nutrient uptake by the root system is limited, for example, in conditions of drought, excessive soil compaction, or oxygen deficiency in the rhizosphere. Currently, the foliar fertilization strategy is used in agriculture as a form of complementary plant nutrition, especially in crops with a high potential for yield (Niu et al., 2021; Oliveira et al., 2022; Januszkiewicz, Kulczycki & Samoraj, 2023). Barley (*Hordeum vulgare* L.) ranks fourth among all cereal crops and is widely grown for human consumption, as feed for livestock and for brewing and malting purposes around the world (Meints & Hayes, 2019; FAO, 2025).

Barley requires micronutrients such as copper (Cu), manganese (Mn), molybdenum (Mo), and zinc (Zn) for optimal growth and development, although the significance of specific elements may vary depending on soil properties and environmental conditions (Afzal et al., 2020; Assunção et al., 2022; Nyiraguhirwa et al., 2022). In some agroecosystems, boron (B) or iron (Fe) may also be critical. Effective micronutrient management in barley involves a combination of soil and foliar applications, balanced with macronutrient fertilization. Regular soil testing and tailored fertilization strategies are essential to address specific nutrient deficiencies and optimize barley production (Mazur et al., 2024; Grzanka et al., 2024).

Micronutrients such as copper (Cu) and manganese (Mn) play key roles in plant metabolism, participating in electron transport chains during photosynthesis and respiration and acting as cofactors for numerous antioxidant and defense enzymes (Yruela, 2009; Mir, Pichtel & Hayat, 2021). Manganese plays a crucial role in the functioning of photosystem II, where it catalyzes water splitting and supplies electrons to the photosystem. Although the importance of these elements is well documented, much less is known about their effects under foliar application conditions in the field, particularly with respect to photosynthetic parameters and gas exchange in cereals. Manganese

deficiency negatively affects plants by limiting the functioning of key enzymes responsible for the removal of reactive oxygen species, seed germination, and photosynthesis ([Waldron et al., 2009](#); [Stoltz & Wallenhammar, 2014](#); [Schmidt & Husted, 2019](#)).

Also, selective enzymes use molybdenum to carry out redox reactions. Plant molybdenum enzymes are involved in nitrogen reduction and assimilation, and sulfate metabolism. Molybdenum fertilization by foliar sprays can effectively replenish internal molybdenum deficiencies and support molybdenum enzyme activity ([Kaiser et al., 2005](#); [Rana et al., 2020](#)). Zinc is a catalytic and structural protein cofactor in hundreds of enzymes and performs key structural functions in protein domains that interact with other molecules. The largest class of Zn-binding proteins in organisms is the zinc finger domain ([Broadley et al., 2007](#); [Rudani, Vishal & Kalavati, 2018](#); [Cabot et al., 2019](#); [Stanton et al., 2022](#)). Photosynthesis is one of the most important biochemical pathways by which plants convert solar energy into chemical energy and grow. It is the most basic and complex physiological process in all green plants ([Evans, 2013](#); [Janssen et al., 2014](#); [Ashraf & Harris, 2013](#)). It is the basic physiological activity that determines the formation of plant yield, and the strength of photosynthesis is closely related to the level of yield ([Lawlor, 1995](#); [Long et al., 2006](#); [Zhang et al., 2022](#)). Analysis of chlorophyll fluorescence parameters is a useful technique that reflects the condition of plants. It plays an important role in understanding the basic mechanisms of photosynthesis and the response of plants to environmental changes. Chlorophyll content and chlorophyll fluorescence are important markers of the photosynthetic state of the plant ([Maxwell & Johnson, 2000](#); [Murchie & Lawson, 2013](#); [Goltsev et al., 2016](#); [Kalaji et al., 2016, 2018](#)). Previous studies have rarely comprehensively assessed the effects of foliar micronutrient applications on barley physiology in intensive cropping systems typical of temperate climate zones. In particular, data on the effects of these treatments on chlorophyll fluorescence and gas exchange parameters are lacking, limiting the ability to fully understand their mechanisms of action in agricultural practice. Therefore, there is growing interest in assessing the physiological responses of cereal plants to foliar micronutrients, particularly in the context of photosynthetic efficiency and adaptation strategies in temperate climates. The foliar application of micronutrients has the potential to precisely and rapidly replenish element deficiencies in critical plant development stages ([Fernández & Brown, 2013](#)). However, the application of this technique in malting barley cultivation requires a thorough assessment of plant physiological responses, such as photosynthesis rate, chlorophyll content, transpiration rate, and chlorophyll fluorescence parameters. These parameters are rarely studied in field studies. Previous publications indicate that adequate micronutrient supply can significantly influence photosynthesis rate, water management efficiency, enzyme activity, and plant resistance to abiotic stresses ([Niu et al., 2021](#); [Kaya & Ashraf, 2024](#)). However, comprehensive studies linking these aspects to foliar fertilization in malting barley cultivation are lacking. The study was carried out to investigate the effect of the foliar application of selected microelements on the chlorophyll content, canopy architecture, and physiological parameters of barley plants. The research hypothesis assumes that the application of microelements will have a positive effect on the course of the analyzed photosynthesis parameters of barley plants.

MATERIALS AND METHODS

A three-year field experiment (2019–2021) was conducted in Reczpol (49°47'03"N, 22°34'37"E), in southeastern Poland, according to the methodology described by [Stadnik, Tobiasz-Salach & Migut \(2024\)](#). The experiment was set up in a split-block design with four replications. The main factor (block) was a spring barley cultivar (Baryłka, KWS Irina, RGT Planet), while the effect of a subfactor, *i.e.*, variants of foliar fertilization with micronutrients (Cu, Mn, Mo, Zn and the non-fertilization control), was analyzed within each cultivar. The area of a single crop plot was 15 m². Agrotechnical treatments were conducted according to intensive spring barley cultivation technology, including full protection of the plant against weeds, diseases, and pests. Winter oil seed rape was the preceding crop.

In each study year, certified source seed material was seeded in the first ten days of April (6 April 2019, 2 April 2020, 8 April 2021), at a rate of 165 kg ha⁻¹, in rows 12 cm apart, at a depth of 3 cm. Harvest was carried out at full grain maturity (BBCH 89) ([Lancashire et al., 1991](#)) in the third decade of July (July 22, 2019, July 30, 2020, July 25, 2021).

Before the experiment, the physicochemical properties of the soil were analyzed in an accredited laboratory. The soil pH was determined potentiometrically ([PN-ISO 10390:1997, 1997](#)), organic carbon content using the Tiurin method ([PN-ISO-14235:2003, 2003](#)), available phosphorus and potassium using the Egner-Riehm method ([PN-R-04023:1996, 1996; PN-R-04022:1996+AZ1:2002, 1996](#)) and magnesium using the Schachtschabel method ([PN-R-04020:1994+AZ1:2004 \(1994\)](#)). The trace elements (Cu, Mn, Zn, and Fe) were determined after mineralization in HCl using flame absorption spectrometry ([PN-R-04017:1992, 1992; PN-R-04019:1993, 1993; PN-R-04016:1992, 1992; PN-R-04021:1994, 1994](#)). The soil was slightly acidic, containing approximately 1% organic carbon. Cu content was low in the first year and average in subsequent years, while other trace elements were present at average levels. Mineral (pre-sowing) fertilization included 50 kg ha⁻¹ N, 60 kg ha⁻¹ P₂O₅, and 90 kg ha⁻¹ K₂O. Polifoska® 6 was applied at a rate of 300 kg ha⁻¹ and ammonium nitrate (32% N) at 100 kg ha⁻¹. During the tillering phase (BBCH 25–27), a multi-component foliar fertilizer, Opti Zboża (3 kg ha⁻¹), containing macro- and micronutrients, was additionally applied.

The experimental factors were the following:

- I. Barley varieties: Baryłka (Hodowla Roślin Strzelce Sp. z o.o., IHAR Group), KWS Irina (KWS Lochow GmbH), RGT Planet (RAGT 2n);
- II. Foliar fertilization with micronutrients: Control (no fertilization), Cu (MIKROVIT® COPPER), Mn (MIKROVIT® MANGANESE), Mo (MIKROVIT® MOLYBDENUM), Zn (MIKROVIT® CYNK) ([Table 1](#)).

The application was performed once during the stem elongation phase (BBCH 30–32) ([Lancashire et al., 1991](#)) in windless conditions, using a pressure sprayer. Grain yield was assessed separately for each plot.

The mean temperatures and total rainfall during the growing season were determined based on data from the meteorological station in Ząbrowo (50°19'09"N, 21°48'19"E).

Table 1 Characteristics of foliar fertilizers applied in the field experiment with spring barley (2019–2021).

Trade name	Active ingredient	Chemical form	Application rate	BBCH stage	Method of application
MIKROVIT® COPPER	75 g Cu·L ⁻¹	Copper sulfate (CuSO ₄)	2 L·ha ⁻¹	BBCH 30–32	Aqueous foliar spraying
MIKROVIT® MANGANESE	160 g Mn·L ⁻¹	Manganese sulfate (65 g) + manganese nitrate (95 g)	2 L·ha ⁻¹	BBCH 30–32	Aqueous foliar spraying
MIKROVIT® MOLYBDENUM	33 g Mo·L ⁻¹	Ammonium molybdate ((NH ₄) ₆ Mo ₇ O ₂₄)	1 L·ha ⁻¹	BBCH 30–32	Aqueous foliar spraying
MIKROVIT® ZINC	112 g Zn·L ⁻¹	Zinc sulfate (ZnSO ₄)	2 L·ha ⁻¹	BBCH 30–32	Aqueous foliar spraying

The Sielanianow hydrothermal coefficient (k) was calculated to assess water-thermal conditions. Based on the k value, meteorological conditions were characterized as dry, optimal, humid, or extreme (*Stadnik, Tobiasz-Salach & Migut, 2024*).

Measurements of chlorophyll content, canopy architecture indices, and plant physiological parameters

In each year, measurements were taken twice during the plant vegetation period in BBCH 43–45 and BBCH 50–52 phases (*Lancashire et al., 1991*). The results are presented as averages of two measurement dates.

Chlorophyll content index measurement

The measurement of chlorophyll content index (CCI) content was performed using a CCM-200plus handheld chlorophyll meter (Opti-Sciences, Hudson, NH, USA). Five measurements were made on the subflag leaf of random plants in each plot (*Stadnik, Tobiasz-Salach & Mazurek, 2022*).

Measurement of canopy architecture indicators

Leaf area index (LAI) and mean tilt angle (MTA) measurements were recorded with an LAI-2000 instrument (LI-COR, Lincoln, NE, USA). The LAI measurement was made in each plot by performing one measurement on the canopy and four in the canopy (*Jańczak-Pieniążek & Kaszuba, 2024*).

Measurement of gas exchange parameters

The photosynthesis measurement system LCpro-SD (ADC Bioscientific Ltd., Herts, UK) was used to measure the photosynthesis of leaves. The following parameters were tested: intercellular CO₂ concentration (C_i), transpiration rate (E), stomatal conductance (g_s), and net photosynthetic rate (P_N). The LCpro-SD plant leaf photosynthesis chamber has a flow accuracy of ±2% of its range. During measurement, the light intensity in the measuring chamber was 350 μmol m⁻² s⁻¹, and the temperature was approximately 22 °C, with a relative humidity of 60%. Measurements were taken on three randomly selected subflag leaves in each plot (*Stadnik, Tobiasz-Salach & Mazurek, 2022*).

Chlorophyll fluorescence parameter measurement

Chlorophyll fluorescence was measured using a Pocket PEA continuous excitation fluorimeter (Pocket PEA; Hansatech Instruments, King's Lynn, Norfolk, UK) equipped with black shade clamps that were applied to the leaf blade away from the leaf vein. The leaves were adapted to the dark for a period of 30 min. The fluorescence signal was collected in red actinic light with a maximum light source wavelength of 627 nm and transmitted for 1 s at a maximum available intensity of 3,500 μmol (photon) for photosynthetically active radiation (PAR) $\text{m}^{-2} \text{s}^{-1}$. Measurements were taken on five randomly selected subflag leaves in each plot. The following parameters were measured: maximal quantum yield of PSII photochemistry (F_v/F_m), maximum quantum yield of primary photochemistry (F_v/F_0), fraction of active PSII reaction centers (RC/ABS), and photosynthetic efficiency index (PI) (Stadnik, Tobiasz-Salach & Mazurek, 2022).

Statistical analysis and correlation coefficient

Data from the three-year study were subjected to split-block analysis of variance (ANOVA) using TIBCO Statistica 13.3.0 statistical software. A synthesis of results was performed using a cross-classified hierarchical model, with the year treated as a fixed factor. The structure of the statistical model was aligned with the organization of individual field trials, which enabled the standardization of the comparison schemes and consideration of the seasonal variation in the meteorological conditions, as well as interactions among the experimental factors. Before the analysis was performed, the assumptions of ANOVA were verified. These included the normality of residuals, tested using the Shapiro–Wilk test, and the homogeneity of variance, verified using the Levene test. The mean values were calculated and the significance of the differences between groups was assessed using Tukey's honestly significant difference test at a significance level of $p \leq 0.05$. All quantitative variables analyzed, including yield and twelve physiological parameters, were complete and included 180 observations. Measurements were conducted in 45 unique combinations of the factors of year, cultivar, and micronutrient treatment, which determined the number of comparative units used in the ANOVA.

The relationships between yield and physiological parameters were evaluated using Pearson correlation coefficients. Data were aggregated at the mean level for each combination of cultivar, treatment, and year, preserving variability related to genotype and growing season while minimizing the risk of overestimating the effective sample size. As a result, the final number of observations used for the correlation analysis was 45. All quantitative variables were previously verified for compliance with a normal distribution.

RESULTS

Chlorophyll content index, LAI, and MTA

The experiment carried out demonstrated a significant effect of the application of microelements in the foliar environment on the chlorophyll content and the canopy architecture parameters in the spring barley cultivars tested (Table 2). The average CCI value in the experiment was 40.6. The highest CCI values were recorded in the Baryłka and KWS Irina cultivars after the application of Cu (by 14.4% and 6.4%, respectively, compared

Table 2 Effect of foliar fertilization and cultivar on the chlorophyll content in the leaves and the parameters of the barley canopy architecture.

Cultivar (C)	Fertilization (F)	CCI	LAI (m ² m ⁻²)	MTA (°)
Barylka	Control	36.9 ± 8.2 ^a	4.69 ± 0.38 ^a	42.5 ± 2.6 ^a
	Cu	42.2 ± 9.4 ^a	5.22 ± 0.55 ^a	46.4 ± 4.5 ^a
	Mn	40.9 ± 8.3 ^a	4.88 ± 0.34 ^a	43.8 ± 3.6 ^a
	Mo	41.2 ± 8.3 ^a	5.24 ± 0.47 ^a	45.8 ± 5.6 ^a
	Zn	40.6 ± 7.8 ^a	5.14 ± 0.40 ^a	42.6 ± 3.1 ^a
KWS Irina	Control	39.2 ± 5.5 ^a	4.91 ± 0.62 ^a	41.4 ± 2.4 ^a
	Cu	41.7 ± 5.9 ^a	5.14 ± 1.11 ^a	45.3 ± 4.5 ^a
	Mn	38.6 ± 6.2 ^a	5.08 ± 0.85 ^a	47.8 ± 5.6 ^a
	Mo	39.7 ± 7.3 ^a	5.44 ± 0.83 ^a	53.0 ± 8.3 ^b
	Zn	40.5 ± 8.7 ^a	5.38 ± 1.14 ^a	50.5 ± 7.6 ^{ab}
RGT Planet	Control	38.5 ± 7.6 ^a	5.07 ± 0.97 ^a	46.6 ± 7.9 ^a
	Cu	41.0 ± 8.7 ^a	5.04 ± 0.52 ^a	48.4 ± 6.2 ^a
	Mn	41.2 ± 9.4 ^a	5.12 ± 0.81 ^a	47.4 ± 4.5 ^a
	Mo	43.1 ± 6.7 ^b	5.12 ± 0.77 ^a	45.5 ± 3.9 ^a
	Zn	43.5 ± 11.6 ^b	4.75 ± 0.58 ^a	47.5 ± 4.6 ^a
HSD _{p ≤ 0.05} C×F		** F = 3.7, df = 8.354, p = 0.0026	n.s. F = 1.6, df = 8.354, p = 0.1310	*** F = 6.0, df = 8.354, p = 0.0000
Mean	Barylka	40.4 ± 8.6 ^{AB}	5.04 ± 0.48 ^{AB}	44.2 ± 4.3 ^A
	KWS Irina	39.9 ± 6.9 ^A	5.19 ± 0.93 ^B	47.6 ± 7.2 ^B
	RGT Planet	41.5 ± 9.1 ^B	5.02 ± 0.75 ^A	47.1 ± 5.6 ^{AB}
HSD _{p ≤ 0.05} C		* F = 3.9, df = 2.354, p = 0.0198	* F = 4.0, df = 2.354, p = 0.0186	** F = 6.4, df = 2.354, p = 0.0018
Mean	Control	38.2 ± 7.2 ^A	4.89 ± 0.71 ^A	44.5 ± 5.4 ^A
	Cu	41.6 ± 8.2 ^B	5.13 ± 0.77 ^{AB}	48.1 ± 5.2 ^B
	Mn	40.2 ± 8.1 ^B	5.03 ± 0.70 ^{AB}	47.6 ± 4.9 ^B
	Mo	41.3 ± 7.6 ^B	5.26 ± 0.71 ^C	49.5 ± 7.0 ^C
	Zn	41.5 ± 9.6 ^B	5.09 ± 0.81 ^{AB}	47.9 ± 6.33 ^{BC}
HSD _{p ≤ 0.05} F		*** F = 5.9, df = 4.354, p = 0.0000	*** F = 4.5, df = 4.354, p = 0.0004	*** F = 5.9, df = 4.354, p = 0.0000
Year (Y)	2019	41.9 ± 7.8 ^B	4.87 ± 0.41 ^B	49.3 ± 5.4 ^C
	2020	33.3 ± 5.7 ^A	4.65 ± 0.53 ^A	47.4 ± 6.6 ^B
	2021	46.6 ± 4.6 ^C	5.72 ± 0.76 ^C	42.1 ± 2.9 ^A
HSD _{p ≤ 0.05} Y		*** F = 110.1, df = 2.1170, p = 0.0000	*** F = 215.7, df = 2.1170, p = 0.0000	*** F = 187.2, df = 2.1170, p = 0.0000
Mean		40.6 ± 8.3	5.08 ± 0.75	46.3 ± 6.0

Note:

Asterisks (*, **, ***) indicate significant differences at 5% ($p \leq 0.05$), 1% ($p \leq 0.01$), and 0.1% ($p \leq 0.001$) levels, respectively; n.s. – not significant, according to Tukey's honestly significant difference test (HSD). Mean values followed by different letters (a–b and A–C) within a column differ significantly at $p \leq 0.05$. Statistical analysis based on a split-block ANOVA model.

to the control), while in the RGT Planet cultivar the height effect was achieved by the application of Zn in the foliar (an increase of 13.0% compared to the control) (Table 2). Irrespective of the foliar fertilization used, statistical analysis showed a higher CCI value in the Baryłka and RGT Planet cultivars compared to the KWS Irina cultivar. The application of each of the microelement fertilizers tested (irrespective of the cultivar) influenced the increase in CCI compared to the control. The use of Cu resulted in an increase in CCI in barley leaves on an average of 8.9%, Mn–5.2%, Mo–8.1%, and Zn–8.6% (Table 2). The study assessed the values of the canopy architecture indices based on experimental factors. The highest LAI values were obtained in the Baryłka and KWS Irina cultivars after Mo application (an increase of 11.7% and 10.8%, respectively, compared to the control), but the increase was not statistically confirmed. In the RGT Planet cultivar, in the plots where Mn and Mo foliar fertilization was applied, a significant increase in LAI was observed compared to the control, while the application of Zn caused a decrease in the measured parameter.

Regardless of the application of the microelement, the KWS Irina cultivar was shown to be characterized by a higher LAI value compared to the other cultivars tested (Baryłka and RGT Planet).

The application of each of the microelement fertilizers tested (irrespective of the cultivar) caused a significant increase in LAI compared to the control. The highest average value was recorded after Mo application (an increase of 7.6%) (Table 2).

The value of the MTA index was the highest in the KWS Irina cultivar after Mo application and was 53°. In the Baryłka and RGT Planet cultivars, the highest MTA values were recorded in Cu plant fertilization. The KWS Irina cultivar had 3.4° higher MTA, and the RGT Planet cultivar 2.9° higher MTA compared to the Baryłka (an increase of 7.7% and 6.6%, respectively). The highest average MTA value (irrespective of the cultivar) was recorded after Mo application (5° higher compared to the control –11.2%) (Table 2). Analysis of the results of subsequent years of the study showed a significant effect of the year of vegetation on the chlorophyll content in the leaves and the parameters of the architecture of the barley canopy. In 2021, CCI and LAI were the highest, while MTA was the lowest compared to previous years in which the field experiment was carried out (Table 2).

Gas exchange

In the experiment carried out, the values of the gas exchange parameters depended on the experimental factors applied (Table 3). In each of the cultivars tested, the C_i values were the highest in the plots fertilized with Cu or Zn. In the Baryłka cultivar, in these fertilization variants, a 3.5% increase in C_i was observed compared to the control, while in the KWS Irina cultivar, an increase of 3.8%. The RGT Planet cultivar, after the application of Cu and Zn, had a C_i value higher by 5.9% and 4.2%, respectively, compared to the control. Statistical analysis showed that fertilization (irrespective of cultivar) with each of the microelements tested caused a significant increase in C_i compared to the control. The highest values were observed with the application of Cu and Zn (an increase of 4.2% and 3.8%, respectively) (Table 3).

Table 3 Effect of foliar fertilization and cultivar on gas exchange parameters.

Cultivar (C)	Fertilization (F)	C_i ($\mu\text{mol (CO}_2\text{) mmol}^{-1}$)	E ($\text{mmol (H}_2\text{O) m}^{-2} \text{ s}^{-1}$)	g_s ($\text{mmol(H}_2\text{O)m}^{-2}\text{s}^{-1}$)	P_N ($\mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$)
Baryłka	Control	287 ± 9^{ab}	4.12 ± 0.45^a	0.52 ± 0.06^a	12.1 ± 1.8^a
	Cu	$297 \pm 10^{a-d}$	4.48 ± 0.48^{ab}	0.53 ± 0.08^a	$14.1 \pm 1.8^{a-e}$
	Mn	$292 \pm 15^{a-c}$	4.34 ± 0.88^{ab}	0.53 ± 0.07^a	$13.4 \pm 0.8^{a-c}$
	Mo	$293 \pm 14^{a-c}$	4.42 ± 0.52^{ab}	0.54 ± 0.04^a	$13.5 \pm 1.4^{a-d}$
	Zn	$297 \pm 8^{a-d}$	4.81 ± 0.59^{ab}	0.56 ± 0.08^{ab}	$14.2 \pm 1.6^{a-e}$
KWS Irina	Control	287 ± 12^{ab}	4.30 ± 0.72^a	0.53 ± 0.05^a	13.2 ± 1.3^{ab}
	Cu	$298 \pm 20^{b-d}$	4.80 ± 0.60^{ab}	0.55 ± 0.05^a	$14.9 \pm 1.3^{b-e}$
	Mn	$293 \pm 13^{a-d}$	4.99 ± 0.70^b	0.58 ± 0.04^b	$15.1 \pm 0.8^{b-e}$
	Mo	$290 \pm 29^{a-c}$	4.94 ± 0.91^{ab}	0.57 ± 0.04^b	$14.9 \pm 1.3^{b-e}$
	Zn	$298 \pm 11^{b-d}$	4.93 ± 0.77^{ab}	0.56 ± 0.06^{ab}	$14.4 \pm 1.6^{b-e}$
RGT Planet	Control	287 ± 15^a	4.70 ± 0.54^{ab}	0.55 ± 0.06^a	$14.6 \pm 2.3^{b-e}$
	Cu	304 ± 16^d	4.97 ± 0.56^b	0.54 ± 0.07^a	16.1 ± 2.3^f
	Mn	$296 \pm 13^{a-d}$	5.01 ± 0.38^b	0.53 ± 0.06^a	$15.4 \pm 1.8^{c-e}$
	Mo	$294 \pm 11^{a-d}$	5.04 ± 0.35^b	0.54 ± 0.05^a	$15.5 \pm 1.3^{c-e}$
	Zn	299 ± 10^{cd}	5.08 ± 0.52^b	0.54 ± 0.05^a	$15.6 \pm 1.1^{d-e}$
$\text{HSD}_{p \leq 0.05} \text{ C} \times \text{F}$		n.s. $F = 0.9$, $\text{df} = 8.61$, $p = 0.4859$	** $F = 1.6$, $\text{df} = 8.104$, $p = 0.0024$	*** $F = 1.1$, $\text{df} = 8.104$, $p = 0.0000$	** $F = 0.5$, $\text{df} = 8.104$, $p = 0.0020$
Mean	Baryłka	293 ± 12^A	4.43 ± 0.64^A	0.53 ± 0.07^A	13.5 ± 1.7^A
	KWS Irina	293 ± 19^A	4.79 ± 0.79^B	0.56 ± 0.05^B	14.5 ± 1.4^B
	RGT Planet	296 ± 14^A	4.96 ± 0.49^C	0.54 ± 0.06^A	15.4 ± 1.9^C
$\text{HSD}_{p \leq 0.05} \text{ C}$		n.s. $F = 3.8$, $\text{df} = 2.61$, $p = 0.0857$	*** $F = 3.0$, $\text{df} = 2.104$, $p = 0.0001$	*** $F = 4.3$, $\text{df} = 2.104$, $p = 0.0004$	*** $F = 4.7$, $\text{df} = 2.104$, $p = 0.0000$
Mean	Control	287 ± 13^A	4.37 ± 0.62^A	0.53 ± 0.06^A	13.3 ± 2.1^A
	Cu	299 ± 16^C	4.75 ± 0.59^B	0.54 ± 0.07^{AB}	15.0 ± 2.0^C
	Mn	294 ± 14^B	4.78 ± 0.75^B	0.55 ± 0.07^{AB}	14.6 ± 1.5^B
	Mo	292 ± 20^B	4.80 ± 0.69^B	0.55 ± 0.05^B	14.6 ± 1.6^B
	Zn	298 ± 10^C	4.94 ± 0.64^C	0.55 ± 0.06^B	14.7 ± 1.6^B
$\text{HSD}_{p \leq 0.05} \text{ F}$		*** $F = 20.5$, $\text{df} = 4.61$, $p = 0.0000$	*** $F = 13.7$, $\text{df} = 4.104$, $p = 0.0000$	** $F = 10.4$, $\text{df} = 4.104$, $p = 0.0097$	*** $F = 3.1$, $\text{df} = 4.104$, $p = 0.0000$
Year (Y)	2019	294 ± 11^B	4.56 ± 0.65^B	0.53 ± 0.06^A	14.9 ± 1.1^B
	2020	283 ± 15^A	4.32 ± 0.46^A	0.53 ± 0.05^A	12.9 ± 1.5^A
	2021	306 ± 11^C	5.31 ± 0.50^C	0.58 ± 0.06^B	15.7 ± 1.7^C
$\text{HSD}_{p \leq 0.05} \text{ Y}$		*** $F = 305.7$, $\text{df} = 2.1077$, $p = 0.0000$	*** $F = 182.3$, $\text{df} = 2.1077$, $p = 0.0000$	*** $F = 279.6$, $\text{df} = 2.1077$, $p = 0.0000$	*** $F = 33.8$, $\text{df} = 2.1077$, $p = 0.0000$
Mean		294 ± 15	4.73 ± 0.69	0.54 ± 0.06	14.5 ± 1.9

Note:

Asterisks (*, **, ***) indicate significant differences at 5% ($p \leq 0.05$), 1% ($p \leq 0.01$), and 0.1% ($p \leq 0.001$) levels, respectively; n.s. – not significant, according to Tukey's honestly significant difference test (HSD). Mean values followed by different letters (a–b and A–C) within a column differ significantly at $p \leq 0.05$. Statistical analysis based on a split-block ANOVA model.

The value of the transpiration rate E was the highest in the RGT Planet cultivar after Zn application (an increase of 8.1% compared to the control). A significantly higher value compared to the control (16.0%) was also observed for the KWS Irina cultivar when fertilized with Mn (Table 3). The KWS Irina and RGT Planet cultivars were characterized by a higher average E value compared to the Baryłka cultivar (0 8.1% and 12.0%,

respectively). The application of each of the microelements tested on the leaf (irrespective of the cultivar) caused a significant increase in E compared to the control—the highest increase (by 13.0%) was observed with the application of Zn. The average value of g_s in the experiment was 0.54 (Table 3). The highest g_s values were observed for the KWS Irina cultivar after Mn and Mo application (an increase of 9.4% and 7.5%, respectively, compared to the control). In Baryłka and RGT Planet, no significant differences were shown after the application of microelements compared to the control. The application of microelements to the foliage (irrespective of the cultivars tested) caused a significant increase in g_s compared to the control after the application of Mo and Zn (an increase in both variants of 3.4%).

The experimental factors applied significantly modified the value of the P_N parameter (Table 3). The highest value of the measured parameter was recorded in the RGT Planet cultivar after the application of Cu (an increase of 10.3% compared to the control). The analysis of this gas exchange parameter (irrespective of foliar fertilization) showed that its value in the RGT Planet cultivar was higher compared to Baryłka and KWS Irina by 14.1% and 6.2%, respectively (Table 3).

Foliar fertilization with each of the microelements tested (irrespective of the cultivar) had a positive effect on the value of P_N and caused a significant increase compared to the control. The highest increase—12.8%—was recorded after spraying the plants with Cu.

In the studies carried out, significant differences were observed depending on the year of the field experiment. The highest values of the gas exchange parameters were observed in 2021, and the lowest in 2019 (Table 3). In June 2019, the lowest level of precipitation and the highest average daily temperature were recorded compared to 2020 and 2021 (Stadnik, Tobiasz-Salach & Migut, 2024). This resulted in drought, which could have a negative impact on the course of physiological processes in barley plants.

Chlorophyll fluorescence

The average value of the F_v/F_m was 0.82. The highest values were recorded in the KWS Irina cultivar after spraying the plants with Zn (0.84). Compared to the control, the increase was 5.0%. The Baryłka cultivar (irrespective of fertilization) obtained a significantly higher value of F_v/F_m by 1.2% compared to KWS Irina. The application of the foliage of each of the microelements tested (irrespective of the cultivar) caused an increase in F_v/F_m compared to the control of 3.8% (Table 4).

The RC/ABS parameter was also dependent on the experimental factors used. The highest values were recorded in the Baryłka cultivar with Mn and Mo fertilization (an increase of 17.1% and 16.7%, respectively, compared to the control). In the RGT Planet cultivar, an increase in this chlorophyll fluorescence parameter was observed after Mo application (an increase of 7.8% compared to the control), which was confirmed by variance analysis.

Regardless of fertilization, Baryłka was shown to have a higher average value of RC/ABS by 10.8% compared to KWS Irina and by 9.2% compared to RGT Planet. The foliar application of microelements in barley plants caused a significant increase in RC/ABS, and

Table 4 Effect of foliar fertilization and cultivar on chlorophyll fluorescence parameters.

Cultivar (C)	Fertilization (F)	F_v/F_m	RC/ABS	F_v/F_0	PI
Barylka	Control	0.80 ± 0.02^{ab}	2.87 ± 0.48^a	4.66 ± 0.44^a	8.44 ± 1.31^a
	Cu	0.83 ± 0.04^{ab}	3.11 ± 0.57^{ab}	4.68 ± 0.37^a	10.38 ± 1.47^{ab}
	Mn	0.83 ± 0.03^{ab}	3.36 ± 0.54^b	4.68 ± 0.41^a	10.77 ± 1.29^b
	Mo	0.84 ± 0.04^{ab}	3.35 ± 0.56^b	4.57 ± 0.55^a	10.78 ± 1.26^b
	Zn	0.84 ± 0.04^b	3.26 ± 0.44^{ab}	4.74 ± 0.34^a	10.67 ± 1.21^{ab}
KWS Irina	Control	0.79 ± 0.04^a	2.50 ± 0.43^a	4.09 ± 0.85^a	8.28 ± 0.86^a
	Cu	0.82 ± 0.02^{ab}	2.92 ± 0.57^a	4.69 ± 0.43^a	9.72 ± 1.08^a
	Mn	0.82 ± 0.02^{ab}	2.92 ± 0.45^a	4.54 ± 0.48^a	9.57 ± 1.14^a
	Mo	0.82 ± 0.03^{ab}	2.97 ± 0.36^a	4.66 ± 0.49^a	9.63 ± 1.25^a
	Zn	0.83 ± 0.03^{ab}	3.09 ± 0.55^a	4.70 ± 0.40^a	10.26 ± 1.64^a
RGT planet	Control	0.82 ± 0.02^{ab}	2.95 ± 0.42^a	4.62 ± 0.44^a	9.14 ± 1.07^a
	Cu	0.83 ± 0.02^{ab}	2.71 ± 0.41^a	4.67 ± 0.46^a	9.35 ± 1.20^a
	Mn	0.82 ± 0.02^{ab}	2.85 ± 0.40^a	4.69 ± 0.44^a	9.46 ± 1.12^a
	Mo	0.83 ± 0.03^{ab}	3.18 ± 0.71^{ab}	4.85 ± 0.46^b	10.35 ± 2.06^{ab}
	Zn	0.83 ± 0.02^{ab}	2.92 ± 0.40^a	4.75 ± 0.37^{ab}	9.74 ± 1.51^a
HSD _{p ≤ 0.05} C × F		*** F = 2.2, df = 8.558, p = 0.0000	*** F = 2.6, df = 8.558, p = 0.0000	*** F = 2.1, df = 8.558, p = 0.0000	*** F = 1.8, df = 8.558, p = 0.0000
Mean	Barylka	0.83 ± 0.04^B	3.19 ± 0.55^B	4.67 ± 0.43^B	10.21 ± 1.58^B
	KWS Irina	0.82 ± 0.03^A	2.88 ± 0.52^A	4.54 ± 0.60^A	9.49 ± 1.38^A
	RGT planet	0.82 ± 0.02^{AB}	2.92 ± 0.51^A	4.72 ± 0.44^B	9.61 ± 1.49^A
HSD _{p ≤ 0.05} C		** F = 3.0, df = 2.558, p = 0.0083	*** F = 4.1, df = 2.558, p = 0.0001	*** F = 6.0, df = 2.558, p = 0.0048	*** F = 14.2, df = 2.558, p = 0.0001
Mean	Control	0.80 ± 0.03^A	2.77 ± 0.49^A	4.46 ± 0.66^A	8.62 ± 1.15^A
	Cu	0.83 ± 0.03^B	2.91 ± 0.54^B	4.68 ± 0.42^B	9.82 ± 1.33^B
	Mn	0.83 ± 0.03^B	3.04 ± 0.52^C	4.64 ± 0.45^B	9.93 ± 1.32^B
	Mo	0.83 ± 0.03^{BC}	3.17 ± 0.58^D	4.69 ± 0.51^B	10.26 ± 1.63^C
	Zn	0.83 ± 0.03^C	3.09 ± 0.49^{CD}	4.73 ± 0.37^B	10.22 ± 1.51^C
HSD _{p ≤ 0.05} F		*** F = 8.4, df = 4.558, p = 0.0000	*** F = 11.3, df = 4.558, p = 0.0000	*** F = 4.6, df = 4.558, p = 0.0000	*** F = 22.7, df = 4.558, p = 0.0000
Year (Y)	2019	0.84 ± 0.04^C	2.90 ± 0.51^B	4.90 ± 0.38^C	9.46 ± 1.08^B
	2020	0.81 ± 0.02^A	2.83 ± 0.44^A	4.40 ± 0.42^A	8.99 ± 1.24^A
	2021	0.82 ± 0.02^B	3.26 ± 0.57^C	4.63 ± 0.55^B	10.86 ± 1.53^C
HSD _{p ≤ 0.05} Y		*** F = 133.1, df = 2.1117, p = 0.0000	*** F = 84.5, df = 2.1117, p = 0.0000	*** F = 141.7, df = 2.1117, p = 0.0000	*** F = 113.9, df = 2.1117, p = 0.0000
Mean		0.82 ± 0.03	3.00 ± 0.54	4.64 ± 0.50	9.77 ± 1.52

Note:

Asterisks (*, **, ***) indicate significant differences at 5% ($p \leq 0.05$), 1% ($p \leq 0.01$), and 0.1% ($p \leq 0.001$) levels, respectively; n.s. – not significant, according to Tukey's honestly significant difference test (HSD). Mean values followed by different letters (a–b and A–C) within a column differ significantly at $p \leq 0.05$. Statistical analysis based on a split-block ANOVA model.

the highest average values were observed after spraying the plants with Mo and Zn (an increase of 14.4% and 11.6%, respectively, compared to the control) (Table 4).

The value of F_v/F_0 was the highest in the RGT Planet cultivar after Mo and Zn application, while the lowest in KWS Irina in the control variant. The value of the parameter varied among the examined cultivars. The Baryłka and RGT Planet cultivars had significantly higher F_v/F_0 values compared to the KWS Irina cultivar (by 2.9% and 4.0%, respectively). The foliar application of each of the microelement fertilizers tested caused a significant increase in F_v/F_0 compared to the control. The best effect was observed after the application of Zn (an increase of 6.0%).

The highest PI values were observed in the Baryłka cultivar after the application of Mn and Mo. The increase compared to the control was 27.6% and 27.7%, respectively. The Baryłka cultivar (irrespective of foliar fertilization) was characterized by a significantly higher PI compared to the KWS Irina and RGT Planet cultivars (by 7.6% and 6.2%, respectively). The application of each of the microelement fertilizers caused a significant increase in PI compared to the control (irrespective of the cultivar). The greatest effect was observed after the application of Mo and Zn (with 16.0% and 15.7%, respectively) (Table 4).

The values of the chlorophyll fluorescence parameters varied depending on the year of the field experiment. The highest values of F_v/F_m and F_v/F_0 were recorded in 2019, while RC/ABS and PI in 2021. In 2019, all measured chlorophyll fluorescence parameters were the lowest (Table 4). This year, at the time of the measurements, relatively high temperatures and low rainfall were recorded, which could have influenced the course of physiological processes in plants (Stadnik, Tobiasz-Salach & Migut, 2024).

Pearson's correlation coefficient

The barley grain yield of the field experiment was presented in the publication by Stadnik, Tobiasz-Salach & Migut (2024). All correlation coefficients refer to aggregated data for application, operation, and year, with a sample size of $n = 45$. The table also presents the results of the correlations extracted from independent users and Fisher's tests, which are distributed between the data sets ($p \leq 0.05$ between all users). The strongest positive correlations with yield were recorded for transpiration rate ($r = 0.81$), chlorophyll content index (0.69), intercellular CO_2 concentration (0.62), and net photosynthesis rate (0.57). This relationship between MTA and yield ($r = -0.28$) was not statistically significant (Fig. 1).

DISCUSSION

Plant growth and development depend on environmental conditions, including the availability of macro and microelements. Differences in nutrient content significantly affect the photochemical process of photosynthesis, therefore, they play a key role in biomass production (Kalaji et al., 2018; Cakmak & Engels, 2024). Micronutrients, although needed by plants in small amounts, play an important role in metabolic processes related to photosynthesis, chlorophyll formation, cell wall development, and respiration

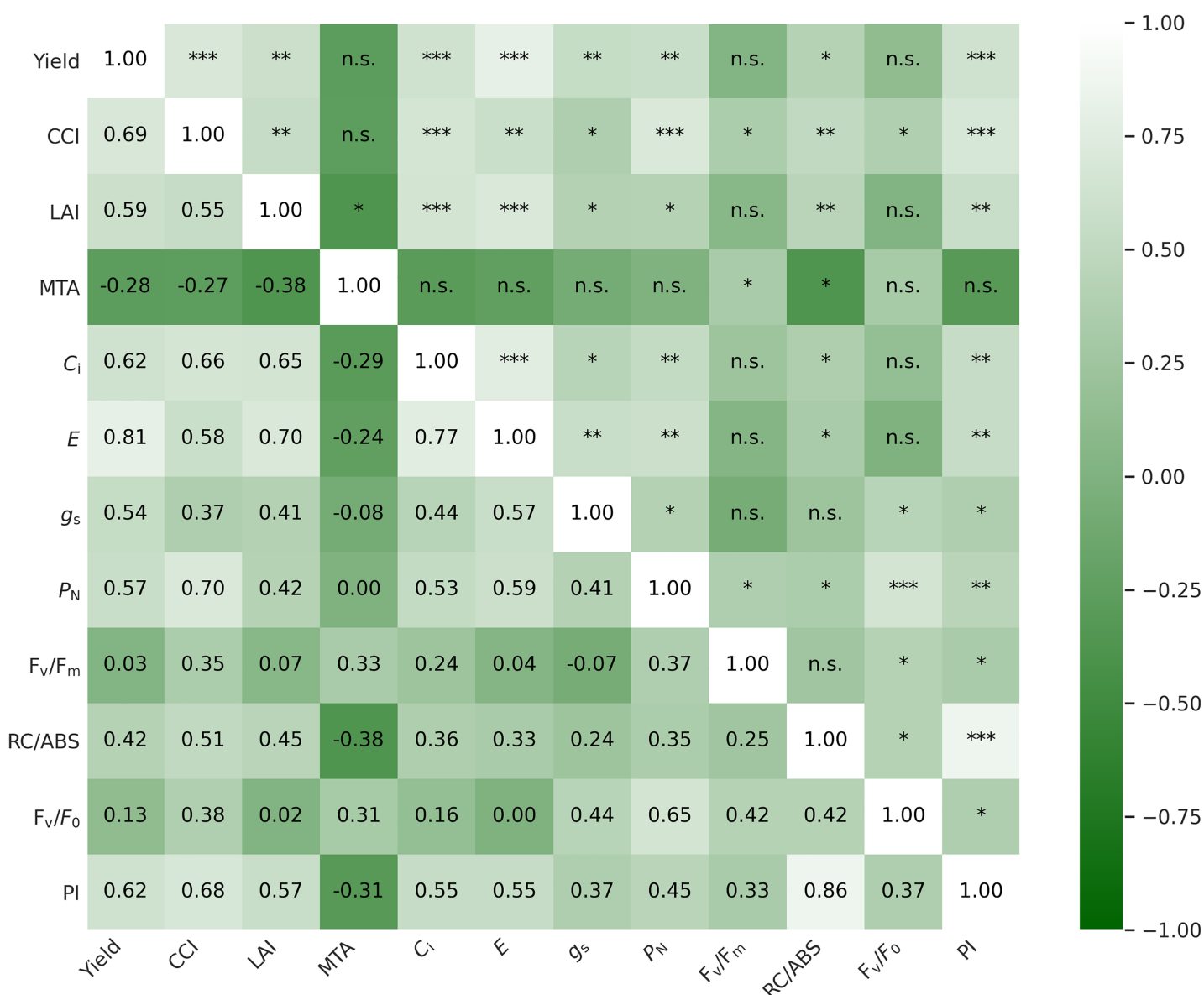


Figure 1 Correlation coefficients (r) between grain yield and canopy architecture indices and plant physiological parameters. The table presents Pearson correlation coefficients (r) between yield and physiological parameters; Asterisks (*, **, and ***) indicate significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively; n.s. denotes non-significant correlations ($p > 0.05$); all correlations were calculated based on $n = 45$, using mean values for each combination of year, cultivar, and micronutrient treatment; prior to analysis, variables were tested for compliance with the normal distribution. [Full-size !\[\]\(8cb3c1b7258e251dd106b0c7de4436bc_img.jpg\) DOI: 10.7717/peerj.19966/fig-1](https://doi.org/10.7717/peerj.19966/fig-1)

(Ram et al., 2017; Therby-Vale et al., 2022). Scientific studies on the effect of the foliar application of important micronutrients for plants focus primarily on their effect on mitigating environmental stresses and improving yield and its components (El-Magid, 2001; Ahanger et al., 2016; Kaur et al., 2023; Singhal et al., 2023). The aim of our study was to determine the effect of foliar fertilization with selected microelements on chlorophyll content, canopy architecture parameters, and the course of photosynthesis in spring barley under field conditions.

Leaf chlorophyll is a key indicator of leaf greenness, often used to determine nutrient deficiencies in leaves (Schlichting et al., 2015; Shah, Houborg & McCabe, 2017; Liu et al., 2019). In the field experiment conducted, the application of each of the microelements tested increased CCI in barley leaves, and the highest mean values were recorded in the plots fertilized with Cu and Zn (Table 1). Copper is an essential transition metal with redox activity, and it is involved in many physiological processes in plants. Cu deficiency affects young leaves, causing chlorosis and reduced photosynthetic activity. The positive effect of the foliar application of copper can be attributed to an important metabolic function, since this metal participates in photosynthesis and chloroplast development (Amberger, 1974; Yruela, 2005; El-Metwally et al., 2010; Yruela, 2013; Harangozo et al., 2017). Also, the study by Tobiasz-Salach & Augustyńska-Prejsnar (2020) conducted on barley, copper fertilization had a positive effect on chlorophyll content and, similarly to our study, the effect of copper was more visible than that of manganese. Improvements in physiological functions and an increase in chlorophyll content compared to control were also observed in Syuhada et al. (2014) in maize leaves sprayed with Cu. Noreen et al. (2021) indicate that the foliar application of Zn in barley cultivation increases the content of photosynthetic pigments, which was also confirmed by the results of our own studies.

The LAI index describes the size of the leaf area per unit of horizontal ground surface. This index is an important biophysical variable to understand the efficiency of the use of radiation by field crops and their potential yield. The LAI value depends on many factors, including genetic traits of plants, their habitat, and agrotechnical factors such as sowing density and the phenological stage of the plant (Chen & Black, 1992; Zou et al., 2018). LAI and MTA indices are primarily used to assess the growth rate and biomass accumulation (Feledyn-Szewczyk, 2009; Lepiarczyk et al., 2005; Dereń et al., 2018; Fang et al., 2019). In our study, the foliar application of each of the microelement fertilizers tested had a positive effect on the LAI and MTA values of barley plants, and the best results were obtained on plots fertilized with Mo (Table 2). Significant genotypic differences were also demonstrated. In the study by Tobiasz-Salach, Jańczak-Pieniążek & Bobrecka-Jamro (2018) in which the foliar application of microelements was used in four barley cultivars, the LAI index also depended on the cultivar and the application of foliar microelement fertilization. There are no reports in the scientific literature on the effect of single-component microelement fertilizers on the MTA value.

Carbon assimilation in photosynthesis and water loss through transpiration are key physiological processes that affect biomass production (Lambers, Oliveira & Pons, 2019; Hatfield & Dold, 2019). The analysis of the effect of fertilization with the microelements tested shows that each of the fertilizers used improved gas exchange parameters in *H. vulgare* L. The highest increases in values were observed after the application of Cu and Zn. In the conducted experiment, C_i and E were significantly higher after the application of Zn. Zinc plays an important role in the activation of enzymes, N metabolism, and is involved in photosynthesis and DNA reproduction during cell division (Ram et al., 2017). In the studies by Liu et al. (2016), the use of Zn at an optimal dose (30 kg ZnSO₄ 7H₂O) in maize caused an increase in P_N , had a positive effect on the chlorophyll content in the leaves, and increased grain yield. Studies conducted on various species of crop plants

report that zinc deficiencies in plants cause disorders in the functioning of the photosynthetic apparatus ([Mattiello et al., 2015](#); [Rudani, Vishal & Kalavati, 2018](#); [Li et al., 2020](#)). The particularly visible improvement in gas exchange parameters in the experiment carried out after the use of zinc may indicate that the plants were provided with an adequate supply of this nutrient and, consequently, increased photosynthetic efficiency.

In the research conducted, among the microelements tested, the highest C_i and P_N values were recorded after the application of Cu ([Table 2](#)). The increase in photosynthetic parameters may indicate the optimal dose of Cu for barley plants. In the study by [Moraes et al. \(2025\)](#) on coconut seedlings, in which Cu was applied foliarly at low concentrations, an improvement was observed in the rate of photosynthesis, transpiration, and stomatal conductance. In addition, Cu at lower concentrations increased the efficiency of photosystem II. Copper is potentially harmful when present at concentrations that exceed optimal ones. Excess accumulation can destabilize membrane integrity, reduce photosynthesis, and change enzyme activity, consequently inhibiting plant development ([Moustakas et al., 1997](#); [Shabbir et al., 2020](#); [Mir, Pichtel & Hayat, 2021](#)). The study also noted a beneficial effect of foliar Mo spraying on plant gas exchange. [Oliveira et al. \(2022\)](#) showed that the application of Mo to soybeans and corn increased net photosynthesis. The study authors indicated that Mo-based foliar fertilization could effectively improve nitrogen metabolism and plant response to carbon fixation, resulting in improved yields.

The analysis of the values of the chlorophyll fluorescence parameters indicates a particularly significant effect of molybdenum and zinc on the shape of the values of individual indicators. After the application of fertilizers based on these microelements, the highest values of F_v/F_m , RC/ABS , F_v/F_0 and PI were recorded ([Table 3](#)). Decreases in chlorophyll fluorescence parameters are recorded in plants both under conditions of Zn deficiency ([Wang & Jin, 2005](#)) and at too high doses ([Andrejić et al., 2018](#)). Studies have indicated a positive effect of foliar application of Zn on the accumulation of photosynthetic pigments and chlorophyll fluorescence, especially in stress conditions ([Narimani & Sharifi, 2020](#); [Klofac, Antosovsky & Skarpa, 2023](#)). An increase in F_v/F_0 by 6.7% compared to the control was recorded in studies with sugar beet after foliar fertilization with Zn, and the total chlorophyll content increased by more than 25% ([Zhao et al., 2024](#)). There are no reports in the literature on the effect of the foliar application of Mo on the chlorophyll fluorescence parameters. [Han et al. \(2020\)](#) investigated the effect of soil Mo application under stress from cadmium (Cd) on rapeseed. In this study, the application of Mo alleviated the negative effect of Cd on plants, among others, by improving F_v/F_0 and F_v/F_m .

The response of crop plants to microelement foliar fertilization varies by species and genotype. Barley cultivars, similar to studies by other authors, showed differences in the values of measured physiological parameters ([Tobiasz-Salach & Augustyńska-Prejsnar, 2020](#); [Moshfeghi et al., 2019](#)). In a laboratory study conducted by [Jarecki, Lachowski & Migut \(2024\)](#) on soybean where various microelements were applied in foliar form, differences in the response of the cultivars were also shown. In our own studies, a significant increase in CCI , E , and P_N was noted in the RGT Planet cultivar compared to the Baryłka and KWS Irina cultivars ([Tables 1, 2](#)). In the study by [Jalakas et al. \(2018\)](#) on malted barley, the genotype had a significant effect on the P_N and g_s values. The

chlorophyll fluorescence parameters analyzed from the KWS Irina cultivar showed statistically lower values of the F_v/F_m and F_v/F_0 indexes compared to the RGT Planet and Baryłka cultivars (Table 3).

Pearson's correlation analysis showed the influence of the parameters analyzed on grain yield. The strongest correlations were shown between yield and CCI, E , P_N , and PI. A better understanding of the physiological conditions of crop yield formation and the identification of traits related to grain yield help improve the efficiency of crop breeding and cultivation. However, in long-term experiments, physiological parameters are relatively rarely measured in relation to yield (Araus *et al.*, 2008; Jalakas *et al.*, 2018). Jalakas *et al.* (2018) reported that the correlation between leaf gas exchange traits and grain yield depends on the climatic conditions during the growing season. In studies on wheat and barley, stomatal conductance and CO_2 assimilation rate were reported to correlate with grain yield (Fischer *et al.*, 1998; Gonzalez, Bermejo & Gimeno, 2010). In the study by Wasaya *et al.* (2021), strong positive correlations between P_N , g_s , and E were observed with grain yield in wheat subjected to drought stress and irrigation. Zhu, Long & Ort (2010) reported that increased photosynthesis in the crop under standard field cultivation conditions resulted in higher yields. Parry *et al.* (2011) reported an improvement in wheat yield due to increased photosynthesis. Our results also confirm the relationship between the course of plant photosynthesis and the efficiency of barley cultivation.

CONCLUSIONS

The studies carried out demonstrated a positive effect of foliar application of fertilizers containing Cu, Mn, Mo, and Zn on the relative content of chlorophyll in leaves, the parameters of the canopy architecture, and the selected parameters of chlorophyll fluorescence and gas exchange in barley plants. The cultivars studied were characterized by a varied response to foliar application of microelements. The values of selected parameters were strongly correlated with grain yield. The analysis carried out indicates that the measurement of physiological parameters during plant vegetation may be useful in forecasting crop productivity. The conducted experiment provides information on the importance of foliar application of micronutrients in the cultivation of an economically important crop species. The research results may be useful in optimizing barley grain production for brewing purposes. Increasing crop efficiency through fertilization without interfering with the soil environment supports the achievement of sustainable development goals. The varied response of the cultivars indicates the need for more research on the optimization of fertilization strategies based on genotypic traits. The research results have significant application implications for precision agriculture and environmentally friendly agriculture. The use of foliar microelement fertilization may contribute to increasing the efficiency of nutrient management, improving the condition of plants under stress conditions, and optimizing yield. This can find practical application in modern crop management systems, supporting farmers in adapting fertilization strategies to changing site conditions and cultivar specificity.

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Author Contributions

- Barbara Stadnik conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Renata Tobiasz-Salach conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Dagmara Migut analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw measurements are available in the [Supplemental File](#).

Supplemental Information

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Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

Barbara Stadnik
(Imię i nazwisko autora)

Rzeszów, 23.03.2026r.
(miejscowość i data)

OŚWIADCZENIE

o merytorycznym wkładzie współautora

Oświadczam, że w pracy Stadnik B., Tobiasz-Salach R., Migut D. 2025. *Effect of foliar application of microelements on chlorophyll content, canopy architecture indicators, and physiological parameters of Hordeum vulgare L. plants. PeerJ, 13, e19966*, mój wkład był wiodący i polegał na opracowaniu koncepcji i projektu badań, przeprowadzeniu eksperymentów, analizie danych, przygotowaniu tabel i rysunków, opracowaniu pierwotnej wersji artykułu oraz jego redakcji po recenzji, a także zatwierdzeniu ostatecznej wersji manuskryptu.


(podpis osoby składającej oświadczenie)

Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

Renata Tobiasz-Salach
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OŚWIADCZENIE
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Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2025. Effect of foliar application of microelements on chlorophyll content, canopy architecture indicators, and physiological parameters of Hordeum vulgare L. plants. PeerJ, 13, e19966* mój udział polegał na opracowaniu koncepcji i projektu eksperymentów, analizie danych, recenzji wersji roboczych artykułu i zatwierdzeniu ostatecznej wersji manuskryptu.


.....
(podpis osoby składającej oświadczenie)

Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

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Rzeszów, 23.03.2026r.
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OŚWIADCZENIE
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Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2025. Effect of foliar application of microelements on chlorophyll content, canopy architecture indicators, and physiological parameters of Hordeum vulgare L. plants. PeerJ, 13, e19966* mój udział polegał na analizie statystycznej danych, pisaniu i recenzji wersji roboczych artykułu oraz zatwierdzeniu ostatecznej wersji manuskryptu.

.....*Dagmara Migut*.....
(podpis osoby składającej oświadczenie)

Article

Impact of Foliar Application of Copper, Manganese, Molybdenum, and Zinc on the Chemical Composition and Malting Quality of Barley Cultivars

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Abstract

The aim of this study was to evaluate the effect of foliar application of selected micro-nutrients on the chemical composition and malting quality of spring barley (*Hordeum vulgare* L.). The scientific literature lacks in-depth studies that assess the effect of foliar application of micronutrients on barley malting quality. Most studies (especially under field conditions) focus on nitrogen fertilization rather than individual micronutrients. Three brewing-type barley cultivars (Baryłka, KWS Irina, and RGT Planet) were evaluated under foliar micronutrient fertilization (Cu, Mn, Mo, Zn). Fertilizers were applied at doses of 2 L ha⁻¹ for Cu, Mn, and Zn and 1 L ha⁻¹ for Mo. The experiment examined the hectoliter mass, theoretical extractability, contents of selected micro- and macronutrients, and the protein, fat, fiber, and ash contents of the grain. Furthermore, the following characteristics of barley malt were determined, i.e., moisture, protein, extractivity, Kolbach index, and diastatic power. The results showed significant variability in grain and malt quality depending on the cultivar and year. The Baryłka cultivar was characterized by the highest grain density (66.3 kg hL⁻¹) and protein content (10.9% d.m.), while RGT Planet had the highest extractivity and the most favorable malting profile. Foliar supplementation had a slightly positive effect on the average content of trace elements in barley. Mn application increased grain Ca content by 5.6% compared with the control, while foliar Zn fertilization resulted in the highest zinc concentration (a 24.7% increase). No significant effect of fertilization on malt quality was observed, but a significant interaction of experimental factors in extractivity, Kolbach index, and diastatic power was noted. The obtained results indicate that a single foliar application of microelements affects the contents of minerals and protein in the grain, but it does not lead to a significant improvement in malting parameters. This suggests the need for further research on dosage, application date, and interactions between the cultivar and environmental conditions.

Keywords: foliar spraying; grain composition; *Hordeum vulgare* L.; malt quality; micronutrient



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1. Introduction

Barley (*Hordeum vulgare* L.) is the fourth most important cereal grain in the world in terms of grain production after wheat, maize, and rice. In 2023, barley was cultivated on

46.2 million hectares worldwide, with a yield of over 145 million tons [1]. This species is considered one of the oldest crops, playing an important role in the development of human civilization and research in genetics, biochemistry, and developmental biology [2–4]. It is grown in a wide range of environments, both in high-input agricultural systems and in extensive agriculture. Approximately 65–70% of the grain produced is used for animal feed, while 33% is used by the brewing industry for malt production. Barley malt is the main source of fermentable sugars used by yeast in the traditional beer brewing process [5]. Only 2–3% is used directly for human consumption [6–8]. Barley in the human diet contributes to reducing the risk of civilization diseases due to the content of valuable bioactive compounds [9,10].

Nutrient deficiencies in plants limit agricultural production and also impact human nutrition, as crops (primarily cereal grain) constitute the main component of the diet. The level of macro- and micronutrients in the human body can be optimized by diversifying the diet and increasing their concentration or bioavailability in food products, e.g., by means of agrotechnical biofortification. One approach involves applying fertilizers enriched with beneficial elements, which offers a relatively simple and rapid means of supplementing crops with minerals [11–13]. Micronutrients such as zinc (Zn), copper (Cu), manganese (Mn), and molybdenum (Mo) play key biochemical roles in the human body, despite the relatively low requirements for these elements. The recommended daily intake for adults is approximately as follows: Cu—0.9 mg; Mn—2–5 mg; Zn—10–14 mg; and Mo—45 µg [14]. The concentration of microelements in barley grain is determined by genetic factors, soil conditions, and fertilization. Typical ranges of their concentration in barley are as follows: Zn 20–50 mg, Cu 3–8 mg, Mn 15–40 mg, and Mo 0.1–1.0 mg per 1 kg of grain. During the malting process, the microelement contents are generally maintained at similar levels [12,15].

There are two botanical types of barley: two-row and six-row. In Europe, Australia, and South America, two-row cultivars are used primarily for brewing purposes, while six-row malting barley was more widely cultivated in North America [16,17]. Typical two-row barley cultivars are plumper and have a larger proportion of starchy endosperm relative to six-row cultivars. Barley malt produced from two-row barley has a lower protein-to-starch ratio, resulting in higher fermentation extract yields [5]. There are many different barley traits that are important for malting, mainly related to the speed and consistency of germination, endosperm cell wall breakdown, and starch degradation to fermentable sugars [18,19].

The main component of barley grain is starch, which can constitute over 70% of the dry matter [20]. Protein content ranges from 10 to 14%, and fiber is 19–21% [21]. Protein affects the rate of starch degradation in barley through its interaction with starch granules, thus influencing the level of modification during malting. High protein content is not preferred in brewing because it can not only affect the rate of starch degradation but also affect the properties of the malt wort and the quality of the beer [22–24].

The quality criteria are stringent for the barley used in malting. The importance of the malting process has led to intensive research on grain structure, development, and germination in barley [2,25]. The quality of the malt depends on various grain parameters, such as grain shape, size, density, protein content, etc., which influence quality traits [26]. The grain used in the brewing industry should be from a pure variety, have a germination capacity of at least 95%, a protein content of 11% to 12.5% d.m., and a moisture content of at most 13.5%, and be free from diseases, pests, and thermal and mechanical damage [5,27,28].

The current goal of barley breeding is to optimize agrotechnical performance while improving processing efficiency. Identifying malting barley cultivars with desirable grain parameters is crucial for improving production efficiency and malt quality. Agronomic

practice research is important to increase grain suitability for brewing purposes [19,26]. Previous research indicates that micronutrient deficiencies can lead to reduced yield, grain unevenness, changes in protein content, and a deterioration of traits important for malting. However, most of these studies refer to soil fertilization or the use of mixtures containing several micronutrients, making it difficult to assess the impact of individual elements. Furthermore, barley's response to micronutrient supplementation depends on the dose, application timing, cultivar characteristics, and weather conditions, leading to ambiguous conclusions regarding their impact on malting quality. Few studies focus on the foliar application of single-nutrient fertilizers and their impact on both grain chemical composition and malt parameters. Despite the recognized physiological importance of micronutrients, previous research has provided inconsistent results regarding their agronomic and technological effects on barley. Most studies have focused on soil fertilization or the use of complex micronutrient mixtures rather than on single-element foliar application under field conditions [29,30]. The available evidence suggests that the dose, timing, and method of micronutrient application may influence grain yield, protein accumulation, and starch deposition; however, their effects on key malting parameters such as extractivity, Kolbach index, and diastatic power are still poorly understood. Liszewski and Błażewicz [31] examined the effect of foliar fertilization with Cu, Mn, and Fe on grain yield and the brewing value of spring barley, the Quench cultivar. The results of this study showed that the foliar application of fertilizers containing Cu and Fe contributed to improved malting suitability of malting grain. Previous studies on fertilization and grain quality of malting barley have focused primarily on the effect of nitrogen fertilization on the chemical composition of grain [32–36]. The level of nitrogen fertilization determines the protein content in the grain, and too high a percentage of this nutrient negatively affects the malting process by reducing extracts for the brewer. It also slows water absorption during steeping, potentially affecting the final malt quality. Low protein levels result in a deficiency of enzymes necessary for barley grain modification and starch degradation during brewing [19,24]. Therefore, there is a research gap regarding the extent to which individual micronutrients applied foliarly at specific developmental stages can modify malting barley grain quality and its malting suitability. Filling this gap is crucial to assessing whether targeted foliar treatments can be an effective agronomic tool to enhance malting quality. Agricultural techniques used have a significant impact on grain quality. In particular, they influence the grain's size and chemical composition, which determine its suitability for beer production [37]. The foliar application of nutrients can modify the grain chemical composition and barley yield, which are primarily determined by the genotype [38–40]. Understanding the chemical variability of malting barley cultivars will allow for greater diversity of breeding programs to develop or improve product flavor [19].

This study was conducted to investigate the effect of foliar fertilization with microelements (copper, manganese, molybdenum, and zinc) on the malting suitability of grain of three malting barley cultivars. The research hypothesis assumes that foliar feeding with selected micronutrients positively affects grain nutrient content and malt quality parameters.

2. Materials and Methods

2.1. Field Experiment Scheme

Field studies were conducted in years 2019–2021 in southeastern Poland (49°47' N, 22°34' E). The experiment was designed using a two-factor split-block design with four replications. The experimental factors were as follows:

(1) two-row malting spring barley cultivar (Baryłka (Hodowla Roślin Strzelce Ltd., IHAR Group, Strzelce, Poland), KWS Irina (KWS Lochów Polska Ltd., Prusy, Poland), RGT Planet (R.A.G.T. Semences Polska Ltd., Toruń, Poland)), and (2) foliar micronutrient

application. Foliar fertilization treatments included a control treatment (no fertilization) and application of single micronutrients: copper (Cu), manganese (Mn), molybdenum (Mo), or zinc (Zn). The sources of microelements were single-component fertilizers from the Mikrovit® series (Intermag Ltd., Olkusz, Poland), applied foliarly in the form of aqueous solutions: MIKROVIT® COPPER (75 g L⁻¹ copper sulfate CuSO₄ dose 2 L ha⁻¹); MIKROVIT® MANGANESE (160 g L⁻¹ manganese sulfate MnSO₄ (65 g L⁻¹) and manganese nitrate Mn(NO₃)₂ (95 g L⁻¹) dose 2 L ha⁻¹); MIKROVIT® MOLYBDENUM (33 g L⁻¹ ammonium molybdate (NH₄)₆Mo₇O₂ dose 1 L ha⁻¹); and MIKROVIT® CYNK (112 g L⁻¹ zinc sulfate ZnSO₄, dose 2 L ha⁻¹). The applied doses of micronutrient fertilizers were selected in accordance with the manufacturer's agronomic recommendations for cereal crops and are consistent with commonly used rates in field trials evaluating the effects of foliar micronutrient supplementation in barley and other cereals [29,30]. Spraying was carried out at the stem elongation stage (BBCH 30–32) [41] using a pressure sprayer in windless weather. Foliar fertilization is generally most effective during the stem elongation phase, as this is when the plant has a high nutrient demand and leaf assimilation activity. This allows for rapid and efficient nutrient absorption [30,42,43]. A detailed description of the agrotechnical treatments, soil conditions, and weather conditions during the field experiment is presented in Stadnik et al. [44] and Stadnik et al. [45]. Grain was harvested at full maturity (BBCH 89) [41] in the last ten days of July each year (22 July 2019, 30 July 2020, 25 July 2021). The yield from each plot was weighed, and the grain was cleaned and prepared for laboratory analysis.

2.2. Preparation of Material for Analysis

After harvest, the grain was cleaned, dried in the laboratory to a stable storage moisture, and conditioned to room temperature before being separated for analysis. Homogeneous analytical samples were prepared by grinding in a laboratory grinder, and the portion size and homogenization method were in accordance with the recommendations of the ISO standards appropriate for the assays described below. For quality control, a blank, reference material, or internal control was included in each analytical run, and at least 10% of the measurements were duplicated, using the repeatability criteria described in the individual standards [46–49].

2.3. Laboratory Analysis of Grain

2.3.1. Extractivity of Grain

Theoretical extractivity of barley grain (*E*) was calculated according to Bishop's formula [50,51]. This formula, developed for two-row barley, has the following form:

$$E = 84.5 - 0.75B + 0.1TGW$$

where *B*—protein content in grain (% d.m.); TGW—1000-grain weight (g). The value of 84.5 is a constant characteristic for two-row barley. TGW was presented in the study by Stadnik et al. [44].

2.3.2. Grain Density

The hectoliter mass of grain was determined with a Dрамиński GMDM grain moisture and density meter, type WZW2 (Dрамиński Inc., Szabruk, Poland), using the routine method according to ISO 7971-3, and using a calibrated device for measuring mass per hectoliter. The sample was prepared in accordance with the requirements of the standard by performing triplicate measurements and calculating the result as an average [52].

2.3.3. Chemical Composition

Samples were prepared by uniform grinding in a knife mill Knifetec 1095 (Foss Tecator), designed for the rapid homogenization of cereal materials. Water content was determined using the reference method for cereals in accordance with PN-EN ISO 712:2012 [53] in the current version for the product. For barley, the Analytica EBC procedure for barley grain moisture, which refers to ISO 712 [54], was additionally considered, ensuring consistency with the methodology used in the assessment of brewing raw material. In both cases, the moisture result was used for conversion to dry matter in accordance with the reporting principles provided in the standard methods [54]. Total protein was determined from total nitrogen using the Kjeldahl method in accordance with PN-EN ISO 20483 [55], and for barley, procedural compliance was confirmed with the Analytica EBC 3.3.1 method for determining nitrogen in grain. Protein content was calculated using a conversion factor of 6.25 and related to dry matter [55,56]. Crude fat was determined by the extraction method in accordance with PN-EN ISO11085 [57], using the Randall/Soxtec procedure appropriate for cereal products. After the removal of solvent, the residue was dried to a constant weight, and the result was expressed as a percentage of dry matter [57]. Crude fiber was determined by the indirect filtration method in accordance with PN EN ISO6865, which involves digesting the sample with acid and alkali solutions under conditions specified in the standard for drying and ashing and calculating the fiber content from the difference in masses [58]. Total ash was determined gravimetrically by ashing the sample in a muffle furnace in accordance with PN-EN ISO2171 [59], and the result was expressed as a percentage by mass on a dry matter basis. All determinations were subject to ongoing quality control, including verification of repeatability based on three independent replicates and stability of results across analytical runs. Each determination was performed in triplicate, and the results were expressed as dry weight.

Mineralization was carried out in an open system on a Tecator heating block, using a mixture of HNO_3 : HClO_4 : H_2SO_4 in a volume ratio of 20:5:1, until clear solutions were obtained. The mixture and digestion regime were selected based on reference methodologies for the wet mineralization of plant material, while maintaining safety recommendations for HClO_4 . Ca, Cu, Fe, K, Mg, Mn, and Zn were determined by flame atomic absorption spectrometry on a Hitachi Z 2000 spectrophotometer with air-acetylene atomization, and background correction using the Zeeman polarization effect. Analytical parameters and sample preparation for measurement were adapted to the requirements of the ISO6869 [60] reference method for AAS, including the use of the recommended analytical lines: 422.6 nm (Ca), 324.8 nm (Cu), 248.3 nm (Fe), 766.5 nm (K), 285.2 nm (Mg), 279.5 nm (Mn), and 213.8 nm (Zn). Calibration was performed using external standard solutions prepared in the same acidic environment as the samples; each sample was analyzed in triplicate, and a reagent blank was included in each series.

2.4. Laboratory Analyses of Malt

2.4.1. Malt Production

The grain malting process was carried out on a laboratory scale according to the standard scheme for barley [61]. Malting was performed in three parallel replicates. Each sample consisted of a batch of grain weighing 425 g on a dry matter basis. Steeping (soaking) and germination took place in the micro-malting room at a constant air temperature of 14 ± 1 °C and at a relative humidity of above 95%. The grain was soaked in water at approximately 14 °C until the target hydration degree of 45% was achieved. The total steeping time was approximately 72 h, with the water changed every 24 h and the grain regularly aerated (with breaks to allow for air access). The steeping scheme was as follows: Day 1: 4 h under water, then ~20 h in air (during a break from steeping); Day 2: up to 2 h

under water (soaking), and the rest of the time exposed to air; Day 3: the grain was sprayed with water to reach the target moisture content of 45%, after which it was left exposed to air until the next day (beginning of germination). After soaking, the grain was germinated for a total of 5 days under the same temperature and humidity conditions. The weight was monitored daily (weight increase indicating water uptake), and aeration was performed by gently moving and mixing the germinating grain in the germination tank to ensure even oxygen access and prevent clumping. After 5 days of germination, the obtained green malt (germinated grain) was subjected to convective drying in a single-screen dryer with warm air blowing. Drying was carried out for 23 h according to the following temperature program: 16 h at 50 °C (initial drying of the grain); 1 h at 60 °C; 1 h at 70 °C; and 5 h at 80 °C (final drying of the malt). After cooling, the dried malt was degermed. Root sprouts were removed by grating the malt on a sieve, which allowed for the separation of the brittle, dried roots. The resulting finished barley malt was stored in tightly sealed plastic containers until laboratory analysis.

2.4.2. Analysis of Malt Parameters

Malt quality analysis was performed on grist prepared just prior to testing by grinding the grain in a Knifetec1095 knife mill (Foss Tecator), ensuring a uniform grinding ratio appropriate to reference procedures consistent with EBC standards. Sampling and preparation of the material for testing were performed according to the principles of malt sampling and sample preparation described in the malt section of Analytica EBC to maintain representativeness and repeatability of results [62]. Moisture content in malt was determined by the mass loss method under reference conditions specified for malt in Analytica EBC, and the result was expressed as a percentage and related to dry matter [63]. Total protein content was calculated from total nitrogen determined by the Kjeldahl method according to the Analytica EBC malt procedure, using a conversion factor of 6.25 and converting the results to dry matter [64]. Malt extractivity was determined from laboratory wort obtained in a standard congress mash test conducted according to the temperature program and apparatus requirements specified by the European Brewing Convention; the result was reported as a percentage of extract per malt dry matter [65]. The Kolbach index was calculated as the ratio of soluble nitrogen in the congress wort to total nitrogen in the malt, expressed as a percentage. Soluble nitrogen was determined by the Kjeldahl method according to a dedicated malt procedure, in conjunction with the wort obtained in the congress test, while total nitrogen was determined according to method 4.3.1 [64,66]. Diastatic power was determined spectrophotometrically according to the reference document for malt, under the reaction conditions specified by Analytica EBC, and the result was reported in Windisch Kolbach units [67]. Each determination was performed in three independent replicates.

2.5. Statistical Analysis

Statistical analyses were performed using Statistica (TIBCO Statistica, version 13.3), employing ANOVA modules and mean comparison procedures. The experimental design was modeled as a two-factor analysis of variance with cultivar and foliar fertilization as factors, with year as a random effect and replications using a split-block design. For all traits, the assumptions of normality of residual distribution (Shapiro–Wilk test) and homogeneity of variance (Levene’s test) were verified. For significant main effects or interactions, Tukey’s HSD post hoc tests were performed at $p \leq 0.05$. Results are presented as mean values with standard deviation (SD).

3. Results

3.1. Assessment of Barley Grain

3.1.1. Grain Density and Theoretical Extractability

In the experiment, the average grain bulk density was 64.3 kg hL^{-1} . The highest values for the Baryłka and RGT Planet cultivars were obtained after spraying plants with copper fertilizer (67.8 kg hL^{-1} and 64.3 kg hL^{-1} , respectively), while the highest values for the KWS Irina cultivar were obtained after applying manganese fertilizer (64.2 kg hL^{-1}). Grain bulk density varied depending on the barley cultivar and harvest year. The Baryłka cultivar had a significantly higher average value (66.3 kg hL^{-1}) compared to the KWS Irina cultivars (63.1 kg hL^{-1}) and RGT Planet cultivars (63.5 kg hL^{-1}) (Table 1). Theoretical extractability of the grain averaged 81.2% d.m. The highest value of this parameter was observed in the RGT Planet cultivar from plots fertilized with manganese (82.0% d.m.), while the lowest value was observed in the Baryłka cultivar after application of Cu or M0 (80.8% d.m.).

Table 1. The hectoliter weight and theoretical extractivity of grain depending on the fertilization, cultivar, and year of the field experiment.

Cultivar (C)	Fertilization (F)	Hectoliter Weight of Barley	Extractivity of Grain
		kg hL ⁻¹	% d.m.
Baryłka	Control	64.4 ± 2.5^{bc}	$81.5 \pm 0.28^{a-c}$
	Cu	67.8 ± 6.5^c	81.2 ± 0.36^a
	Mn	66.6 ± 1.8^{bc}	81.2 ± 0.46^{ab}
	Mo	65.5 ± 3.3^{bc}	81.2 ± 0.64^a
	Zn	67.4 ± 4.3^c	81.3 ± 0.46^{ab}
KWS Irina	Control	62.2 ± 1.9^a	$81.8 \pm 0.49^{c-e}$
	Cu	63.3 ± 3.2^{ab}	$81.8 \pm 0.36^{c-e}$
	Mn	64.2 ± 5.6^b	$81.5 \pm 0.37^{a-d}$
	Mo	62.6 ± 3.4^a	$81.6 \pm 0.44^{b-e}$
	Zn	63.3 ± 1.9^{ab}	$81.5 \pm 0.38^{a-d}$
RGT Planet	Control	63.5 ± 1.9^b	$81.8 \pm 0.34^{c-e}$
	Cu	64.3 ± 1.4^{bc}	$81.8 \pm 0.51^{c-e}$
	Mn	63.5 ± 2.4^b	82.0 ± 0.39^e
	Mo	62.5 ± 5.3^a	81.9 ± 0.50^{de}
	Zn	63.7 ± 1.9^b	82.0 ± 0.41^e
HSD $p \leq 0.05 \text{ C} \times \text{F}$		n.s. (0.7863)	* (0.0126)
Mean	Baryłka	66.3 ± 4.1^B	81.3 ± 0.45^A
	KWS Irina	63.1 ± 3.4^A	81.7 ± 0.41^B
	RGT Planet	63.5 ± 2.9^A	81.9 ± 0.43^C
HSD $p \leq 0.05 \text{ C}$		*** (0.0000)	*** (0.0000)

Table 1. Cont.

Cultivar (C)	Fertilization (F)	Hectoliter Weight of Barley	Extractivity of Grain
		kg hL ^{−1}	% d.m.
Mean	Control	63.4 ± 2.2 ^A	81.7 ± 0.40 ^A
	Cu	65.1 ± 4.6 ^A	81.6 ± 0.50 ^A
	Mn	64.7 ± 3.8 ^A	81.6 ± 0.52 ^A
	Mo	63.5 ± 4.2 ^A	81.6 ± 0.60 ^A
	Zn	64.8 ± 3.4 ^A	81.6 ± 0.51 ^A
HSD $p \leq 0.05$ F		n.s. (0.0582)	n.s. (0.5881)
Year (Y)	2019	62.5 ± 2.0 ^A	81.3 ± 0.49 ^A
	2020	65.3 ± 2.0 ^B	81.7 ± 0.40 ^C
	2021	65.1 ± 5.4 ^B	81.9 ± 0.51 ^B
HSD $p \leq 0.05$ Y		*** (0.0000)	*** (0.0000)
Average		64.3 ± 3.8	81.6 ± 0.50

*** and * indicate significant differences at $p \leq 0.001$ and $p \leq 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). Data are presented as mean ± standard deviation (SD). Different lower-case letters (a–e) indicate significant differences among treatments; uppercase letters (A–C) indicate significant differences among means for fertilization, cultivars, or years according to Tukey's HSD at $p \leq 0.05$.

Theoretical extractivity was determined by genotype. The highest result was obtained for the RGT Planet cultivar, while foliar fertilization had no significant effect on the mean values of the analyzed parameter (Table 1).

Both parameters varied significantly depending on the year of field testing. Higher values were recorded in 2020 and 2021 compared to 2019 (Table 1).

3.1.2. Elemental Profile of Grain

An analysis of the elemental composition of barley grain revealed significant differences in the response of individual barley cultivars to foliar fertilization. Significant interactions of experimental factors were demonstrated for the content of Ca, Fe, K, Mg, and Zn (Table 2).

The highest Ca content was observed in the Baryłka cultivar from the control treatment (305 mg kg^{−1}), in the KWS Irina cultivar after Mo application (306 mg kg^{−1}), and in the RGT Planet cultivar from plots with Mn application (343 mg kg^{−1}).

The Baryłka cultivar demonstrated relatively stable Fe content regardless of the fertilization type (approximately 76–89 mg kg^{−1}), while KWS Irina responded strongly to foliar fertilization. The highest iron content was found in the RGT Planet cultivar from plots fertilized with Mo (95.2 mg kg^{−1}). In the experiment, the highest Mg content was found in the grain of the KWS Irina cultivar after the foliar application of Mn (1201 mg kg^{−1}), while the lowest content of this element was found in the RGT Planet cultivar after the application of Mo (1098 mg kg^{−1}).

The foliar application of the tested micronutrients had a significant effect on the average Ca, Fe, Mn, and Zn contents in grain. The highest Ca content was obtained after Mn fertilization (302 mg kg^{−1}), while the lowest Ca content was obtained in the Mo fertilization variant (292 mg kg^{−1}). The Fe content was the highest in the control treatments and after Mo fertilization (84.5 mg kg^{−1}). The application of each of the tested micronutrient fertilizers resulted in a significant increase in Mn content in grain compared

to the control. The application of zinc fertilizer significantly increased Zn content in grain (34.8 mg kg^{-1}) compared to the other fertilization treatments.

Table 2. The contents of selected macro- and microelements in barley grain depending on the fertilization, cultivar, and year of the field experiment.

Cultivar (C)	Fertilization (F)	Ca	Cu	Fe	K	Mg	Mn	Zn
mg kg^{-1}								
Baryłka	Control	$305 \pm 35^{\text{cd}}$	$5.68 \pm 0.78^{\text{cd}}$	$88.9 \pm 46.0^{\text{d}}$	$4112 \pm 302^{\text{ab}}$	$1128 \pm 62^{\text{b}}$	$16.7 \pm 4.94^{\text{b}}$	$30.8 \pm 4.16^{\text{a}}$
	Cu	$265 \pm 35^{\text{a}}$	$5.70 \pm 0.97^{\text{cd}}$	$76.7 \pm 25.8^{\text{b}}$	$3984 \pm 475^{\text{a}}$	$1151 \pm 80^{\text{b}}$	$12.9 \pm 2.13^{\text{a}}$	$30.3 \pm 5.34^{\text{a}}$
	Mn	$279 \pm 47^{\text{bc}}$	$5.37 \pm 1.18^{\text{b-d}}$	$88.5 \pm 44.6^{\text{d}}$	$3899 \pm 180^{\text{a}}$	$1165 \pm 74^{\text{bc}}$	$14.0 \pm 1.69^{\text{a}}$	$32.8 \pm 10.9^{\text{a}}$
	Mo	$273 \pm 45^{\text{b}}$	$5.45 \pm 1.09^{\text{b-d}}$	$88.3 \pm 54.7^{\text{d}}$	$3933 \pm 288^{\text{a}}$	$1187 \pm 46^{\text{d}}$	$13.1 \pm 1.78^{\text{a}}$	$32.0 \pm 10.1^{\text{a}}$
	Zn	$267 \pm 52^{\text{a}}$	$6.00 \pm 1.41^{\text{d}}$	$67.4 \pm 18.5^{\text{a}}$	$3969 \pm 357^{\text{a}}$	$1217 \pm 71^{\text{e}}$	$13.5 \pm 1.01^{\text{a}}$	$41.0 \pm 13.6^{\text{b}}$
KWS Irina	Control	$267 \pm 65^{\text{a}}$	$4.99 \pm 0.61^{\text{a-c}}$	$84.5 \pm 20.8^{\text{c}}$	$4649 \pm 354^{\text{d}}$	$1165 \pm 50^{\text{bc}}$	$13.7 \pm 1.22^{\text{a}}$	$26.6 \pm 8.76^{\text{a}}$
	Cu	$292 \pm 65^{\text{bc}}$	$5.09 \pm 1.30^{\text{a-c}}$	$60.1 \pm 18.3^{\text{a}}$	$4652 \pm 656^{\text{d}}$	$1176 \pm 67^{\text{c}}$	$12.3 \pm 0.82^{\text{a}}$	$28.1 \pm 8.49^{\text{a}}$
	Mn	$283 \pm 52^{\text{bc}}$	$4.81 \pm 1.04^{\text{a-c}}$	$61.1 \pm 18.6^{\text{a}}$	$4675 \pm 422^{\text{d}}$	$1201 \pm 106^{\text{d}}$	$12.5 \pm 1.02^{\text{a}}$	$29.0 \pm 7.22^{\text{a}}$
	Mo	$306 \pm 20^{\text{d}}$	$4.62 \pm 0.84^{\text{ab}}$	$70.0 \pm 20.0^{\text{ab}}$	$4454 \pm 499^{\text{cd}}$	$1190 \pm 68^{\text{d}}$	$12.4 \pm 1.23^{\text{a}}$	$27.5 \pm 4.27^{\text{a}}$
	Zn	$272 \pm 32^{\text{a}}$	$4.78 \pm 0.89^{\text{a-c}}$	$65.9 \pm 19.9^{\text{a}}$	$4366 \pm 411^{\text{b}}$	$1191 \pm 76^{\text{d}}$	$12.3 \pm 0.91^{\text{a}}$	$30.1 \pm 5.32^{\text{a}}$
RGT Planet	Control	$287 \pm 49^{\text{bc}}$	$4.36 \pm 0.39^{\text{a}}$	$76.9 \pm 45.3^{\text{b}}$	$4438 \pm 386^{\text{cd}}$	$1166 \pm 33^{\text{bc}}$	$13.7 \pm 2.76^{\text{a}}$	$26.4 \pm 1.55^{\text{a}}$
	Cu	$304 \pm 48^{\text{cd}}$	$4.73 \pm 0.74^{\text{ab}}$	$66.7 \pm 30.7^{\text{a}}$	$4244 \pm 259^{\text{b}}$	$1087 \pm 48^{\text{a}}$	$12.8 \pm 1.20^{\text{a}}$	$27.7 \pm 3.92^{\text{a}}$
	Mn	$343 \pm 42^{\text{e}}$	$4.66 \pm 0.82^{\text{ab}}$	$83.5 \pm 48.2^{\text{c}}$	$4260 \pm 426^{\text{b}}$	$1110 \pm 77^{\text{ab}}$	$13.6 \pm 1.72^{\text{a}}$	$30.2 \pm 6.07^{\text{a}}$
	Mo	$298 \pm 53^{\text{b-d}}$	$4.38 \pm 0.53^{\text{a}}$	$95.2 \pm 49.6^{\text{e}}$	$4291 \pm 313^{\text{b}}$	$1098 \pm 57^{\text{a}}$	$13.4 \pm 1.86^{\text{a}}$	$27.4 \pm 5.05^{\text{a}}$
	Zn	$307 \pm 45^{\text{d}}$	$4.88 \pm 1.02^{\text{a-c}}$	$70.3 \pm 30.9^{\text{ab}}$	$4409 \pm 372^{\text{b-d}}$	$1104 \pm 85^{\text{ab}}$	$13.3 \pm 1.46^{\text{a}}$	$33.3 \pm 9.15^{\text{a}}$
HSD $p \leq 0.05 \text{ C} \times \text{F}$		*** (0.0000)	n.s. (0.5824)	*** (0.0001)	n.s. (0.4714)	*** (0.0006)	** (0.0019)	n.s. (0.2387)
Mean	Baryłka	$278 \pm 45^{\text{A}}$	$5.64 \pm 1.09^{\text{B}}$	$81.9 \pm 39.8^{\text{B}}$	$3979 \pm 331^{\text{A}}$	$1170 \pm 72^{\text{B}}$	$14.1 \pm 2.94^{\text{C}}$	$33.4 \pm 10.0^{\text{B}}$
	KWS Irina	$284 \pm 50^{\text{A}}$	$4.86 \pm 0.94^{\text{A}}$	$68.4 \pm 20.09^{\text{A}}$	$4559 \pm 480^{\text{C}}$	$1185 \pm 74^{\text{B}}$	$12.6 \pm 1.15^{\text{A}}$	$28.3 \pm 6.90^{\text{A}}$
	RGT Planet	$308 \pm 50^{\text{B}}$	$4.60 \pm 0.74^{\text{A}}$	$78.5 \pm 41.6^{\text{B}}$	$4328 \pm 353^{\text{B}}$	$1113 \pm 67^{\text{A}}$	$13.4 \pm 1.84^{\text{B}}$	$29.0 \pm 6.07^{\text{A}}$
HSD $p \leq 0.05 \text{ C}$		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean	Control	$286 \pm 52^{\text{A}}$	$5.01 \pm 0.81^{\text{A}}$	$83.4 \pm 38.4^{\text{B}}$	$4400 \pm 406^{\text{A}}$	$1153 \pm 51^{\text{A}}$	$14.7 \pm 3.56^{\text{B}}$	$27.9 \pm 5.87^{\text{A}}$
	Cu	$287 \pm 52^{\text{A}}$	$5.17 \pm 1.08^{\text{A}}$	$67.8 \pm 25.7^{\text{A}}$	$4293 \pm 552^{\text{A}}$	$1138 \pm 75^{\text{A}}$	$12.7 \pm 1.47^{\text{A}}$	$28.7 \pm 6.15^{\text{A}}$
	Mn	$302 \pm 55^{\text{B}}$	$4.95 \pm 1.04^{\text{A}}$	$77.7 \pm 40.1^{\text{B}}$	$4278 \pm 476^{\text{A}}$	$1159 \pm 93^{\text{A}}$	$13.4 \pm 1.60^{\text{A}}$	$30.6 \pm 8.23^{\text{A}}$
	Mo	$292 \pm 43^{\text{AB}}$	$4.82 \pm 0.95^{\text{A}}$	$84.5 \pm 44.2^{\text{B}}$	$4226 \pm 429^{\text{A}}$	$1158 \pm 71^{\text{A}}$	$13.0 \pm 1.66^{\text{A}}$	$29.0 \pm 7.13^{\text{A}}$
	Zn	$282 \pm 46^{\text{A}}$	$5.22 \pm 1.23^{\text{A}}$	$67.9 \pm 23.1^{\text{A}}$	$4248 \pm 421^{\text{A}}$	$1171 \pm 90^{\text{A}}$	$13.0 \pm 1.24^{\text{A}}$	$34.8 \pm 10.7^{\text{B}}$
HSD $p \leq 0.05 \text{ F}$		** (0.0044)	n.s. (0.0820)	*** (0.0000)	n.s. (0.2896)	n.s. (0.1701)	*** (0.0000)	*** (0.0000)
Year (Y)	2019	$309 \pm 31^{\text{B}}$	$5.61 \pm 1.23^{\text{C}}$	$68.0 \pm 17.3^{\text{B}}$	$4090 \pm 450^{\text{A}}$	$1170 \pm 76^{\text{B}}$	$13.1 \pm 2.95^{\text{A}}$	$36.3 \pm 9.39^{\text{C}}$
	2020	$244 \pm 45^{\text{A}}$	$5.11 \pm 0.80^{\text{B}}$	$48.2 \pm 11.6^{\text{A}}$	$4279 \pm 473^{\text{B}}$	$1178 \pm 86^{\text{B}}$	$12.9 \pm 1.55^{\text{A}}$	$28.8 \pm 6.66^{\text{B}}$
	2021	$317 \pm 34^{\text{B}}$	$4.39 \pm 0.56^{\text{A}}$	$112.6 \pm 34.7^{\text{C}}$	$4497 \pm 357^{\text{C}}$	$1119 \pm 52^{\text{A}}$	$14.1 \pm 1.58^{\text{B}}$	$25.6 \pm 2.30^{\text{A}}$
HSD $p \leq 0.05 \text{ Y}$		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Average		290 ± 50	5.03 ± 1.03	76.3 ± 35.7	4289 ± 459	1156 ± 77	13.3 ± 2.18	30.2 ± 8.12

*** and ** indicate significant differences at $p \leq 0.001$, and $p \leq 0.01$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). Data are presented as mean $\pm$ standard deviation (SD). Different lower-case letters (a–e) indicate significant differences among treatments; uppercase letters (A–C) indicate significant differences among means for fertilization, cultivars, or years according to Tukey's HSD at $p \leq 0.05$.

The statistical analysis of the experimental results demonstrated a strong effect of cultivar on the average content of the analyzed elements in grain. The Baryłka cultivar had the highest concentration of Cu, Fe, Mn, and Zn in grain, while the highest K and Mg values were found in the KWS Irina cultivar. The RGT Planet cultivar had a significantly

higher Ca content (30 mg kg^{−1} compared to Baryłka and 24 mg kg^{−1} compared to KWS Irina, respectively) (Table 2).

The year of study had a significant, strong effect ($p \leq 0.001$) on the content of all analyzed minerals. In 2019, the highest average Cu and Zn contents were recorded, while in 2020, the lowest Fe and Ca values were obtained. In turn, in 2021, the highest Fe and K levels were observed (Table 2).

3.1.3. Organic Chemical and Ash Content

In the experiment, the average protein content was 10.4% d.m. Spraying the plants with each of the tested micronutrient fertilizers resulted in a significant increase in the average protein content compared to the control, with the highest content recorded after the application of Mo (by 0.2% d.m.). The grain of the Baryłka cultivar contained the highest protein content (by 0.6% and 0.9% d.m., respectively, compared to the KWS Irina and RGT Planet cultivars).

The fat content of the tested grain averaged 2.39% d.m. In the Baryłka and KWS Irina cultivars, the highest fat content was recorded in grain from the control plots, while in the RGT Planet cultivar, the highest percentage of this nutrient was observed after the foliar application of zinc. Statistical analysis showed a significant decrease in the fat content in the grain of plants fertilized with micronutrients compared to the control. The lowest value (2.33% d.m.) was recorded on the plots fertilized with Cu (Table 3).

Table 3. The chemical composition of grain depending on the fertilization, cultivar, and year of the field experiment.

Cultivar (C)	Fertilization (F)	Protein	Fat	Fiber	Ash
		[% d.m.]			
Baryłka	Control	10.6 ± 0.44 ^{bc}	2.49 ± 0.22 ^c	3.97 ± 0.42 ^a	2.75 ± 0.16 ^{ab}
	Cu	11.0 ± 0.42 ^c	2.20 ± 0.24 ^{ab}	4.40 ± 0.77 ^c	2.86 ± 0.15 ^c
	Mn	11.0 ± 0.55 ^c	2.28 ± 0.18 ^{a-c}	4.26 ± 0.74 ^{bc}	2.86 ± 0.18 ^c
	Mo	11.0 ± 0.65 ^c	2.19 ± 0.16 ^a	4.30 ± 0.74 ^{bc}	2.87 ± 0.19 ^c
	Zn	10.9 ± 0.51 ^c	2.21 ± 0.20 ^{ab}	4.33 ± 0.66 ^c	2.83 ± 0.17 ^{bc}
KWS Irina	Control	10.1 ± 0.50 ^a	2.50 ± 0.22 ^{cd}	3.97 ± 0.86 ^a	2.71 ± 0.17 ^a
	Cu	10.2 ± 0.61 ^{ab}	2.40 ± 0.26 ^{b-d}	4.01 ± 0.69 ^{bc}	2.71 ± 0.13 ^a
	Mn	10.4 ± 0.63 ^{ab}	2.38 ± 0.21 ^b	3.99 ± 0.76 ^b	2.73 ± 0.17 ^{ab}
	Mo	10.4 ± 0.69 ^{ab}	2.44 ± 0.18 ^{cd}	3.90 ± 0.92 ^b	2.71 ± 0.15 ^{ab}
	Zn	10.4 ± 0.61 ^{ab}	2.37 ± 0.25 ^b	4.13 ± 0.77 ^{bc}	2.73 ± 0.16 ^{ab}
RGT Planet	Control	10.0 ± 0.33 ^{ab}	2.49 ± 0.36 ^c	3.95 ± 1.34 ^b	2.67 ± 0.15 ^a
	Cu	10.0 ± 0.56 ^a	2.38 ± 0.25 ^{b-d}	3.87 ± 0.68 ^b	2.69 ± 0.20 ^a
	Mn	10.0 ± 0.53 ^a	2.46 ± 0.17 ^c	3.77 ± 0.71 ^{ab}	2.65 ± 0.19 ^a
	Mo	10.1 ± 0.61 ^a	2.47 ± 0.24 ^{cd}	3.87 ± 0.80 ^b	2.67 ± 0.20 ^a
	Zn	10.0 ± 0.65 ^a	2.57 ± 0.15 ^d	3.70 ± 0.64 ^a	2.65 ± 0.22 ^a
HSD $p \leq 0.05$ C × F		n.s. (0.1281)	* (0.0282)	n.s. (0.1322)	n.s. (0.0765)
Mean	Baryłka	10.9 ± 0.53 ^C	2.27 ± 0.22 ^A	4.25 ± 0.67 ^C	2.83 ± 0.17 ^C
	KWS Irina	10.3 ± 0.60 ^B	2.42 ± 0.22 ^B	4.00 ± 0.78 ^B	2.72 ± 0.15 ^B
	RGT Planet	10.0 ± 0.53 ^A	2.48 ± 0.24 ^B	3.83 ± 0.85 ^A	2.67 ± 0.19 ^A

Table 3. Cont.

Cultivar (C)	Fertilization (F)	Protein	Fat	Fiber	Ash
		[% d.m.]			
HSD $p \leq 0.05$ C		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean	Control	10.3 ± 0.48 ^A	2.49 ± 0.26 ^B	3.96 ± 0.92 ^A	2.71 ± 0.16 ^A
	Cu	10.4 ± 0.67 ^{AB}	2.33 ± 0.26 ^A	4.09 ± 0.73 ^A	2.75 ± 0.18 ^A
	Mn	10.4 ± 0.68 ^{AB}	2.37 ± 0.20 ^A	4.01 ± 0.74 ^A	2.75 ± 0.19 ^A
	Mo	10.5 ± 0.76 ^B	2.37 ± 0.23 ^A	4.03 ± 0.83 ^A	2.75 ± 0.20 ^A
	Zn	10.4 ± 0.67 ^{AB}	2.38 ± 0.25 ^{AB}	4.05 ± 0.73 ^A	2.74 ± 0.19 ^A
HSD $p \leq 0.05$ F		* (0.0451)	** (0.0018)	n.s. (0.6789)	n.s. (0.0711)
Year (Y)	2019	10.8 ± 0.50 ^C	2.26 ± 0.22 ^A	4.90 ± 0.49 ^C	2.92 ± 0.10 ^C
	2020	9.94 ± 0.57 ^A	2.50 ± 0.23 ^C	3.45 ± 0.48 ^A	2.57 ± 0.11 ^A
	2021	10.5 ± 0.60 ^B	2.40 ± 0.23 ^B	3.73 ± 0.44 ^B	2.73 ± 0.12 ^B
HSD $p \leq 0.05$ Y		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Average		10.4 ± 0.66	2.39 ± 0.25	4.03 ± 0.79	2.74 ± 0.18

***, **, and * indicate significant differences at $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). Data are presented as mean ± standard deviation (SD). Different lowercase letters (a–d) indicate significant differences among treatments; uppercase letters (A–C) indicate significant differences among means for fertilization, cultivars, or years according to Tukey's HSD at $p \leq 0.05$.

The experiment demonstrated an interaction between experimental factors in grain fiber content. In the Baryłka and KWS Irina cultivars, the fiber content in grain was the highest after the application of copper or zinc, while in the RGT Planet cultivar, the highest values were recorded in the grain of control plants. Genotype significantly determined fiber content. Grain of the Baryłka cultivar was characterized by a significantly higher content of this nutrient compared those of the KWS Irina and RGT Planet cultivars (an increase of 0.25 and 0.42%, respectively). The foliar application of each of the micronutrient fertilizers increased the average fiber content compared to the control, and the highest value was recorded after the application of copper (4.09% d.m.); however, these differences were not statistically confirmed (Table 3).

Barley grain averaged 2.74% d.m. of ash. The highest ash content in the Baryłka cultivar was recorded in grain fertilized with molybdenum (2.87% d.m.), while the lowest ash content (2.65% d.m.) was recorded in the RGT Planet cultivar after manganese and zinc application. The ash content in grain was significantly determined by the cultivar. Baryłka cultivars recorded 0.11% d.m. and 0.16% d.m. higher values than KWS Irina and RGT Planet, respectively (Table 3).

The chemical composition of grain depended on the year of the field experiment. Over the three-year field study, the grain of the tested cultivars contained significantly more protein, fiber, and ash in 2019, while the content of these components was the lowest in 2020. The fat content was higher in 2020 and 2021 compared to 2019 (Table 3).

3.2. Malt Quality Parameters

The experiment found that both the barley cultivar and the growing year had a significant impact on the analyzed quality characteristics of the malted grain, while the application of foliar micronutrients did not cause significant changes in the studied quality parameters compared to the control (without fertilization). Higher average extractivity

and diastatic power were noted after the application of Mo and Zn, but these were not statistically significant. The statistical analysis of the results confirmed differences between the cultivars in terms of moisture, protein content, extractivity, Kolbach index, and diastatic power of the malt.

The analysis of malt showed a significant interaction between fertilization and cultivar in the values of extractivity, Kolbach index, and diastatic power. In the Baryłka cultivar, the highest extractivity was recorded after the application of Zn; in the KWS Irina cultivar, this parameter was the highest after the application of Mo, while in the RGT Planet cultivar, the best results were obtained in the Mn and Zn variants. The highest Kolbach index was observed in malt obtained from the KWS Irina grain after Mn application (43.5%). This cultivar also had the highest diastatic power (294 W.K.) after Mo fertilization.

Malt obtained from the Baryłka cultivar was characterized by the highest total protein content (11.4% d.m.) and moisture (4.01%). The KWS Irina cultivar achieved the highest Kolbach index values (average 42.9%) and diastatic power (288 W.K. units). Malt from the RGT Planet cultivar exhibited the highest extractivity (82.8% d.m.) with the lowest protein content (10.5% d.m.) and moisture content (3.92%) (Table 4).

Table 4. The characteristics of barley malt depending on experimental factors and the year of grain harvest.

Cultivar	Fertilization (F)	Moisture	Protein	Extractivity	Kolbach Index	Diastatic Power
		[%]	[% d. m.]	[% d. m.]	[%]	[W.K. Units]
Baryłka	Control	3.87 ± 0.35 ^a	11.1 ± 0.15 ^{bc}	82.2 ± 0.18 ^{a-c}	40.9 ± 0.27 ^c	273 ± 3.45 ^a
	Cu	3.95 ± 0.25 ^c	11.5 ± 0.53 ^c	81.3 ± 0.42 ^a	40.6 ± 0.31 ^{bc}	278 ± 5.12 ^{ab}
	Mn	3.96 ± 0.12 ^{bc}	11.5 ± 0.24 ^c	82.1 ± 0.36 ^{ab}	40.3 ± 0.33 ^b	284 ± 5.82 ^b
	Mo	4.03 ± 0.24 ^{bc}	11.5 ± 0.35 ^c	82.4 ± 0.12 ^a	40.9 ± 0.12 ^c	283 ± 3.14 ^b
	Zn	4.23 ± 0.06 ^c	11.4 ± 0.51 ^c	82.9 ± 0.38 ^{ab}	40.8 ± 0.29 ^c	277 ± 6.07 ^{ab}
KWS Irina	Control	3.87 ± 0.86 ^a	10.6 ± 0.33 ^a	82.6 ± 0.41 ^{c-e}	42.4 ± 0.17 ^d	291 ± 3.69 ^c
	Cu	4.01 ± 0.69 ^{bc}	10.7 ± 0.41 ^{ab}	82.7 ± 0.22 ^{c-e}	43.1 ± 0.15 ^e	277 ± 5.97 ^{ab}
	Mn	3.95 ± 0.76 ^b	10.9 ± 0.13 ^{ab}	82.5 ± 0.19 ^{a-d}	43.5 ± 0.34 ^e	285 ± 4.83 ^{bc}
	Mo	3.94 ± 0.92 ^b	10.9 ± 0.63 ^{ab}	82.8 ± 0.23 ^{b-e}	43.3 ± 0.51 ^e	294 ± 3.54 ^d
	Zn	4.01 ± 0.77 ^{bc}	10.9 ± 0.29 ^{ab}	82.5 ± 0.11 ^{a-d}	42.0 ± 0.36 ^d	292 ± 6.50 ^{cd}
RGT Planet	Control	3.99 ± 1.34 ^b	10.6 ± 0.47 ^{ab}	82.7 ± 0.46 ^{c-e}	39.6 ± 0.29 ^a	288 ± 3.12 ^{bc}
	Cu	3.95 ± 0.68 ^b	10.5 ± 0.26 ^a	82.9 ± 0.37 ^{c-e}	39.8 ± 0.11 ^a	279 ± 4.76 ^{ab}
	Mn	3.91 ± 0.71 ^{ab}	10.5 ± 0.49 ^a	82.9 ± 0.49 ^e	38.9 ± 0.34 ^a	274 ± 4.88 ^a
	Mo	3.96 ± 0.80 ^b	10.5 ± 0.41 ^a	82.8 ± 0.53 ^{de}	39.6 ± 0.12 ^a	285 ± 3.87 ^{bc}
	Zn	3.81 ± 0.64 ^a	10.5 ± 0.27 ^a	82.9 ± 0.11 ^e	39.7 ± 0.56 ^a	291 ± 4.02 ^c
HSD $p \leq 0.05$ C × F		n.s. (0.2971)	n.s. (0.3039)	* (0.0201)	* (0.0152)	* (0.0195)
Mean	Baryłka	4.01 ± 0.14 ^C	11.4 ± 0.53 ^C	82.2 ± 0.58 ^A	40.7 ± 0.27 ^B	279 ± 4.53 ^A
	KWS Irina	3.96 ± 0.06 ^B	10.8 ± 0.60 ^B	82.6 ± 0.13 ^B	42.9 ± 0.65 ^C	288 ± 6.91 ^C
	RGT Planet	3.92 ± 0.07 ^A	10.5 ± 0.53 ^A	82.8 ± 0.09 ^C	39.5 ± 0.34 ^A	283 ± 6.88 ^B
HSD $p \leq 0.05$ C		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)

Table 4. Cont.

Cultivar	Fertilization (F)	Moisture	Protein	Extractivity	Kolbach Index	Diastatic Power
		[%]	[% d. m.]	[% d. m.]	[%]	[W.K. Units]
Mean	Control	3.91 ± 0.07 ^A	10.8 ± 0.48 ^A	82.5 ± 0.26 ^A	40.9 ± 1.39 ^A	284 ± 9.64 ^A
	Cu	3.97 ± 0.03 ^A	10.9 ± 0.67 ^A	82.3 ± 0.87 ^A	41.1 ± 1.75 ^A	278 ± 1.00 ^A
	Mn	3.94 ± 0.03 ^A	10.9 ± 0.68 ^A	82.5 ± 0.40 ^A	40.9 ± 2.36 ^A	281 ± 6.08 ^A
	Mo	3.98 ± 0.05 ^A	11.0 ± 0.76 ^A	82.7 ± 0.23 ^A	41.3 ± 1.91 ^A	287 ± 5.86 ^A
	Zn	4.02 ± 0.21 ^A	10.9 ± 0.67 ^A	82.8 ± 0.23 ^A	40.8 ± 1.15 ^A	287 ± 8.39 ^A
HSD $p \leq 0.05$ F		n.s. (0.6789)	n.s. (0.2901)	n.s. (0.5932)	n.s. (0.6021)	n.s. (0.4854)
Year (Y)	2019	3.99 ± 0.27 ^C	11.3 ± 0.50 ^C	82.2 ± 0.58 ^A	40.6 ± 0.65 ^B	271 ± 5.41 ^A
	2020	3.80 ± 0.29 ^A	10.4 ± 0.57 ^A	82.6 ± 0.13 ^C	42.8 ± 0.43 ^C	283 ± 3.95 ^B
	2021	3.91 ± 0.24 ^B	11.0 ± 0.60 ^B	82.8 ± 0.09 ^B	39.7 ± 0.47 ^A	288 ± 6.07 ^C
HSD $p \leq 0.05$ Y		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Average		3.96 ± 0.09	10.9 ± 0.66	82.5 ± 0.43	41.0 ± 1.50	283 ± 6.84

*** and * indicate significant differences at $p \leq 0.001$ and $p \leq 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). Data are presented as mean ± standard deviation (SD). Different lower-case letters (a–e) indicate significant differences among treatments; uppercase letters (A–C) indicate significant differences among means for fertilization, cultivars, or years according to Tukey's HSD at $p \leq 0.05$.

Significant differences were found in the assessed parameters depending on the year of the field experiment. Malt obtained from grain produced in 2019 was characterized by the highest protein content (11.3%) and moisture (3.99%) and the lowest diastatic power (271 W.K.). In 2020, the lowest moisture (3.80%) and protein content (10.4%) and the highest Kolbach index (42.8%) were recorded, while in 2021, extractivity and diastatic power were the highest (Table 4).

4. Discussion

Malting is a process in which cereal grain is germinated and biochemically modified, and its starch becomes available for conversion into simple sugars, which constitute the substrate for fermentation [19]. Because barley is soaked prior to malting, determining the physical properties of the grain is important, which helps improve malt production technology [68,69]. One of the longest-used quality measures of malting barley is the specific gravity of grain. It is a measure of bulk density, i.e., the weight of the grain per unit volume [70,71]. This characteristic plays an important role in determining appropriate storage, transport, and processing conditions, and provides indirect information about the starch and protein content of the grain [69,72].

The typical weight of a hectoliter of malting barley grain is 68–75 kg hL^{−1} [61,73]. Kumar et al. [72] indicate that values above 65 kg hL^{−1} are considered optimal for malting barley. In our study, grain obtained from a field experiment in 2019 was characterized by lower density (Table 1). Of the cultivars tested, only the Baryłka cultivar had an average bulk density above 65 kg hL^{−1}. These differences may result from the genetic characteristics of individual cultivars, which influence grain structure and composition, and consequently affect its density. This was also confirmed in the study by Sharma and Verma [74]. However, Hoyle et al. [71] did not demonstrate a significant effect of cultivar on this parameter. The foliar application of Cu had the most beneficial effect on the hectoliter weight of grain. This effect was not demonstrated in the study by Karamanos et al. [75] in which the foliar application of CuSO₄ 5H₂O was used in the cultivation of another cereal, wheat.

Theoretical extractivity is a useful indicator of the malting suitability of barley grain, particularly in multi-year studies, as it enables the accurate prediction of extract yields for Pilsen-type malts [51]. The effect of fertilization on grain density and theoretical extractivity was statistically insignificant, suggesting that under the study conditions, the doses and types of fertilizers used were not crucial for these parameters. Minor differences between fertilization groups could be masked by natural variability in varietal characteristics and environmental conditions. However, a significant interaction between cultivar and fertilization was observed in terms of theoretical extractivity, indicating that different cultivars may respond differently to fertilization.

An analysis of the effect of experimental factors on the elemental composition of grain showed that the application of Cu effectively increased the content of this trace element in grain, especially in the Baryłka and RGT Planet cultivars. This effect was also observed in the experiment for manganese and zinc. This confirms the effectiveness of exogenous application of trace elements in increasing their concentration in grain. The high Fe content in the control treatments and after Mo fertilization suggests that foliar application of molybdenum may indirectly support Fe accumulation by influencing nitrogen metabolism and protein synthesis associated with iron transport [76,77]. Overall, foliar fertilization with trace elements had a positive effect on the mineral composition of barley grain. It can be concluded that the foliar application of trace elements is an effective way to biofortify barley grain with valuable minerals, which may improve its malting and nutritional value.

Barley grain characteristics such as protein content and moisture determine the malting process and result. Protein content in barley grain influences the metabolomic composition and enzyme levels in malt. High protein content limits starch degradation, affects beer flavor, influences foam stability, and reduces malt extractability [19,24]. Conversely, low protein content limits enzymatic activity [19]. Genotypic differences in barley and the harvest year or location influence malting and brewing processes. Barley cultivars exhibit very different malting properties and flavor characteristics, which can influence other quality parameters, such as enzyme levels, protein levels, and flavor [19,78].

An analysis of the chemical composition of barley grain revealed higher total protein and crude ash content in plants foliarly fertilized with micronutrients. Genotypic differences were also noted. Similar results were demonstrated in the study by Tobiasz-Salach et al. [40]. In the conducted experiment, the foliar application of Mo resulted in the greatest increase in grain protein content among the elements tested. Molybdenum, although required by plants in very small amounts, plays a key role in nitrogen metabolism, primarily as an active component of enzymes such as nitrite reductase (NR) and nitroreductase (NiR), as well as nitrogenase in legumes [79,80]. The foliar application of molybdenum allows for bypassing the limitations associated with the uptake of this element from the soil, particularly in acidic conditions, where its mobility and bioavailability are limited [81]. Increased Mo availability supports efficient mineral nitrogen metabolism in the plant, i.e., the conversion of nitrates (NO_3^-) to ammonium forms (NH_4^+), which are directly used for amino acid and protein synthesis. As a result, a higher protein concentration was observed in the grain. Furthermore, molybdenum can increase the activity of enzymes involved in the biosynthesis of nucleic acids and other nitrogen compounds, promoting more intensive general plant metabolism and more efficient utilization of nitrogen taken up from basal fertilization [82]. Similar effects were demonstrated in studies conducted by Khot et al. [83] on wheat, where the foliar application of molybdenum on low-pH soil led to an increase in protein content in the grain.

The activity of all starch-degrading factors in barley malt is called diastatic power, which is an important parameter used in the malting industry. Alpha- and beta-amylase together constitute over 99% of the total diastatic activity of malt [84]. Despite some dif-

ferences observed at the mean value level, micronutrient spraying did not demonstrate a statistically significant effect on the analyzed malt quality parameters. These observations are consistent with previous studies, which indicate that the effect of micronutrients on grain quality is often dependent on the site conditions, plant development stage, and interactions with other nutrients [85]. The results obtained in this study do not confirm the findings of Liszewski and Błażewicz [31], who reported an improvement in malting suitability following the foliar application of Cu and Fe. This discrepancy may be explained by differences in soil micronutrient availability, cultivar sensitivity, and the impact of environmental conditions. Under conditions of sufficient Cu supply, additional foliar application may increase the element concentration in the grain without translating into changes in enzymatic activity or extractability. It is possible that the application of micronutrients for the application date or rate was insufficient to achieve a qualitative effect, or that the response potential was dependent on the cultivar.

The stem-shooting phase is a period of high metabolic activity, but key processes responsible for the synthesis of storage proteins and amylolytic enzymes occur primarily during grain pouring [86]. Applying trace elements too early may not have directly affected these processes, as the metabolic shift toward the formation of malting enzymes occurs later. This may explain the lack of differences in diastatic power and Kolbach index between the treatments. Although foliar supplementation increased the concentration of micronutrients in the grain, this effect did not translate into significant changes in the analyzed malting parameters. A likely explanation lies in the physiological thresholds required for micronutrients to influence key biochemical processes during grain filling. If the plant is not experiencing functional micronutrient deficiency, additional foliar supply may increase the elemental concentration in tissues without triggering measurable changes in metabolic pathways responsible for protein modification or enzyme synthesis [29,87]. Furthermore, the efficiency of foliar uptake and subsequent translocation to developing kernels varies among micronutrients. Elements such as Mn and Zn are moderately mobile in the phloem, while Cu and Fe show restricted mobility, which may limit their delivery to the grain even when leaves are adequately supplied [42]. This suggests that the applied doses may have been sufficient to correct or maintain tissue micronutrient status but not high enough to surpass the metabolic threshold necessary to affect diastatic activity, protein solubility, or extractability. Consequently, the lack of significant changes in malt quality parameters can be interpreted not as a general ineffectiveness of foliar fertilization, but as evidence that the effects of micronutrients are strongly influenced by the initial nutritional status, the needs of a given cultivar, and environmental factors during grain development. The results of the conducted research confirm the significant influence of both cultivars and the year of cultivation on the quality of malt raw material. Consistent with previous reports [88,89], cultivar differences determine basic biochemical parameters of barley grain, directly affecting its suitability for malting and beer production. The higher total protein content found in the Baryłka cultivar may indicate its greater enzymatic potential, but from a practical perspective, excessive protein can limit extractability and compromise malt wort clarity. RGT Planet, on the other hand, with its lower protein content but its highest extractability, demonstrates superior characteristics from the perspective of the brewing industry, where high extraction efficiency is crucial. KWS Irina demonstrated a balanced profile, particularly favorable in terms of Kolbach index and diastatic power, which may indicate good protein solubility and high enzymatic activity, important in mashing processes [90]. Malt extractivity is the main qualitative characteristic of malting barley grain. It determines the total amount of extractable substances that can be obtained from malt during the process of obtaining beer wort [91].

Significant qualitative differences between the study years confirm the high sensitivity of malting barley to climatic variability. It should be noted that wide variability in environmental conditions may mask the effects of foliar treatments, which may be a limitation of this study. Dry and hot climates tend to produce more protein [24]. The highest extractive yield and enzymatic activity values recorded in 2021 suggest beneficial conditions for the synthesis of amylolytic and proteolytic enzymes, which is confirmed by previous studies on the effect of atmospheric conditions on malt quality [72,92].

5. Conclusions

Under the conditions of this study, the foliar application of the examined micronutrients modified the chemical composition of the grain, and differences in the grain's elemental composition were observed depending on the treatment. Protein content (an important quality parameter) increased as a result of fertilization, particularly after molybdenum application. The higher protein levels observed following molybdenum treatment indicate that its use in malting barley should be approached with caution to avoid exceeding acceptable limits. The research hypothesis that the exogenous application of micronutrients has a significant impact on the parameters characterizing malt quality was not confirmed. The genotype and year of barley harvest had the greatest impact on the studied parameters. The RGT Planet cultivar demonstrated the highest extractive properties, while KWS Irina showed the most favorable enzymatic profile. Significant differences in grain chemical composition and malting properties were observed between years, highlighting the strong impact of environmental conditions on the tested material. The obtained results confirm the key role of cultivar selection in obtaining high-quality grain, while the effect of fertilization (particularly micronutrients) appears to be more complex and requires further detailed investigation. Considering the interactions between cultivar, fertilization, and climatic conditions allows for a better adjustment of agronomic practices to optimize grain yield and quality. A single foliar application of Cu, Mn, Mo, and Zn at the stem-shooting stage altered the mineral composition of the grain and slightly increased protein content, without a significant main effect on extractivity, Kolbach index, and diastatic power. Future research should test different doses, forms, and application timings, including later developmental stages, under multisite conditions, which remains a limitation of the present study.

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Załącznik nr 4. Oświadczenie o merytorycznym wkładzie współautora.

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Rzeszów, 23.03.2026r.
(miejscowość i data)

OŚWIADCZENIE

o merytorycznym wkładzie współautora

Oświadczam, że w pracy Stadnik B., Tobiasz-Salach R., Migut D. 2025. *Impact of foliar application of copper, manganese, molybdenum, and zinc on the chemical composition and malting quality of barley cultivars. Agronomy 15, 2667*, mój wkład był wiodący i polegał na sformułowaniu celów i zadań badawczych, opracowaniu metodyki i wykonaniu badań, zarządzaniu danymi, analizie statystycznej wyników, przygotowaniu wersji roboczej artykułu, wizualizacji danych oraz zredagowaniu pracy zgodnie z uwagami recenzentów.


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Oświadczam, że w pracy Stadnik B., Tobiasz-Salach R., Migut D. 2025. *Impact of foliar application of copper, manganese, molybdenum, and zinc on the chemical composition and malting quality of barley cultivars. Agronomy, 15, 2667* mój udział polegał na sformułowaniu celów i zadań badawczych, zredagowaniu pracy zgodnie uwagami recenzentów oraz nadzorze nad danymi, realizacją badań i publikacją artykułu naukowego.



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Oświadczam, że w pracy *Stadnik B., Tobiasz-Salach R., Migut D. 2025. Impact of foliar application of copper, manganese, molybdenum, and zinc on the chemical composition and malting quality of barley cultivars. Agronomy 15, 2667* mój udział polegał na opracowaniu metodyki badań, analizie statystycznej wyników badań, przygotowaniu wersji roboczej artykułu oraz zredagowaniu pracy zgodnie uwagami recenzentów.


.....
(podpis osoby składającej oświadczenie)