Impacts of Organic Farming on Zinc and Iron Bioavailability in Edible Crop Parts: Evidence from Long-term Field Study and Meta-analysis

by

Jing Hou

A Thesis
Submitted to the Faculty of Graduate Studies of
The University of Manitoba
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

ABSTRACT

Jing Hou, M.Sc., The University of Manitoba, June 2025. Impacts of Organic Farming on Zinc and Iron Bioavailability in Edible Crop Parts: Evidence from Long-term Field Study and Meta-analysis. Supervisors: Xiaopeng Gao, Martin H. Entz.

Zinc (Zn) and iron (Fe) deficiencies are prevalent health concerns across the world, especially in populations that rely heavily on plant-based diets. Organic agriculture is often considered one of the most promising agronomic strategies for enhancing the nutritional quality of crops. Bioavailability of micronutrients in crops were determined not only by their total concentrations, but also the presence of anti-nutritional compounds like phytate. This thesis evaluates the effects of organic farming on Zn and Fe concentrations and their bioavailability in edible crop parts through a long-term field study conducted at Glenlea, Manitoba, and a comprehensive global meta-analysis.

In the long-term field study, spring wheat (*Triticum aestivum* L.) grain produced under organic management exhibited higher Zn concentration than conventionally grown wheat, particularly when perennial crops like alfalfa were included in the rotation. Organic systems with annual-perennial crop rotation also significantly decreased grain phytate concentration, leading to enhanced bioavailability of Zn and Fe. However, these micronutrient benefits were accompanied by reduced crop yield, primarily due to phosphorus (P) limitation. While compost application significantly improved wheat productivity, it simultaneously increased grain phytate concentrations, thereby diminishing the beneficial impact on micronutrient bioavailability.

The global meta-analysis included 322 paired observations from 54 peer-reviewed studies. The results further confirmed an average increase of 14.2% in Zn concentrations in the edible parts of organically produced crops, with vegetables showing the strongest responses. No overall statistically significant increase in Fe concentrations was observed, except in high precipitation regions where organic crops showed significant higher Fe concentrations in edible crop parts. Despite these micronutrient improvements, organic agriculture exhibited an average yield penalty of 24.7%, with the most notable reduction observed for cereals and in arid regions.

Our research revealed the potential of organic agriculture to produce crops with greater micronutrient concentrations and bioavailability in their edible parts, but this nutritional advantage is frequently accompanied by significant yield trade-off. The findings underscore the necessity of integrated soil fertility and crop management strategies, such as selecting organic amendment types with higher micronutrient but lower P levels, and breeding crop ideotypes with enhanced P uptake but reduced P accumulation/translocation into crop edible parts under low soil P conditions. Overall, this thesis work provides valuable insights for guiding organic agriculture practices aimed at reducing the global micronutrient deficiencies.

Keywords: organic agriculture, zinc (Zn), iron (Fe), phytate, crop rotation, meta-analysis

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my major advisor, Dr. Xiaopeng Gao, for his insightful guidance and consistent support throughout every stage of my master’s program study. I am grateful to my co-advisor, Dr. Martin Entz, for your thoughtful advice and valuable feedback, which significantly improved the quality of my research. I appreciate the support from my committee members, Dr. Inoka Amarakoon and Dr. Nasem Badreldin, for your contributions of knowledge to my research.

I sincerely acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the GO-EC Seed Project at the University of Manitoba, which enables me to pursue my academic goals. I am also thankful to the Faculty of Graduate Studies for awarding me the International Graduate Student Entrance Scholarship.

My special thanks go to Dr. Mingyuan Yin and Dr. Wennong Kuang for their expert guidance and continuous support during the data analysis process in my Meta-analysis project. I also want to thank my fellow graduate students, summer students, technicians, and administrative staffs in the Department of Soil Science. Your encouragement and assistance made my study experience more productive and enjoyable.

Finally, I extend my deepest appreciation to my family. To my parents, thank you for always believing in me and supporting my choices. To my husband, Shengkan Lu, I am truly grateful for your encouragement, unwavering support, and for always being there for me. To Skyler and Tiana, thank you for your presence in my life, and for bringing joy and balance into it. You made this journey unforgettable and rewarding.

DEDICATION

To my family, whose enduring support and faith in me has made this possible.

FOREWORD

This thesis was prepared in manuscript format, following the guidelines of the Department of Soil Science at the University of Manitoba. It consists of four chapters. Chapter 1 presents a literature review on zinc (Zn) and iron (Fe) uptake, transport, and accumulation in crops, factors influencing their availability, and the bioavailability of these two micronutrients for human nutrition. Chapter 2 and 3 are research manuscripts prepared for submission to peer-reviewed journals. Chapter 2 evaluates the effects of organic farming and crop rotation on Zn and Fe bioavailability in wheat grains from the Glenlea Long-term Rotation Study. Chapter 3 presents a global meta-analysis examining the effects of organic and conventional agricultural practices on Zn and Fe concentrations in edible crop parts. The analysis considers crop type, soil characteristics, and climate conditions as moderators to explore how these factors influence micronutrient concentrations across agricultural systems. Chapter 4 integrates the key findings from Chapter 2 and 3, discusses their limitations and broader implications, and proposes recommendations for future research to enhance micronutrient concentrations in organically grown crops.

Publication based on Chapter 2:

Hou, J., Gao, X., & Entz, M. H. (2025). Enhancing zinc and iron bioavailability through crop rotation and organic farming: Insights from a long-term study. *Field Crops Research*, 322, 109710. https://doi.org/10.1016/j.fcr.2024.109710

Publication based on Chapter 3:

Hou, J., Gao, X., & Entz, M. H. (2025). Organic agriculture enhances zinc concentrations in edible crop parts: A global meta-analysis. *Field Crops Research* (under review).

CONTRIBUTION OF AUTHORS

The contributions of the authors for Chapter 2 and 3 are as follows:

- Jing Hou: conducted experiments, collected and analyzed data, interpreted results, prepared figures and tables, wrote the initial manuscript drafts.
- Xiaopeng Gao: Conceptualized the experiments, acquired funding, provided major supervision for the project, reviewed and revised manuscript drafts.
- Martin H. Entz: Conceptualized the experiments, supervised the project, reviewed and revised manuscript drafts.

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Chapter 1. Literature Review

1.1 Introduction

Zinc (Zn) and iron (Fe) are essential micronutrients for plant development and human health. In plants, they are involved in key metabolic processes, such as photosynthesis, respiration, the synthesis of chlorophyll and carotenoid (Negi et al., 2021). In humans, Zn is required for the activity of numerous enzymes and supports a wide range of biochemical, immunological and clinical functions (Knez and Graham, 2013). Iron is found in two protein forms in the human body: hemoglobin in red blood cells and myoglobin in the muscle tissues that help to accept, carry and release oxygen. It contributes to oxygen transport, oxidative metabolism, and cellular growth (Knez and Graham, 2013).

However, Zn and Fe deficiencies represent widespread health challenges in both developing and developed countries. It is estimated that more than 30% of the global population is affected by Zn deficiency, and more than 60% suffers from Fe deficiency (White and Broadley, 2009). The regions with the highest prevalence of inadequate dietary Zn intake and Fe deficiency anemia are South Asia and Sub-Saharan Africa (Mwangi et al., 2021; Berhe et al., 2019). Several intervention strategies, including supplementation, food fortification, dietary diversification, have been used to alleviate the micronutrient deficiency problem. Among these strategies, biofortification is considered as the most promising intervention due to its low cost and sustainability. It is particularly important in developing countries, where micronutrient deficiencies are prevalent and access to other interventions is often limited.

Biofortification of food crops with Zn and Fe can be achieved through two main approaches: genetic biofortification and agronomic biofortification. Genetic biofortification involves increasing micronutrient concentrations in crops via conventional plant breeding or genetic engineering. Agronomic biofortification refers to optimizing agricultural management practices to enhance micronutrient concentrations, such as fertilization, crop rotation, soil moisture management, tillage and organic farming (Lagoriya et al., 2023).

1.2 Crop uptake, transport, and accumulation of Zn and Fe

The effective implementation of crop biofortification requires a fundamental understanding of the mechanisms regulating the uptake, transport, and accumulation of Zn and Fe in plants. Zinc is the second most abundant transition metal in organisms after Fe, and the only metal identified in all six classes of enzymes (oxidoreductases, transferases, hydrolases, lyases, isomerases, ligases) (Broadley et al., 2007). Zinc is taken up by plant roots mainly as divalent cation (Zn^{2+}), sometimes it can also be absorbed in the form of organic ligand-Zn complexes (Gupta et al., 2016; Broadley et al., 2007). In plant roots, Zn^{2+} is transported radially through tissues including epidermis, cortex, endodermis, and pericycle before reaching the xylem for transport to shoot. Zinc ions move through the root tissues via symplastic and apoplastic pathways, and it is assumed that most Zn^{2+} is transported symplastically across the root to the xylem (White and Broadley, 2009). Within the xylem sap, metal ions such as Zn^{2+} and Fe^{2+} can be transported in the ionic form or as metal complexes with histidine, nicotianamine (NA), and organic acids, facilitating micronutrient movement from roots to aerial plant tissues (White and Broadley, 2009). Zinc can then be unloaded from the xylem for utilization and storage in leaves or loaded into the phloem for remobilization to developing leaves and seeds. The pH of the phloem sap promotes the formation of NA-Zn^{2+} and NA-Fe^{2+} complexes, enabling their transport within the plant (Huertas et al., 2022).

Although Fe is the fourth most abundant element in the earth’s crust, it primarily exists as Fe^{3+}, a form with limited solubility and availability to plant roots. Plants have evolved two strategies to acquire Fe from the soil. Strategy I is a reduction-based mechanism employed mainly by non-graminaceous plants, and strategy II is a chelation-based mechanism used by graminaceous plants (Kim and Guerinot, 2007; Kobayashi et al., 2019). In strategy I, plants release protons (H^+) into the rhizosphere, decreasing soil pH and enhancing the solubility of Fe^{3+}. Ferric reduction oxidase 2 (FRO2) then reduces Fe^{3+} to Fe^{2+} at the root surface, after which Fe^{2+} is taken up by plant root via the iron-regulated transporter 1(IRT1). In strategy II, plants secrete phytosiderophores (PS), such as mugineic acid (MA), which chelate Fe^{3+} to form soluble complex in the rhizosphere. These Fe^{3+}-PS complexes are taken up into plant root by transporters like yellow stripe 1 (YS1) and yellow stripe 1-like (YSL) transporters (Kobayashi and Nishizawa, 2012; Kim and Guerinot, 2007).

Once inside the root cell, Fe forms complexes with chelators such as NA, MA, and citrate. This chelation prevents harmful redox reactions associated with soluble Fe^{2+} and improves the mobilization of Fe^{3+} (Connorton et al., 2017; Kobayashi et al., 2019). Chelated Fe then moves radially through the root symplast toward the vascular tissue, particularly the xylem. Although the mechanisms underlying long-distance Fe transport are not fully understood (Shahzad et al., 2014), Fe^{3+}-citrate complexes are generally considered the dominant Fe form in the xylem sap (White and Broadley, 2009; Kobayashi and Nishizawa, 2012). Iron also exists in a chelated form in the phloem to maintain solubility during transport. This is essential to prevent precipitation of ionic Fe^{2+} and Fe^{3+}, which are insoluble under the slightly alkaline pH (above 7) of the phloem sap (Kim and Guerinot, 2007). After being delivered to sink tissues via the phloem, Fe is stored through two primary mechanisms: sequestration into vacuoles and incorporation into ferritin (Connorton et al., 2017). Ferritins are Fe storage proteins of plant cell that play a central role in maintaining Fe homeostasis and preventing oxidative damage. In addition to intracellular storage, the distribution of Zn and Fe across plant tissues also influences their nutritional value. For example, in cereal grains like wheat and rice, most Zn and Fe are concentrated in the aleurone layer, which is usually removed during grain milling. Therefore, understanding nutrient uptake and transport in plants is essential to improving their bioavailability for human consumption.

1.3 Factors influencing Zn and Fe availability

1.3.1 Soil characteristics

The availability of Zn and Fe to plants depends largely on soil characteristics, such as pH, redox potential, texture and moisture conditions. Globally, approximately 30% of soils are Zn-deficient (Prasad et al., 2014), and up to 50% of wheat-cultivated soils worldwide are low in plant available Zn (Cakmak and Kutman, 2018). Zinc deficiency is typically observed in calcareous soils with high pH and semi-arid climate (Alloway, 2008). The availability of micronutrients such as Zn and Fe is greatly influenced by soil pH, with their solubility declining at higher pH levels due to increased sorption and precipitation reactions. Each unit increase in soil pH between 5.5 and 7.0 reduces Zn concentration in soil solution by 30 to 50-fold, severely limiting its availability to plants (Marschner, 1993). Therefore, the common practice of liming acidic soils to promote crop growth could lead to decreased availability of Zn and Fe.

Movement of Zn and Fe from soil solution to root surface occurs primarily through diffusion, a process that is strongly dependent on soil moisture (Cakmak, 2008). In regions such as Australia, Turkey, and several Asian countries, Zn deficiency in wheat frequently occurs due to limited soil moisture caused by inadequate and inconsistent rainfall (Cakmak and Kutman, 2018). Maintaining sufficient soil moisture is essential to improve Zn solubility and facilitate its diffusion in soil, thus minimizing the risk of water stress-induced Zn deficiency (Alloway, 2009). Prolonged waterlogging or flooding creates anaerobic conditions, increasing the risk of Zn deficiency in crops (Alloway, 2008). On the other hand, excessive soil moisture or waterlogged conditions decrease soil redox potential, facilitating the reduction of Fe^{3+} to Fe^{2+}, which is more soluble. However, excessive uptake of Fe^{2+} may cause Fe toxicity, resulting in damage to plant cell membranes and significantly reduced crop growth and yield, especially in paddy rice systems (Alloway, 2008; Harish et al., 2023).

Improving soil properties through the application of animal manure and plant residues can effectively enhance the availability of Zn and Fe to plants (Prasa et al., 2014). In addition, sandy soils with low organic matter content and high permeability typically exhibit low total and plant-available Zn and Fe, resulting in reduced nutrient availability and adverse effects on crop growth and productivity.

1.3.2 Agricultural management practices

Agronomic practices, including fertilization, crop rotation, tillage, and organic farming can effectively enhance the availability and uptake of essential nutrients from the soil. Among these practices, soil and foliar fertilization are particularly important for increasing Zn and Fe concentrations in food crops. Zinc sulphate ($ZnSO_4 \cdot 7H_2O$) is the most commonly used Zn fertilizer, while other forms such as Zn chloride ($ZnCl_2$), Zn nitrate ($Zn(NO_3)_2$), and chelated Zn compounds are also employed (Alloway, 2009). Commonly used Fe fertilizers include ferrous sulfate ($FeSO_4 \cdot 7H_2O$) and chelated forms such as Fe-EDTA, Fe-DPTA, and Fe-EDDHA. Numerous studies have demonstrated that both soil and foliar application of Zn fertilizers effectively increased Zn concentrations in cereal, pulse, oilseed, vegetable and fruit crops (Avnee et al., 2023). Foliar application of Zn fertilizer during the reproductive stage is particularly effective in improving Zn concentration and bioavailability in wheat grain (Cakmak, 2008). Compared to Zn, soil application of Fe fertilizers has generally shown minimal to no impact on increasing Fe concentration in cereal grain (Shahzad et al., 2014). In contrast, foliar application of Fe fertilizers has been shown to effectively increase both grain yield and Fe concentration in wheat (Zeidan et al., 2010). Compared to a control treated with deionized water, foliar spraying of $FeSO_4$ and DTPA-Fe increased Fe concentration in polished rice grain by 11.1% and 20.4%, respectively (He et al., 2013). The combined foliar application of Zn and Fe (0.5% $ZnSO_4$ and 1% $FeSO_4$) has been reported to improve yield-related traits and grain quality parameters in wheat. Therefore, this integrated approach is recommended as an effective strategy to simultaneously enhance both grain nutritional quality and wheat productivity (Ramzan et al., 2020; Zhang et al., 2010).

Nitrogen (N) and phosphorus (P) fertilization are widely used to maximize crop productivity. It is generally reported that Zn and Fe interact positively with N and negatively with P (Prasad et al., 2014). Adequate N supply promotes protein synthesis, and since protein serves as a major sink for Zn and Fe, this leads to increased accumulation of these micronutrients in cereal grains (Kutman et al., 2010; Cakmak et al., 2010). Improved N supply significantly increased shoot and grain Zn content in wheat, indicating that N and Zn act synergistically in enhancing Zn accumulation (Kutman et al., 2010). High N availability promotes the abundance and activity of Zn transporter proteins and nitrogenous compounds which facilitate root uptake, shoot transport, and seed deposition of Zn (Wang et al., 2014). In contrast, high application rates of P fertilizer have been frequently documented as a primary cause of low Zn concentrations in cereal crops due to an antagonistic interaction between these two nutrients (Yu et al., 2020). This antagonism may occur through the formation of insoluble Zn-phosphate complexes in soil, which significantly reduce Zn solubility and availability to plants (Wang et al., 2014). Furthermore, elevated soil P levels may indirectly limit Zn uptake by suppressing root colonization with arbuscular mycorrhizal fungi (AMF) (Wang et al., 2014; Ryan et al., 2008; Xu et al., 2020).

Considering the influence of N and P on micronutrient availability in soil, crop rotation serves as a vital approach to manage nutrient availability and sustain soil fertility. Diversified crop rotation enhances soil health through improving soil structure, increasing soil organic matter content, and creating favorable conditions for mycorrhizal colonization (Stangoulis and Knez, 2022). For example, maize grown after deep-rooted forage crops like alfalfa exhibited greater N uptake and improved acquisition of essential micronutrients such as Zn, copper (Cu), and magnesium (Mg) compared to continuous maize cropping systems (Ma and Zheng, 2018). Another long-term study found that bioavailable Zn and Cu levels in soil are higher in cereal-legume rotation than continuous maize after 18 years of cropping (Wei et al., 2006).

The use of organic farming practices along with diversified crop rotation provides additional benefits to soil quality and crop productivity. Organic nutrient management relies on compost, green manure, and other organic amendments instead of synthetic fertilizers, which can enhance soil microbial activity, promote nutrient cycling and increase micronutrient availability (Venkatesh et al., 2017). Although organic systems tend to yield less than conventional systems, they are usually more profitable, environmentally friendly, and produce food with equal or higher nutritional value and lower pesticide residues (Reganold and Wachter, 2016).

1.4 Bioavailability of Zn and Fe in crops

Bioavailability refers to the proportion of a nutrient that is effectively digested, absorbed, and utilized for physiological and metabolic processes in the human body (Welch and Graham, 2004; Akhtar et al., 2018). The bioavailability of micronutrients is affected not only by their contents, but also by their interactions with other nutrients, and the presence of absorption inhibitors and promoters (Akhtar et al., 2018). Zinc absorption from the diet ranges from 15% to 35%, primarily influenced by the amount of Zn consumed and the level of dietary phytate (Gibson, 2012). Iron in the human diet exists primarily in two forms: heme Fe, derived from animal sources, and non-heme Fe, which is mainly found in plant-based foods such as cereals, legumes, fruits, and vegetables. Although heme Fe intake is usually lower, it is two to three times more bioavailable (15%-35%) than non-heme Fe (2-20%), and its absorption is less affected by other dietary factors (Akhtar et al., 2018).

Cereal and legume grains are major dietary sources of Zn and Fe. However, the bioavailability of these micronutrients from plant-based foods is generally lower than animal-based diets. Specifically, only about 5-10% of Fe and 25% of Zn from cereal and legume seeds are bioavailable (Bouis and Welch, 2010). The low bioavailability of Zn and Fe from plant-based foods can be improved by reducing the levels of absorption inhibitors or increasing dietary enhancers that promote their uptake.

1.4.1 Absorption inhibitors

It is well recognized that phytate (myo-inositol hexakisphosphate), the dominant P storage form in crop seeds, is a major inhibitor of Zn and Fe absorption and is commonly present in cereal grains, legumes and nuts. It strongly binds to divalent and trivalent mineral cations, forming insoluble complexes that limit their bioavailability. Zinc bioavailability is particularly influenced by phytate. Similarly, non-heme Fe absorption is significantly reduced in the presence of phytate. Several studies have demonstrated that phytate lead to a 12 to 15-fold decrease in Zn and Fe absorption (Knex and Graham, 2013). The phytate to mineral molar ratios are important indicators of mineral bioavailability in human foods. A phytate to Zn molar ratio above 15:1 considerably inhibits Zn absorption and leads to suboptimal Zn status in humans (Lopez et al., 2002). A phytate to Fe molar ratio exceeding 1:1 adversely affects Fe absorption and maintaining this ratio below 0.4:1 significantly improves Fe bioavailability in cereal and legume-based diets (Hurrell and Egli, 2010; Tako et al., 2016). In addition to phytate, polyphenols also contribute to reduced Zn and Fe bioavailability by forming insoluble complexes, thereby amplifying the inhibitory effect. Dietary fiber can further impair Zn and Fe absorption by forming insoluble complexes and accelerating their movement through gastrointestinal tract, thus limiting the available time for mineral absorption (Akhtar et al., 2018; Knez and Stangoulis, 2023).

Given the strong inhibitory effect of phytate on mineral absorption, various phytate reduction strategies have been developed to enhance Zn and Fe bioavailability. Traditional thermal and mechanical food processing methods, including heating, soaking, germination, and fermentation, can effectively decrease phytate and tannin content, hence increasing the bioavailability of micronutrients from foods (Singh and Prasad, 2023). Humans, like other monogastric animals, lack the phytase enzyme required for phytate degradation (Shahzad et al., 2014). As a result, the addition of exogenous phytase during food processing or immediately before human consumption is anticipated to positively affect mineral bioavailability (Huertas et al., 2022).

1.4.2 Absorption Enhancers

Many studies have reported that chemical compounds, such as ascorbic acid, citric acid and other organic acids, significantly enhance the bioavailability of Zn and Fe (Nielsen et al., 2013; Akhtar et al., 2018). Ascorbic acid promotes Fe absorption by converting Fe^{3+} to Fe^{2+} and preventing the precipitation of Fe as ferric hydroxide. It also forms a stable and soluble ferric ascorbic acid chelate, thus maintaining Fe in a bioavailable form under high pH conditions (Akhtar et al., 2018). These reducing and chelating properties make ascorbic acid the most efficient enhancer of non-heme Fe absorption (Lopez et al., 2002; Singh and Prasad, 2023). The beneficial roles of ascorbic acid and citric acid on Fe absorption have been reported to be additive, which explains the relatively high Fe bioavailability observed when consumed with citrus fruits and juices (House, 1999). Additionally, ethylenediaminetetraacetic acid (EDTA) can enhance Fe absorption especially from phytate-rich foods (Hurrell, 2004). It may also improve Zn absorption when used at EDTA to Zn molar ratios greater than 1(Brown et al., 2007).

1.5 Research gaps and thesis objectives

Organic agriculture is widely promoted as a sustainable approach to improving soil health, conserving biodiversity, and enhancing ecological resilience through reduced reliance on synthetic fertilizers and chemical pesticides. Most existing comparative studies of organic and conventional agriculture have predominantly focused on yield performance, soil organic matter, macronutrient availability, and other soil health indicators. Nevertheless, the long-term effects of organic agriculture and crop rotation on the concentration and bioavailability of Zn and Fe remain unclear. Further research is needed to fully elucidate how sustained organic management and diversified crop rotation influence crop nutritional quality.

Moreover, existing research comparing organic versus conventional agriculture has often revealed inconsistent findings on Zn and Fe concentrations in crops. The variability is often attributed to differences in crop species, soil properties, agronomic practices, and climate conditions. Therefore, a global and systematic meta-analysis is essential to quantitatively determine the specific conditions that lead to increased Zn and Fe concentrations in edible crop parts.

This thesis aims to address these research gaps by exploring the impact of organic agriculture on crop nutritional quality through two related studies. The specific objectives are: (i) to evaluate the long-term effects of organic farming and diversified crop rotation on Zn and Fe concentrations and bioavailability in wheat grain (Chapter 2); and (ii) to systematically assess how soil properties, crop type and environmental conditions influence Zn and Fe concentrations and crop yield between organic and conventional agriculture (Chapter 3). The outcomes from this research will provide valuable insights to support sustainable management strategies within organic agriculture, which will contribute to the mitigation of global micronutrient deficiencies.

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Chapter 2. Enhancing Zinc and Iron Bioavailability through Crop Rotation and Organic Farming: Insights from A Long-term Study

2.1 Abstract

Agronomic biofortification of Zinc (Zn) and iron (Fe) in cereal grains is a critical strategy to address human deficiencies in these micronutrients. Our study examined the effects of crop rotation and farming system on Zn and Fe bioavailability in wheat grains, using data from 2011 to 2020 from the Glenlea Long-term Crop Rotation Study, Canada's longest running study on organic farming. Two crop rotations, continuous annual (spring wheat, flax, oat, soybean) and annual-perennial (spring wheat, flax, alfalfa, alfalfa), managed both organically and conventionally, were fully phased. Compared to conventional farming, organic farming significantly increased grain Zn concentration in six out of ten years, with no significant effect on grain Fe. Additionally, grain Zn was also significantly higher in the annual-perennial rotation compared to the annual rotation in seven of the ten years. A significant interactive effect was observed for grain phytate, which was approximately 35% lower in the annual-perennial rotation under organic farming than in other treatments. Consequently, the diversified rotation under organic farming significantly reduced the phytate/Zn and phytate/Fe molar ratios, indicating enhanced micronutrient bioavailability for human consumption. However, these effects were strongly associated with reduced phosphorus (P) availability in organic systems, particularly following alfalfa, which limited grain yields. Livestock manure-based compost application improved grain yield and nutrient uptake, but reduced Zn/Fe bioavailability due to increased phytate accumulation. This study demonstrates that diversified crop rotation and organic farming could improve micronutrient bioavailability, but at a cost of lower grain production tied to reduced P availability.

2.2 Introduction

Zinc (Zn) and iron (Fe) are essential micronutrients for the growth and development of plants, animals, and humans. In plants, Zn serves as a functional, structural or regulatory co-factor for numerous enzymes and proteins involved in critical biochemical processes. In animals and humans, approximately 3,000 proteins, or 10% of all proteins, require adequate Zn for their optimal function (Cakmak and Kutman, 2018). Zinc is a critical component in all six classes of enzymes including oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases (Barak and Helmke, 1993). Similarly, Fe is an integral part of hemoglobin and myoglobin, where it is directly involved in oxygen transport, DNA synthesis, enzymatic functions, and energy production. Malnutrition resulting from Zn and Fe deficiencies, commonly referred to as "hidden hunger", represents one of the most significant global health challenges. It is estimated that over 60% of the global population is affected by Fe deficiency, while more than 30% are suffering from Zn deficiency (White and Broadley, 2009). According to Hotz and Brown (2004), about one-third of the global population lives in countries at high risk for Zn deficiency, leading to approximately 1.1 billion people are at risk, with 90% residing in Asia and Africa (Kumssa et al., 2015).

The primary cause of Zn and Fe deficiencies is inadequate dietary intake, particularly in regions where people rely heavily on cereal-based foods that have lower Zn and Fe concentrations, and bioavailability compared to animal-based foods. Cereal crops naturally have low Zn and Fe concentration and cultivating them on nutrient-deficient soil further reduces their bioavailability in grains (Cakmak, 2008). Wheat (*Triticum aestivum* L.), the most extensively grown cereal crop in the world, provides 70% of daily calorie intake and feeds around 40% of the world's population (Giraldo et al., 2019). Despite being the most traded commodity globally, wheat is considered a poor source of minerals, particularly Zn, Fe, and vitamins. A meta-analysis of 109 studies reported that Zn concentrations in wheat grain from major wheat-producing regions around the world vary from 20.4 to 30.5 mg kg^{-1} with an average of 27.3 mg kg^{-1} (Chen et al., 2017), far below the target level of 40-60 mg kg^{-1} to meet needs of human body (Cakmak, 2008). Minerals in wheat grain are concentrated in the aleurone layer, which is usually removed during milling, resulting in refined flour with only small amounts of Zn and Fe. Bioavailability of micronutrients such as Zn and Fe is further impacted by presence of phytate, which is the dominant storage form of phosphorus (P) in cereal grains and binds micronutrients strongly to prevent their absorption by the human digestive system. The phytate to Zn or Fe molar ratio has been generally used to categorize their bioavailability (Bouis and Welch, 2010).

Several strategies are employed to tackle micronutrient deficiency, including supplementation, food fortification, dietary diversification, and biofortification. Supplementation provides nutrients directly in the form of chemical or pharmaceutical products. Food fortification involves adding nutrients to commonly consumed foods, beverages or condiments to increase their nutrient contents, such as iodized salt. Dietary diversification focuses on expanding the variety of nutrient-rich foods consumed to improve overall nutritional intake. These strategies, however, often face challenges related to accessibility and affordability, particularly in remote or impoverished regions where dietary options are limited. Biofortification, which increases nutrient levels in edible plant parts through agricultural practices, could offer a more sustainable solution to global nutritional deficiencies. For Zn biofortification in food crops, a combination of conventional breeding, genetic engineering, and agronomic practices like soil amendments and fertilization is typically used (Yadav et al., 2023; Younas et al., 2023). Compared to breeding or genetic approach, the agronomic approaches provide a timesaving, economical, and effective solution to improving Zn bioavailability in cereal grains, along with increased grain yield (Zou et al., 2012; Zulfiqar et al., 2020). Many studies have demonstrated that soil and foliar Zn fertilization effectively improved wheat grain Zn concentration and bioavailability (Rehman et al., 2018; Erdal et al., 2002; Cakmak 2008; Wang et al., 2015). In contrast, the impact of crop rotation and farming system management on micronutrient biofortification in crop grain has not been extensively explored.

Organic farming can influence the concentration and uptake of micronutrients in crop grains through its practices of soil management, crop rotation, and the avoidance of synthetic fertilizers. Specifically, organic farming often promotes more diverse crop rotation and the use of natural sources like compost and manure, which can enhance soil organic matter and microbial activity. These factors may improve the availability of micronutrients in the soil, leading to higher uptake by plants. However, the effects of organic farming on grain Zn concentration are not always consistent, as they can vary depending on soil type, crop variety, and specific management practices. For example, a study by Ryan et al. (2004) found that organic grown wheat grain had higher Zn concentrations compared to conventionally grown wheat, which was attributed to increased mycorrhizal colonization in organic systems. Similarly, Nelson et al. (2011) reported higher Zn concentrations in wheat grown organically on the Canadian Prairies, with effects varying by wheat cultivar. Preliminary results from the same site as the current study showed that wheat produced organically in the perennial rotation had higher Zn than annual rotation, whereas there was no crop rotation effect when wheat was produced conventionally (Turmel et al., 2009). Conversely, Mäder et al. (2007) reported no significant differences in Zn concentration between organic and conventional wheat after a 21-year field experiment, despite 14% lower yields in the organic system; this indicated that grain Zn differences between the two systems was not related to yield dilution. In addition to Zn, it has also been documented that Fe levels in organically produced crops are 21% greater than in conventionally grown crops (Rembiałkowska, 2007).

However, other studies have found no significant differences in the nutrient quality between organically and conventionally produced food (Dangour et al., 2009; Smith-Spangler et al., 2012). These inconsistent results indicates that while organic farming has the potential to enhance grain Zn and Fe levels, the outcomes may vary depending on the specific rotation and environmental conditions. Moreover, none of these studies have investigated how these agricultural practices affect grain phytate levels and their impact on Zn and Fe bioavailability. Therefore, to fully understand the nutritional impact of different farming systems and crop rotations, future research should explore the relationship between Zn/Fe concentration and phytate levels in crop grains.

The Glenlea Long-term Crop Rotation Study Site, established in 1992, is Canada's longest-running organic farming systems field plots. The present study, conducted as part of this long-term research, aims to investigate how farming systems and crop rotations affect Zn and Fe bioavailability in wheat grain. The specific objectives are 1) to compare micronutrient bioavailability of wheat grain produced organically versus conventionally; 2) to evaluate the differences in micronutrient bioavailability between wheat grown under annual crop rotation and annual-perennial crop rotation; 3) to examine the relationships between grain Zn levels and other mineral nutrients, grain protein, and crop yield, as influenced by different farming systems and crop rotation strategies; and 4) to understand whether correcting P deficiencies in organic production would compromise Zn and Fe bioavailability due to increases in P availability.

2.3 Materials and Methods

2.3.1 Experimental site and design

The Glenlea Long-term Crop Rotation Study Site (N 49.39.0, W 97.7.0) is located in the Red River Valley in Southern Manitoba, Canada. The site lies within a glaciolacustrine clay floodplain of near-level topography (0 to < 2% slope) and has an extreme humid-continental climate (Köppen *Dfb)*. The soils at this site are classified as Gleyed Humic Vertisols under the Canadian soil classification system and as Typic Humicryerts under the US system, with a clay texture (65% clay, 26% silt and 9% sand).

The experimental design included two crop rotations: annual (oat-soybean-spring wheat-flax) and annual-perennial (spring wheat-flax-alfalfa-alfalfa), both of which were managed under organic and conventional systems. These rotations were fully phased each year across three replicate blocks from 2011 to 2020, during which data for the present study were collected. Under organic management, no synthetic fertilizer herbicide or pesticide were used, whereas under conventional management, fertilizer application followed soil tests and local recommendations for each crop rotation. The experiment employed a randomized complete block design in a split-plot arrangement, where crop rotation served as the main plot and the farming system as the subplot. The plot size for organic systems were 12 m by 4 m, while the conventional systems had a plot size of 28 m by 4 m. Seeding rates were typically 165 kg ha^{-1} for the organic plots and 125 kg ha^{-1} for the conventional plots, with occasional adjustments made depending on spring conditions. The spring wheat cultivar used in this experiment was Cardale, a semi-dwarf hard red cultivar released in 2011 by Agriculture and Agri-Food Canada (Fox et al., 2013). Additionally, a comparison of compost and non-compost treatments was implemented within the annual-perennial crop rotation under the organic farming to evaluate their effects on crop productivity and micronutrient bioavailability. The compost treatment involved the annual application of composted beef cattle manure to achieve a target rate of 80 kg ha^{-1} of P in the soil from 2011 to 2020. Throughout the study years, same source of beef solid manure was used for the compost. The total N content ranged from 0.54% to 0.84%, P_2O_5 ranged from 0.65% to 0.91%, K_2O ranged from 1.1% to 3.9%, total Zn ranged from 65 mg kg^{-1} to 219 mg kg^{-1}, and total Fe ranged from 6,176 mg kg^{-1}

to 9,100 mg kg^{-1}. Total N was reported on an as-received basis for solid manure, while other nutrients were reported on a dry-mass basis. All analyses were conducted by Agvise Laboratories (Northwood, ND, USA). Herbicide and pesticide were applied at the recommended rates in the conventional plots only.

2.3.2 Analysis of grain samples for nutrient concentration

Wheat grain was harvested using a custom plot combine in late August or early September, depending on crop maturity and weather conditions. Harvested grain samples were dried on specialized drying beds, cleaned using a Carter Day dockage tester, and then determined for dry yield. Subsequently, a representative sample was finely ground using a zirconium ball mill, and then digested using a mixture of sulfuric acid and hydrogen peroxide (Westman, 1990). Briefly, 0.4 g of ground wheat grain was added to 4.4 mL of acid solution, left at room temperature for 1 hour, then digested for 1 hour at 100°C followed by 2 hours at 350 °C. Nitrogen (N) in the digest solution was determined using a Technicon Autoanalyzer II (Technicon Industrial Systems, Tarrytown, NY, USA). Other nutrients, including Zn, Fe, P, Mg, Mn and Cu were analyzed using an ICP-MS (Agilent 7850, Agilent, Santa Clara, USA). Grain protein concentration was calculated assuming a protein to N ratio of 6.25.

2.3.3 Analysis of grain samples for phytate concentration and Zn/Fe bioavailability

Grain phytate was determined according to Haug and Lantzsch (1983), with slight modifications. Finely ground wheat grain samples (0.15 g each) were extracted in 25 mL of 0.2 N HCl. The solutions were vortexed, and 0.5 mL of each solution was transferred to 2 mL centrifuge tube, followed by the addition of 1 mL ferric solution. The mixtures were heated in a water bath at 100°C for 30 minutes, then immediately cooled in an ice water bath for 15 minutes before returning to room temperature. After centrifugation at 5,700 rpm for 30 minutes, 1 mL of supernatant was mixed with 1.5 mL of 2,2’-bipyridine solution (prepared by dissolving 5 g of 2,2’-bipyridine and 5 mL of thioglycolic acid in deionized water, then diluted to 500 mL). Phytate concentration was measured by the decrease in absorbance of the pink color developed by unreacted Fe with 2,2’-bipyridine at 519 nm using a UV/visible spectrophotometer (Ultrospec 2100 pro, GE Healthcare, UK). All grain samples for nutrient and phytate determinations were prepared and analyzed in triplicates. Grain nutrient and phytate uptake were calculated by multiplying grain yield with their respective concentrations. Molar ratios of phytate to Zn or Fe were calculated to estimate the bioavailability of Zn and Fe in wheat grain, with lower ratios indicating higher bioavailability.

$$\text{Phytate:Zn molar ratio}=\frac{(\text{phytate concentration in mg kg}^{-1})/660.04}{(\text{Zn concentration in mg kg}^{-1})/65.38}$$

$$\text{Phytate:Fe molar ratio} = \frac{(\text{phytate concentration in mg kg}^{-1})/660.04}{(\text{Fe concentration in mg kg}^{-1})/55.85}$$

2.3.4 Statistical analysis

Data analysis was conducted using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). An initial three-way analysis of variance (ANOVA) was performed with the Mixed procedure, treating farming system and crop rotation as fixed effects and year as a random effect. For each individual year, a two-way ANOVA was applied to evaluate the main and interactive effects of farming system and crop rotation. When significant main or interactive effects were detected, means were compared using Tukey’s Honestly Significant Differences test. Differences between compost and non-compost treatments within the annual-perennial crop rotation under the organic farming system were assessed using a paired t-test. Linear regression was used to examine relationships between measured parameters. In all analyses, statistical significance was set at a 5% probability level.

2.4 Results

2.4.1 Impact of farming system and crop rotation on grain nutrients, protein and yield

Wheat grain yield and nutrient concentrations of Zn, Mg and P were significantly ($p < 0.05$) affected by farming system, crop rotation, year and their interactions (Table 2.1). Grain protein concentration was significantly ($p < 0.05$) affected by crop rotation and year. Additionally, grain Cu concentration varied across years, and was significantly ($p < 0.05$) impacted by the interactions between farming system and crop rotation. In contrast, grain Fe concentration differed between years but did not show significant response to farming systems, crop rotation, or their interactions. Grain Mn concentration was only affected by the three-way interaction among farming system, crop rotation and year, but was not significantly affected by each factor individually.

Compared to conventional farming, organic farming exhibited significantly ($p < 0.05$) higher Zn concentrations in wheat grain in six out of ten years (Table 2.2). Across the study period, grain Zn concentrations ranged between 25.6 and 36.9 mg kg^{-1} for the organic system, and between 19.7 and 31.7 mg kg^{-1} for the conventional system. The 10-year average Zn concentration in the organic system was 16.9% higher than that in the conventional system. Wheat in the annual-perennial rotation had significantly ($p < 0.05$) higher grain Zn concentrations than that in the continuous annual rotation in seven out of ten years. As a result, the 10-year average grain Zn in the annual-perennial rotation was 19.6% higher than that in the annual rotation. In six out of ten years, grain Zn was significantly ($p < 0.05$) affected by an interaction between farming system and crop rotation, where the combination of organic system and annual-perennial rotation consistently had the highest grain Zn concentrations.

Table 2.1. *p*-values of three-way ANOVA evaluating the effect of farming system (FS), crop rotation (CR) and year (Y) on wheat grain nutrient concentrations, protein and yield from the Glenlea Long-term Crop Rotation study over 2011–2020.

Source	DF	Mg	P	Mn	Fe	Cu	Zn	Protein	Yield
FS	1	**<0.0001**	**<0.0001**	0.0696	0.5236	0.5720	**<0.0001**	0.9208	**<0.0001**
CR	1	**<0.0001**	**<0.0001**	0.1720	0.1899	0.3155	**<0.0001**	**0.0046**	**<0.0001**
Y	9	**<0.0001**	**<0.0001**	0.0962	**<0.0001**	**0.0043**	**<0.0001**	**<0.0001**	**<0.0001**
FS × CR	1	**<0.0001**	**<0.0001**	0.3304	0.7398	**0.0131**	**<0.0001**	0.9353	**0.0003**
FS × Y	9	**<0.0001**	**0.0011**	0.1023	0.4329	**0.0370**	**0.0347**	0.7687	**0.0396**
CR × Y	9	0.2601	0.1433	0.1985	0.7794	0.0692	0.2956	0.1626	**0.0024**
FS × CR × Y	9	**0.0189**	**0.0210**	**0.0475**	0.7284	0.1984	**0.0197**	0.7208	**0.0394**

There was a large variation in grain Fe concentration among different years, ranging from 25.5 to 71.1 mg kg^{-1} over the 10-year study period, with relatively higher values observed in 2017 and 2018 compared to other years (Table 2.3). Farming system, crop rotation and their interaction did not influence grain Fe concentration in any individual year ($p > 0.05$), except for 2016, where the annual-perennial rotation exhibiting significantly ($p < 0.05$) higher Fe concentration compared to the annual rotation.

Table 2.2. Effect of farming system (FS) and crop rotation (CR) on wheat grain Zn concentration at the Glenlea Long-term Crop Rotation study site over 2011–2020.

	Grain Zn concentration (mg kg^{-1})										
Treatment	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2011-2020
FS											
Org.	27.9±1.6 a	28.5±2.4 a	25.6±1.5 a	25.6±2.1 a	26.9±1.7 a	27.2±1.1 a	29.1±2.9 a	31.5±3.4 a	30.8±2.6 a	36.9±1.9 a	29.0±0.8 a
Conv.	22.5±2.2 a	22.2±0.6 b	23.3±0.7 b	21.9±0.4 b	25.3±0.5 a	25.0±0.4 b	19.7±0.6 b	29.4±1.3 b	27.1±1.1 a	31.7±0.9 b	24.8±0.5 b
CR											
A.	22.9±2.3 a	22.4±0.8 b	22.4±0.6 b	21.5±0.5 b	24.3±0.6 b	24.7±0.5 b	21.8±1.5 b	26.4±1.1 b	26.1±2.2 a	32.6±1.9 a	24.5±0.6 b
A.P.	27.6±1.6 a	28.3±2.4 a	26.4±1.2 a	26.0±1.9 a	27.9±1.3 a	27.5±0.9 a	27.0±3.6 a	34.5±2.0 a	31.8±1.2 a	36.0±1.5 a	29.3±0.7 a
FS × CR											
Org.-A.	26.4±2.8 a	23.6±1.3 b	22.5±1.2 b	21.1±1.1 b	23.5±0.1 b	25.1±1.0 b	23.3±2.8 b	25.2±0.8 c	27.2±4.6 a	35.1±3.6 a	25.3±0.9 b
Conv.-A.	19.3±2.5 a	21.2±0.4 b	22.3±0.5 b	22.0±0.2 b	25.1±0.9 b	24.3±0.2 b	20.3±1.1 b	27.7±1.9 bc	25.0±1.1 a	30.2±0.6 a	23.7±0.7 b
Org.-A.P.	29.4±1.6 a	33.3±1.7 a	28.7±0.9 a	30.1±1.0 a	30.3±1.7 a	29.3±0.5 a	34.9±0.5 a	37.9±0.4 a	34.4±0.9 a	38.8±1.6 a	32.6±0.7 a
Conv.-A.P.	25.7±2.7 a	23.2±0.6 b	24.2±1.2 b	21.9±0.8 b	25.5±0.7 b	25.7±0.6 b	19.0±0.5 b	31.1±0.9 b	29.3±0.6 a	33.2±1.3 a	25.9±0.8 b
Analysis of Variance											
Source	Pr≥F										
FS	0.0613	**0.0005**	**0.0215**	**0.0018**	0.1460	**0.0087**	**0.0002**	0.0363	0.1704	**0.0365**	**<0.0001**
CR	0.0922	**0.0007**	**0.0018**	**0.0007**	**0.0082**	**0.0025**	**0.0042**	**0.0001**	0.0501	0.1443	**<0.0001**
FS × CR	0.5140	**0.0086**	**0.0296**	**0.0006**	**0.0146**	0.0647	**0.0014**	**0.0017**	0.5504	0.8710	**0.0015**

Abbreviations: Org. = Organic farming, Conv. = Conventional farming, A. = Annual crop rotation, A.P. = Annual-perennial crop rotation, FS = Farming system, CR = Crop rotation.

Data presented are means ± standard error (n = 3).

Per column, within the farming system, crop rotation, or their interaction, means followed by different letters are significantly different at $p < 0.05$.

Table 2.3. Effect of farming system (FS) and crop rotation (CR) on wheat grain Fe concentration at the Glenlea Long-term Crop Rotation study site over 2011–2020.

	Grain Fe concentration (mg kg^{-1})										
Treatment	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2011-2020
FS											
Org.	41.8±7.2 a	30.7±1.7 a	28.3±2.5 a	25.5±1.0 a	29.4±2.6 a	42.8±6.6 a	68.1±7.2 a	53.0±4.9 a	32.8±4.6 a	46.2±12.4 a	39.4±2.4 a
Conv.	32.6±2.2 a	29.4±0.7 a	27.0±0.3 a	29.1±1.4 a	33.0±4.1 a	35.7±3.6 a	70.3±14.3 a	71.1±11.1 a	53.7±10.3 a	39.5±2.5 a	42.1±2.9 a
CR											
A.	33.2±2.7 a	31.2±1.6 a	26.3±1.0 a	28.0±1.7 a	27.4±0.9 a	29.6±1.1 b	67.8±14.0 a	56.0±7.3 a	39.9±5.4 a	46.2±12.4 a	38.6±2.6 a
A.P.	41.3±7.2 a	28.9±0.6 a	29.0±2.2 a	26.6±1.0 a	35.0±4.3 a	48.9±4.6 a	70.6±7.7 a	68.1±12.3 a	46.6±11.7 a	39.6±2.4 a	42.9±2.7 a

Analysis of Variance

Source	Pr≥F										
FS	0.2905	0.5071	0.6217	0.0534	0.4688	0.0688	0.9009	0.2398	0.1296	0.6154	0.4651
CR	0.3477	0.2450	0.3337	0.4227	0.1440	**0.0006**	0.8736	0.4229	0.6036	0.6178	0.2519
FS × CR	0.8205	0.8675	0.5055	0.1388	0.7846	0.0596	0.3941	0.8885	0.8357	0.2613	0.8471

Abbreviations: Org. = Organic farming, Conv. = Conventional farming, A. = Annual crop rotation, A.P. = Annual-perennial crop rotation, FS = Farming system, CR = Crop rotation.

Data presented are means ± standard error (n = 3).

Per column, within the farming system or crop rotation, means followed by different letters are significantly different at $p < 0.05$.

Table 2.4. Effect of farming system (FS) and crop rotation (CR) on wheat grain yield at the Glenlea Long-term Crop Rotation study site over 2011–2020.

	Wheat grain yield (kg ha^{-1})										
Treatment	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2011-2020
FS											
Org.	586±120 b	1521±281 b	1691±452 b	1789±359 b	1140±248 b	1675±108 b	1904±540 b	1479±256 b	1014±345 b	1256±226 b	1405±107 b
Conv.	1952±107 a	3606±554 a	3266±240 a	2885±299 a	2508±149 a	3183±210 a	3775±193 a	2038±271 a	2038±324 a	3146±83 a	2840±115 a
CR											
A.	1325±294 a	2705±311 a	3142±338 a	2688±308 a	2142±221 a	2416±294 a	3317±253 a	2341±137 a	2185±330 a	2104±477 a	2436±114 a
A.P.	1214±353 a	2422±846 a	1814±469 b	1987±441 a	1506±426 b	2443±443 a	2362±723 b	1175±144 b	867±214 b	2298±429 a	1809±162 b
FS × CR											
Org.-A.	713±168 b	2091±259 ab	2582±437 a	2506±222 ab	1677±61 b	1823±107 b	3043±391 a	2052±37 b	1615±468 b	1167±497 b	1927±146 b
Conv.-A.	1937±169 a	3319±197 ab	3703±256 a	2869±627 a	2608±151 a	3008±266 a	3591±304 a	2631±94 a	2754±47 a	3040±111 a	2946±116 a
Org.-A.P.	460±167 b	950±37 b	800±196 b	1073±288 b	602±120 c	1527±156 b	765±85 b	906±157 d	414±130 c	1344±20 b	885±77 c
Conv.-A.P.	1967±170 a	3893±1190 a	2829±174 a	2901±230 a	2409±280 ab	3358±346 a	3959±243 a	1444±82 c	1321±85 bc	3252±179 a	2733±199 a
Analysis of Variance											
Source						Pr≥F					
FS	**<0.0001**	**0.0089**	**0.0011**	**0.0204**	**<0.0001**	**0.0002**	**0.0002**	**0.0001**	**0.0033**	**<0.0001**	**<0.0001**
CR	0.2819	0.6241	**0.0026**	0.1026	**0.0062**	0.9131	**0.0053**	**<0.0001**	**0.0007**	0.477	**<0.0001**
FS × CR	0.1844	0.1689	0.1427	0.0903	**0.035**	0.2112	**0.001**	0.8080	0.6512	0.948	**0.0040**

Abbreviations: Org. = Organic farming, Conv. = Conventional farming, A. = Annual crop rotation, A.P. = Annual-perennial crop rotation, FS = Farming system, CR = Crop rotation.

Data presented are means ± standard error (n = 3).

Per column, within the farming system, or crop rotation, or their interaction, means followed by different letters are significantly different at $p < 0.05$.

In each of the ten years, wheat grain yield was significantly ($p < 0.05$) lower in the organic system compared to the conventional system (Table 2.4). The 10-year average yield in the organic system was only approximately half of that in the conventional system. In five out of ten years, yields were significantly ($p < 0.05$) lower in the annual-perennial rotation compared to the annual rotation, leading to a 35% lower 10-year average for the annual-perennial rotation. Additionally, the 10-year average yield was significantly ($p < 0.05$) affected by the interaction between farming system and crop rotation, which was contributed to that wheat yields were significantly lower in the annual-perennial rotation than the annual rotation for the organic system but yields between the two crop rotations were comparable for the conventional system.

2.4.2 Impact of farming systems and crop rotation on phytate, and molar ratios of phytate to Zn/Fe

Over the 10-year study period, the organic annual-perennial rotation had a phytate concentration of 7.9 mg g^{-1}, which was 34.2% lower ($p < 0.05$) than in the other treatments (Fig. 2.1A). Additionally, the [Phytate]:[Zn] ratio ranged from 24.6 to 50.7, and the [Phytate]:[Fe] ratio ranged from 18.4 to 32.3. Both ratios were significantly lower ($p < 0.05$) in the organic annual-perennial rotation system compared to other treatments (Fig. 2.1B, C), suggesting improved bioavailability of Zn and Fe.

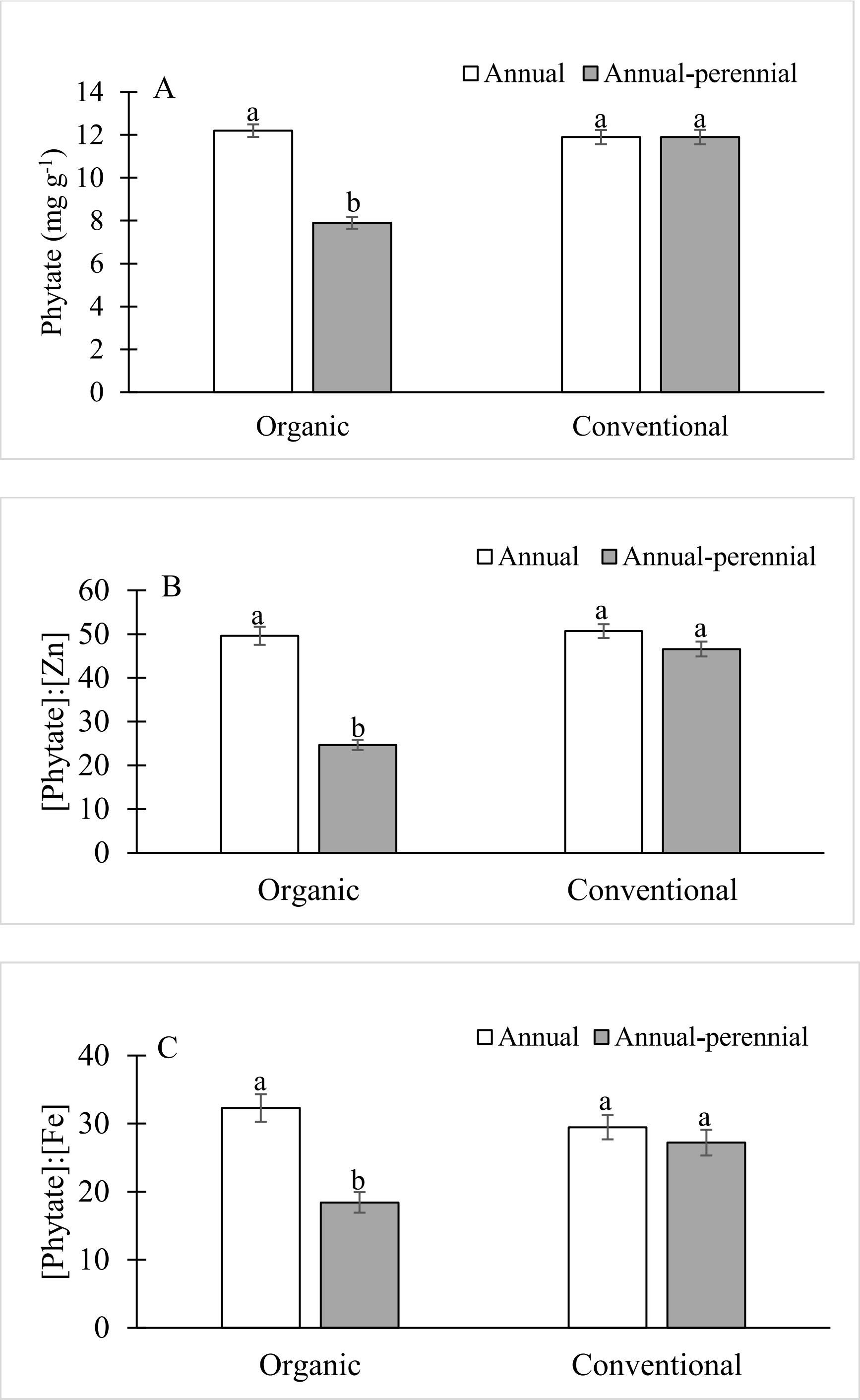


Fig. 2.1. Effect of farming system (organic vs. conventional) and crop rotation (continuous annual vs. annual-perennial) on grain phytate content (A), and molar ratio of phytate to grain Zn (B) and Fe (C). Data presented are the 2011–2020 means ± standard error (n = 30). Bars with different letters indicate statistically significant differences ($p < 0.05$).

2.4.3 Impact of compost application on grain Zn and Fe bioavailability under annual-perennial crop rotation in the organic farming system

Compost application had no effect on grain Fe concentration but significantly ($p < 0.05$) reduced Zn concentration to 26.4 mg kg^{-1}, compared to 32.6 mg kg^{-1} in the non-compost control (Table 2.5). As expected, compost application significantly ($p < 0.05$) increased grain P concentration from 1.3 g kg^{-1} to 1.8 g kg^{-1}, and phytate from 7.9 mg g^{-1} to 10.6 mg g^{-1}. Consequently, the [Phytate]:[Zn] and [Phytate]:[Fe] ratios were significantly ($p < 0.05$) higher with compost application compared to the non-compost control. Additionally, compost nearly doubled grain yield but significantly ($p < 0.05$) reduced grain protein concentration from 15.3% to 13.9% (Table 2.5). As a result, compost application significantly increased grain Zn uptake by 56%, and nearly doubled Fe uptake. More notably, compost led to a 1.6-fold increase in grain P and phytate uptake (Table 2.6).

Table 2.5. Effect of compost application on grain phytate content, molar ratio of phytate to Zn and Fe, protein concentration and yield of wheat under annual-perennial crop rotation in organic farming system.

Treatment	Zn (mg kg^{-1})	Fe (mg kg^{-1})	P (g kg^{-1})	Phytate (mg g^{-1})	[Phytate]:[Zn]	[Phytate]:[Fe]	Protein (%)	Yield (kg ha^{-1})
Non-compost	32.6±0.7 a	41.9±3.6 a	1.3±0.03 b	7.9±0.3 b	24.6±1.2 b	18.2±1.5 b	15.3±0.4 a	884.7±77.1 b
Compost	26.4±0.9 b	46.0±6.3 a	1.8±0.04 a	10.6±0.2 a	41.1±1.5 a	26.4±2.4 a	13.9±0.3 b	1764.1±127.8 a

Means within each column followed by different letters are significantly different at $p < 0.05$.

Data presented are the 2011–2020 means ± standard error (n = 30).

Table 2.6. Effect of compost application on uptake of Zn, Fe, P and phytate in wheat grains under annual-perennial crop rotation in organic farming system.

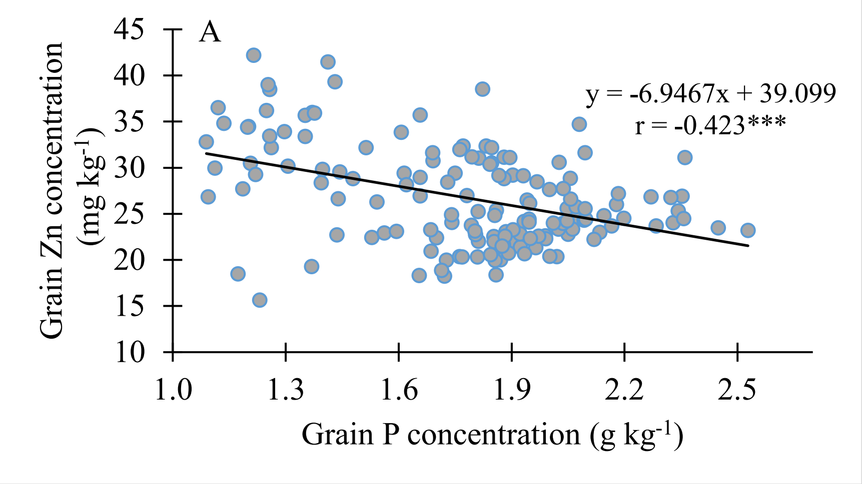
Treatment	Zn (g ha^{-1})	Fe (g ha^{-1})	P (kg ha^{-1})	Phytate (kg ha^{-1})
Non-compost	29.0±2.7 b	35.8±4.4 b	1.2±0.1 b	7.1±0.7 b
Compost	45.1±3.3 a	75.2±9.8 a	3.1±0.2 a	18.6±1.3 a

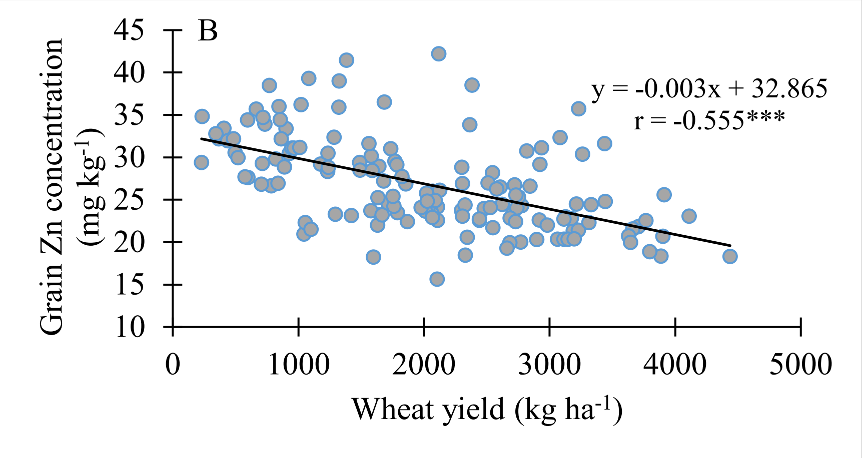
Means within each column followed by different letters are significantly different at $p < 0.05$.

Data presented are the 2011-2020 means ± standard error (n = 30).

2.4.4 Relationships of grain Zn concentration with grain P concentration, yield and protein concentration

Over the 10-year study, grain Zn concentration showed a significantly ($p < 0.001$) negative correlation with both grain P concentration ($r = -0.423$) and grain yield ($r = -0.555$) (Fig. 2.2A, B). In contrast, grain Zn was positively correlated with protein concentration ($r = 0.585$) (Fig. 2.2C).





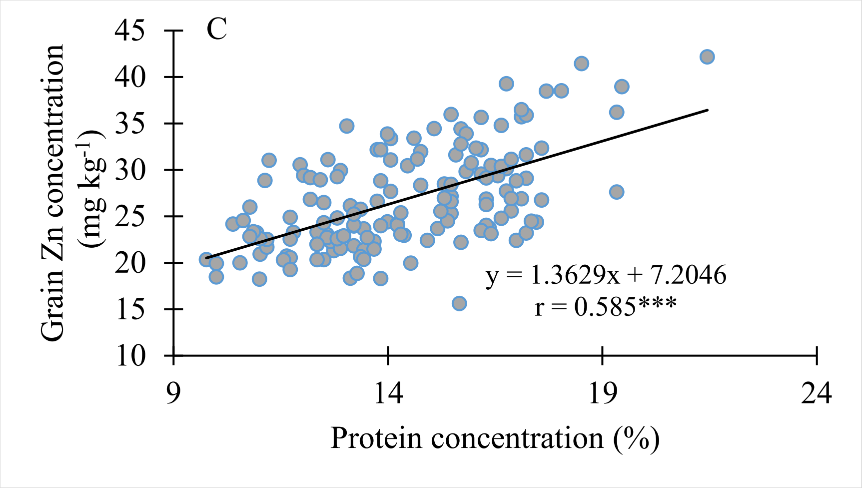


Fig. 2.2. Linear relationships of grain Zn with grain P (A), wheat yield (B), and protein concentration (C). *** indicated significance at $p < 0.001$.

2.5. Discussion

2.5.1 Annual-perennial crop rotation with organic farming enhanced grain Zn and Fe bioavailability

This study revealed key findings on the impact of farming system and crop rotation on micronutrient concentration and bioavailability in wheat grain, focusing on Zn and Fe. Organic farming significantly enhanced Zn concentration compared to conventional systems, while the annual-perennial crop rotation was more effective than continuous annual rotation. Further, the combination of organic farming and annual-perennial rotation led to significantly higher Zn concentration, lower phytate level, and consequently a reduced [phytate]:[Zn] ratio, indicating improved bioavailability for human consumption. These findings are consistent with those of Ryan et al. (2004) and Turmel et al. (2011), who also reported higher Zn and lower P concentration in organic systems with annual-perennial rotations. Therefore, our study confirms that organic farming, particularly when combined with diverse crop rotations, is a promising strategy for enhancing Zn bioavailability in wheat grain. Unlike conventional systems, organic systems' reliance on natural inputs and the absence of synthetic fertilizers could promote the long-term sustainability of micronutrient biofortification in crops.

However, despite these improvement, Zn and Fe bioavailability in wheat grain in the current study remains suboptimal to meet human consumption needs. A [phytate]:[Zn] ratio exceeding 15:1 and [phytate]:[Fe] ratio over 1:1 are associated with poor absorption by humans (Gibson et al., 1997; Hurrell and Egli, 2010). In our study, the organic annual-perennial system had ratios of 24.4 for Zn and 18.2 for Fe, exceeding critical thresholds. Similarly, previous studies have also reported low Zn and Fe bioavailability in wheat varieties. For example, Hussain et al. (2011) reported [phytate]:[Zn] ratios ranging from 23.9 to 41.1 in 65 bread wheat varieties in Pakistan, indicating low Zn bioavailability. Magallanes-López et al. (2017) and Tran et al. (2020) analyzed 46 and 101 wheat genotypes, respectively, and found that all genotypes fell into the low bioavailability category for both Zn and Fe. This outcome is not surprising, given that wheat grain inherently contains low levels of Zn and is rich in compounds such as polyphenols and phytate that inhibit micronutrient absorption (Cakmak, 2008).

Furthermore, we observed a considerable trade-off between improved micronutrient bioavailability and reduced yield productivity, highlighting the challenges for organic farming systems. At the Glenlea study site, organic systems produced only about half the yield of the conventional systems. Organic farming often produces lower yields due to reliance on natural inputs, slower nutrient availability, higher weed pressure, and potential soil nutrient depletion over time, particularly P deficiency (Welsh et al., 2009; Nelson et al., 2011). A survey of 14 organic farms in the Canadian prairie provinces and North Dakota revealed that while these farms generally maintain sufficient levels of N, K, and S, they often lack adequate P (Entz et al., 2001). Similarly, a long-term crop rotation study conducted in Saskatchewan of Canada also reported significant soil P depletion, particularly when legume hay crops are part of the rotation (Campbell et al., 1993). In the current study, wheat was grown after two years of alfalfa in the rotation. High nutrient removal of harvesting alfalfa appeared to be responsible for depleted soil P reserves (Welsh et al., 2009). Therefore, the reduced P availability and its effects on subsequent wheat grain yield and nutrient composition are partially attributed to the two years of alfalfa in the rotation.

Additionally, higher Zn concentration in organic than conventional systems could be attributed to enhanced root arbuscular mycorrhizal fungi (AMF) colonization, which facilitate nutrient absorption. For instance, on low-P soils in Australia, Ryan et al. (2004) reported higher Zn concentration in organically grown wheat grains, which correlated positively with the percentage of root length colonised by AMF. Previous studies at the Glenlea study site also reported greater colonization and spore populations of AMF in organic than conventional systems (Welsh, 2006) but with less AMF in the manure amended organic system compared with the unmanured organic system (Mukungu et al., 2025). Therefore, the enhanced Zn and Fe bioavailability in organic farming with diversified crop rotation can be attributed to several factors including a concentration effect due to yield reduction, reduced phytate accumulation, and increased Zn uptake facilitated by mycorrhizal fungi. While the organic systems show promise for improving micronutrient bioavailability, the associated yield reductions highlight the need for strategies that enhance productivity while at the same time reducing P accumulation in the crop (Carkner et al., 2003).

2.5.2 Compost application decreased Zn and Fe bioavailability for organic annual-perennial crop rotation

Though livestock manure-based compost is a good source of micronutrients, we observed that compost application significantly increased grain [Phytate]:[Zn] and [Phytate]:[Fe] ratios, indicating reduction of their bioavailability. The decreased Zn bioavailability was a combination of a yield dilution impact and an increase in phytate level resulted from compost application. The doubling of wheat yields following compost application reflects its effectiveness in replenishing soil P reserves, a common limitation in organic systems that rely on natural inputs (Ryan et al., 2004). Studies have shown that the benefits of compost, such as improved soil water retention and nutrient availability, are critical for maintaining yields in organic systems, which often suffer from lower productivity compared to conventional systems (Edmeades, 2003). As evidenced in the current study, enhanced yield productivity by compost application accompanied with significant increases in grain uptake of micronutrients including Zn and Fe. However, compost application also resulted in significantly higher grain phytate concentration and uptake, leading to decreased Zn and Fe bioavailability. This highlights the complexity of nutrient management in organic systems, where interventions aimed at improving macronutrient availability can inadvertently hinder micronutrient biofortification. Effective compost management, therefore, must consider enhancing the bioavailability of essential micronutrients like Zn and Fe, while promoting yield in organic farming systems. For instance, selecting manure sources with low P content could possibly maintain a balanced nutrient profile in the soil, and minimize phytate accumulation in crop grains. This approach can thus help achieve a more sustainable nutrient management in organic farming to improve crop productivity and nutritional quality.

2.5.3 Grain Zn concentration correlates negatively with grain P concentration, but positively with protein concentration

We found that grain Zn concentration was negatively correlated with grain P concentration, confirming the well-recognized P-Zn antagonistic relationship in plant nutrition (Bindraban et al., 2020). Ryan et al. (2008) reported that P fertilizer application increased grain P and phytate level and wheat yield, but reduced grain Zn concentration by 33%-39% due to decreased root AMF colonization. This aligns with our previous findings at the same study site, where high soil P availability in conventional systems led to reduced root AMF colonization than organic systems (Entz et al., 2004), but manure still had higher AMF than conventional production (Mukungu et al., 2025). Additionally, our most recent study demonstrated that AMF inoculation significantly increased Zn and Fe uptake in spring wheat under conditions of low soil P availability (Gao and Zhang, 2024). The positive correlation between grain Zn and protein agrees with previous studies, supporting that protein acts as a sink for Zn in the grain (Dapkekar et al., 2018; Cakmak et al., 2010; Kutman et al., 2011; Helfenstein et al., 2016). It implies that strategies aimed at enhancing grain Zn concentration are likely to also increase grain protein concentration, providing dual nutritional benefits for human health. These findings suggest that managing the macronutrient-micronutrient balance is critical to ensuring their availability for plant growth, and the maintenance of micronutrient bioavailability, particularly in organic farming systems.

2.5.4 Implications for organic farming and micronutrient bioavailability

Our study highlights a key challenge in organic farming system: the trade-off between wheat grain yield and micronutrient bioavailability, particularly for Zn and Fe. Organic farming with diverse crop rotation is an effective strategy to improve micronutrient biofortification, whereas it remains a challenge to maintain crop productivity through an optimal nutrient management. The reduced yields observed in the organic annual-perennial crop rotation were likely due to P limitations. Therefore, the reduced phytate and increased Zn levels in the organic system are more likely a consequence of reduced P availability rather than an intrinsic effect of the organic management system. Compost application presents a promising solution to this dilemma by addressing P deficiencies and substantially increasing yields. However, it also led to a marked reduction in grain Zn and Fe bioavailability. This trade-off could be mitigated by using compost sources rich in micronutrient or enriching manure sources with organic micronutrient additives to balance yield and nutrient quality. Such a strategy is particularly valuable for organic farming systems in regions like the Canadian prairies, where P deficiency is prevalent and difficult to manage (Entz et al., 2001). This study thus highlights how P management strategies influence grain nutrient composition is closely tied to soil and climate conditions, and the findings from the current study may not be generalized to all organic systems worldwide. Furthermore, selecting and breeding wheat cultivars with enhanced P uptake capacity while minimizing P accumulation in grain could help offset the negative effects of P addition on wheat grain Zn concentration (Carkner et al., 2023; Yang et al., 2023). Integrating these approaches could optimize both yield and micronutrient bioavailability in organic farming systems, promoting sustainable agriculture and better nutritional outcomes.

2.6 Conclusion

Our long-term field study reveals that crop management can affect the bioavailability of micronutrients in wheat grain. Organic farming, particularly using annual-perennial crop rotations, significantly enhanced grain Zn and Fe bioavailability in wheat. However, the trade-off between achieving high yields and maintaining micronutrient availability presents a significant challenge for organic farming, primarily due to P limitations. While compost application effectively addressed P deficiency and substantially increased grain yields and micronutrient uptake, it also resulted in higher grain phytate levels, thereby reducing Zn and Fe bioavailability. Therefore, our attempt to produce wheat grains with high bioavailability of Zn and Fe was successful only in scenarios where organic yields were unsustainably low. Addition research is required to find more effective mechanisms to raise organic wheat yields at lower levels of available P. We observed that grain Zn correlated negatively with grain P and positively with protein, suggesting the importance of managing the macronutrient-micronutrient balance. To optimize both yield and micronutrient bioavailability, future approaches should emphasize using compost sources rich in micronutrients and low in P, and breeding wheat cultivars with high P uptake efficiency but low accumulation in grain. These integrated strategies could promote sustainable agriculture and improve nutritional outcomes in organic farming systems.

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Chapter 3. Organic Agriculture Enhances Zinc Concentrations in Edible Crop Parts: A Meta-analysis

3.1 Abstract

Zinc (Zn) and iron (Fe) are essential micronutrients for humans, and their deficiencies lead to widespread malnutrition and other related health problems. Organic agriculture is often promoted for its potential to enhance soil health and environmental sustainability, but its effect on Zn and Fe concentrations in crops remain inconsistent. In this meta-analysis, we compiled 322 paired observations from 54 peer-reviewed publications to evaluate the impact of organic and conventional agriculture on Zn and Fe concentrations in crop edible parts, as well as on crop yield. We further examined the influence of crop type, soil properties (soil texture, soil organic carbon, soil pH) and climate factors (climate region, annual mean air temperature, annual precipitation) on the effect sizes. Our results revealed that Zn concentrations in organically grown crops under organic agriculture were 14.2% ($p < 0.001$) higher than those under conventional agriculture, with the effectiveness being more evident in vegetables. Iron concentrations did not show an overall difference between the two systems, except under wet conditions (annual precipitation > 850 mm) where organically grown crops had 14.5% ($p < 0.001$) higher Fe concentration than conventionally grown crops. Despite these benefits on micronutrients, organic agriculture was associated with a 24.7% reduction in crop yield, especially for cereals grown in arid regions. These findings underscore a critical trade-off between micronutrient concentration and crop productivity, emphasizing the need for integrated agronomic strategies that optimize nutrient quality while maintaining productivity. Future research should also investigate the impact of organic agriculture on micronutrient bioavailability, which may provide a more effective approach to combat micronutrient deficiency.

3.2 Introduction

Micronutrient deficiencies affect more than 3 billion people worldwide (Kiran et al., 2022), representing a critical public health issue known as "hidden hunger" due to their less apparent consequences compared to energy or protein deficiencies (Gregory et al., 2017). Among these deficiencies, zinc (Zn) and iron (Fe) are particularly concerning as they are essential trace elements required for human health. Zinc deficiency affects over 30% of the global population and ranks as the fifth leading risk factor for disease in developing countries (Shahzad et al., 2014). It leads to a range of health problems including stunted growth, delayed wound healing, diarrhea, increased risk of abortion, and disorders of the immune system (Shahzad et al., 2014; Jomova et al., 2022). Likewise, Fe deficiency is the primary cause of anemia and affects approximately 2 billion people globally. While adults experience fatigue, weakness and irritability, the consequences are more severe in children, including impaired cognitive development and increased susceptibility to disease infection (Khush et al., 2012). The widespread of Zn and Fe deficiency is primarily attributed to inadequate dietary intake, underscoring the urgent need for effective strategies to improve the micronutrient quality of food systems (Yaseen et al., 2018; Lowe et al., 2024).

Cereals, legumes, and vegetables are dietary staple crops that significantly contribute to Zn and Fe intake. Cereal grains are the most widely consumed foods in the human diet globally, serving as a major source of dietary energy, carbohydrates, dietary fiber, proteins and other plant-based nutrients. Legumes are a rich source of protein, unsaturated fats, dietary fiber, and important bioactive phytochemicals. However, most of these staple crops are inherently low in essential micronutrients such as Zn and Fe, making it difficult to meet daily nutritional requirements (Kiran et al., 2022; Prom-u-thai et al., 2020). Vegetables are a vital component of a well-balanced diet, especially leafy vegetables, are rich sources of Zn and Fe compared to grain, seed, fruit or tuber crops (White and Broadley, 2009). Hence, improving the nutritional quality of these foods represents an effective intervention in alleviating micronutrient deficiencies, particularly in populations reliant on plant-based diets. Zinc fertilization through soil and foliar applications has been shown to improve Zn concentration in cereal grains (Hui et al., 2025). However, the potential of organic agriculture to enhance micronutrient availability remains unclear.

Organic agriculture has been proposed as a more nutrient-enhancing alternative to conventional systems due to its emphasis on soil health, microbial diversity, and ecological balance, with all these factors attributing to nutrient uptake and accumulation in crops (Lori et al., 2017). Rani and Kapoor (2024) conducted a field study involving nine crops and reported higher levels of both macronutrients and micronutrients in crops grown under organic than conventional farming systems. Similarly, Ryan et al. (2004) found higher Zn concentrations in organically grown wheat, linking this to greater root colonization by arbuscular mycorrhizal fungi and improved Zn uptake, which may be suppressed in conventional systems due to phosphate fertilizer use. In a long-term field study in Manitoba, Canada, we also found increased grain Zn concentrations in organically grown wheat but no significant differences in Fe concentrations between organic and conventional systems (Hou et al., 2025). In contrast, some other studies reported the opposite trend. For example, Wszelaki et al. (2005) reported significantly lower Fe concentrations in the skin of organically grown potatoes but higher concentrations in the flesh. Similarly, Mikulioniene and Balezentiene (2009) found reduced grain Zn concentrations in wheat and rye grown under organic farming systems, likely due to inadequate nutrient inputs. These findings underscore the variability in nutrient concentrations across different crops and production systems, reflecting the complex effects of organic farming practices on nutrient levels in edible crop parts.

Given the inconsistency in previous findings, a comprehensive investigation into the effects of organic and conventional agriculture on Zn and Fe concentrations in crop is both necessary and valuable. Therefore, we conducted a meta-analysis to quantitatively assess how organic and conventional agriculture affect Zn and Fe concentrations in edible crop parts at the global scale. The specific objectives were to: (1) compare the differences in Zn and Fe concentrations and crop yields between organic and conventional crops; (2) examine the influence of soil properties, crop type, and environmental conditions on these effects; and (3) provide evidence-based insights on nutrient enhancement strategies aimed at mitigating global micronutrient deficiencies through adoption of organic agriculture.

3.3 Materials and Methods

3.3.1 Data collection

A systematic literature search was performed using Web of Science, Google Scholar and Scopus to retrieve relevant peer-reviewed articles published before January 1, 2025. No restrictions were applied to publication year or geographical region, to maximize coverage in this relatively under-researched topic. The following keywords and their combinations were used in the search: organic agriculture, conventional agriculture, zinc (Zn), iron (Fe), micronutrient, mineral, nutrient, farming system and cropping system. To minimize publication bias, each paper was screened to ensure it met the following criteria: (1) at least one of the selected variables, Zn or Fe concentration in edible crop parts was reported under both organic and conventional agricultural systems; (2) study was conducted under field condition, excluding pot, greenhouse, and hydroponic experiments; (3) study was based on data collection from experimental trials, not market-sources samples; (4) number of replicates for each treatment group was provided; and (5) crop yield data was reported in units convertible to kg ha^{-1}.

Based on these criteria, a total of 54 peer-reviewed papers were collected, providing 322 pairs of observations. Among these studies, we gathered 311 paired observations on Zn concentration from 50 studies, 281 paired observations on Fe concentration from 48 studies, and 107 paired observations on crop yield from 20 studies that comparing organic and conventional agriculture (Supplementary data). For each study, the response variables (Zn concentration, Fe concentration, and crop yield), along with associated standard deviations (SD) and the number of replicates were extracted. When only standard errors (SE) were reported, SD was calculated using Equation (1):

$$\mathrm{SD} = \mathrm{SE}\sqrt{n} \tag{1}$$

where n is the number of replicates.

If neither SD nor SE values were available in a study, we estimated SD using the method of Bracken (1992) as implemented in the metagear package in R (version 4.3.3). Data presented in only graphical format were digitized using the Web Plot Digitizer software (version 4.2).

In addition, geographic location, climate, crop type, soil texture, soil pH, soil organic carbon (SOC), annual mean air temperature, and annual precipitation were collected as explanatory variables. These variables were treated as moderators to evaluate their influence on the three response variables. Climate classification was determined based on study site using the 1966-2010 Köppen-Geiger system (resolution 5 arc-minutes; Source: Koeppen-geiger.vu-wien.ac.at) (Kottek et al., 2006; Rubel et al., 2017), accessed via Google Earth Pro (Version 7.3.6.9796; 64-bit). If only soil organic matter content was provided, SOC was estimated by dividing the value by 1.724 (Oldfield et al., 2019). For studies with missing soil properties, data were retrieved from the Harmonized World Soil Database v2.0 (FAO, 2023) using the geographic location of each study (Kuang et al., 2021). When annual mean air temperature or annual precipitation were not reported, they were obtained from the WorldClim database (http://www.worldclim.org) using the geographic coordinates of each study via QGIS (version 3.40.0-Bratislava) (Yin et al., 2023).

Continuous explanatory variables, including SOC, soil pH, annual mean air temperature and annual precipitation, were analyzed through two different approaches: as continuous moderators to examine trends and variability within the dataset, and as categorical moderators to facilitate comparisons across ranges defined by the distribution of the data. These categorical moderators were classified as follows:

- Crop type was grouped into three categories: cereal, legume, and vegetable.
- Climate was grouped into four types – equatorial, arid, warm temperate, and boreal – based on the Köppen-Geiger climate classification system, which differentiates regions by mean annual and monthly averages of temperature and precipitation (De la Cruz et al., 2023).
- Soil texture was classified according to the USDA (1999) soil classification system into fine (sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, clay), medium (fine sandy loam, loam, silt loam, silt), and coarse (coarse sand, loamy sand, sandy loam, fine sandy loam).
- SOC were grouped into three different levels: low (< 1%), medium (1–2%), and high (> 2%), following the criteria of Kihara et al. (2024).
- Soil pH was grouped into three different levels: acidic (< 6.5), neutral (6.5–7.5), and alkaline (> 7.5) (Sun et al., 2022; Kihara et al., 2024).

- Annual mean air temperature was divided into three ranges: cold (< 7℃), temperate (7–15℃), and warm (> 15℃).
- Annual precipitation was categorized into three levels: dry (< 550 mm), moderate (550–850 mm), and wet (> 850 mm).

3.3.2 Data analysis

This study employed the natural logarithm of the response ratio (lnRR) as the effect size to assess the differences between organic and conventional agriculture (Lipsey and Wilson, 2001). The effect size was calculated using Equation (2):

$$\text{Effect size} = lnRR = ln\frac{\bar{X}_t}{\bar{X}_c} = \ln(\bar{X}_t) - \ln(\bar{X}_c) \quad (2)$$

where $\bar{X}_t$ is the mean value in organic agriculture and $\bar{X}_c$ is the mean value in conventional agriculture, respectively. To account for variability in measurements, the variance (V) of the effect size was calculated using Equation (3) as outlined by Hedges et al. (1999):

$$V = \frac{SD_t^2}{\bar{X}_t^2 \times n_t} + \frac{SD_c^2}{\bar{X}_c^2 \times n_c} \quad (3)$$

where SD_t and SD_c are the standard deviations of $\bar{X}_t$ and $\bar{X}_c$, respectively, n_t and n_c are the number of replicates of $\bar{X}_t$ and $\bar{X}_c$, respectively.

Since meta-analyses involves multiple studies with varying levels of heterogeneity, the total variance (V^*) for each individual study was calculated using Equation (4) by adding the within-study variance (V) and between-study variance (τ^2):

$$V^* = V + \tau^2 \quad (4)$$

where the between-study variance (τ^2) was estimated using the restricted maximum likelihood (REML) method (Veroniki et al., 2016).

To ensure that studies with more reliable estimates had a greater influence on the overall effect size, each individual study was weighted using a nonparametric approach. The weighting factor (W) determined as the inverse of the pooled variance ($1/V^*$) (Hedges et al., 1999), thereby assigning greater weight to studies with lower variance and more replicates. If multiple observations were extracted from the same study, the weights were revised based on the total number of observations in that study (Bai et al., 2013; Yin et al., 2023). The final weight W^* used in our analysis was calculated using Equation (5):

$$W^* = \frac{W}{n} = \frac{1}{n(V+\tau^2)} \qquad (5)$$

where n was the number of observations from the same study.

The weighted effect size ($lnRR_i^*$) for each observation and the overall mean effect size ($\overline{lnRR^*}$) across all observations were estimated using Equation (6) and (7), respectively, as follows (Kuang et al., 2021; Yin et al., 2023).

$$lnRR_i^* = W_i^* \times lnRR_i \qquad (6)$$

$$\overline{lnRR^*} = \frac{\sum_i lnRR_i^*}{\sum_i W_i^*} \qquad (7)$$

where $lnRR_i$, $lnRR_i^*$ and W_i^* are the ith observation for the $lnRR$, $lnRR^*$and W^*, respectively.

To facilitate understanding, mean effect size ($\overline{lnRR^*}$) was back-transformed and presented as percentage change, using Equation (8):

$$\text{Effect size (\%)} = (e^{\overline{lnRR^*}} - 1) \times 100\% \qquad (8)$$

The statistical package metafor in R was used to fit a random-effects model and evaluate whether organic versus conventional agriculture significantly affect on Zn and Fe concentrations in the edible parts of crop and crop yield. The effect was considered statistically significant if the 95% confidence interval (CI) of mean effect size ($\overline{lnRR^*}$) did not overlap zero. To assess the influence of environmental and management factors, we further performed a mixed-effects model using both categorical (crop type, climate, soil texture, soil pH, SOC, soil pH, annual mean air temperature, and annual precipitation) and continuous moderators (SOC, soil pH, annual mean air temperature and annual precipitation). In the mixed effects model, the total heterogeneity (Q_T) of the response variable was divided into the moderator heterogeneity (Q_M) and the residual heterogeneity (Q_E). For categorical moderators, differences between levels were considered significant when Q_M had a *p*-value less than 0.05. For the continuous moderators, the statistical results included Q_M, Q_E, the intercept, the slope, and the corresponding *p*-value, with relationship considered significant at $p < 0.05$.

Funnel plots were generated to visually assess potential publication bias based on plot asymmetry, and Egger's regression test was then applied to statistical confirmation (Sterne and Egger, 2001).

3.4 Result

3.4.1 Descriptive results and publication bias

Approximately half of observations included in this meta-analysis were from Europe (n = 158, 49.1%), followed by Asia (n = 109, 33.9%) and North America (n = 47, 14.6%). Fewer studies originated from Oceania (n = 4, 1.2%), South America (n = 2, 0.6%) and Africa (n = 2, 0.6%), reflecting an uneven geographic data distribution (Fig. 3.1). The funnel plots for Zn concentration (Fig. S1a), Fe concentration (Fig. S1b), and crop yield (Fig. S1c) showed a symmetrical distribution, with Egger's regression test yielding *p*-values > 0.05, suggesting no indication of publication bias.

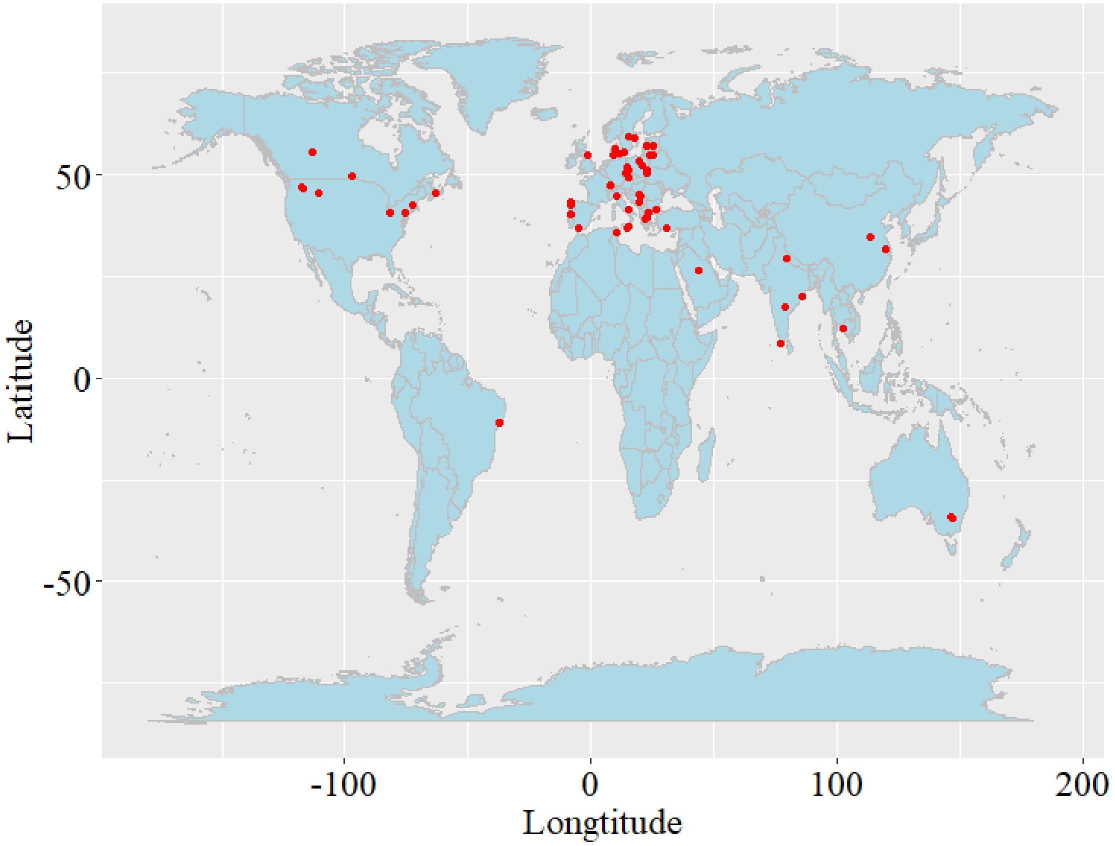

Fig. 3.1. Global distribution of experimental sites included in this meta-analysis.

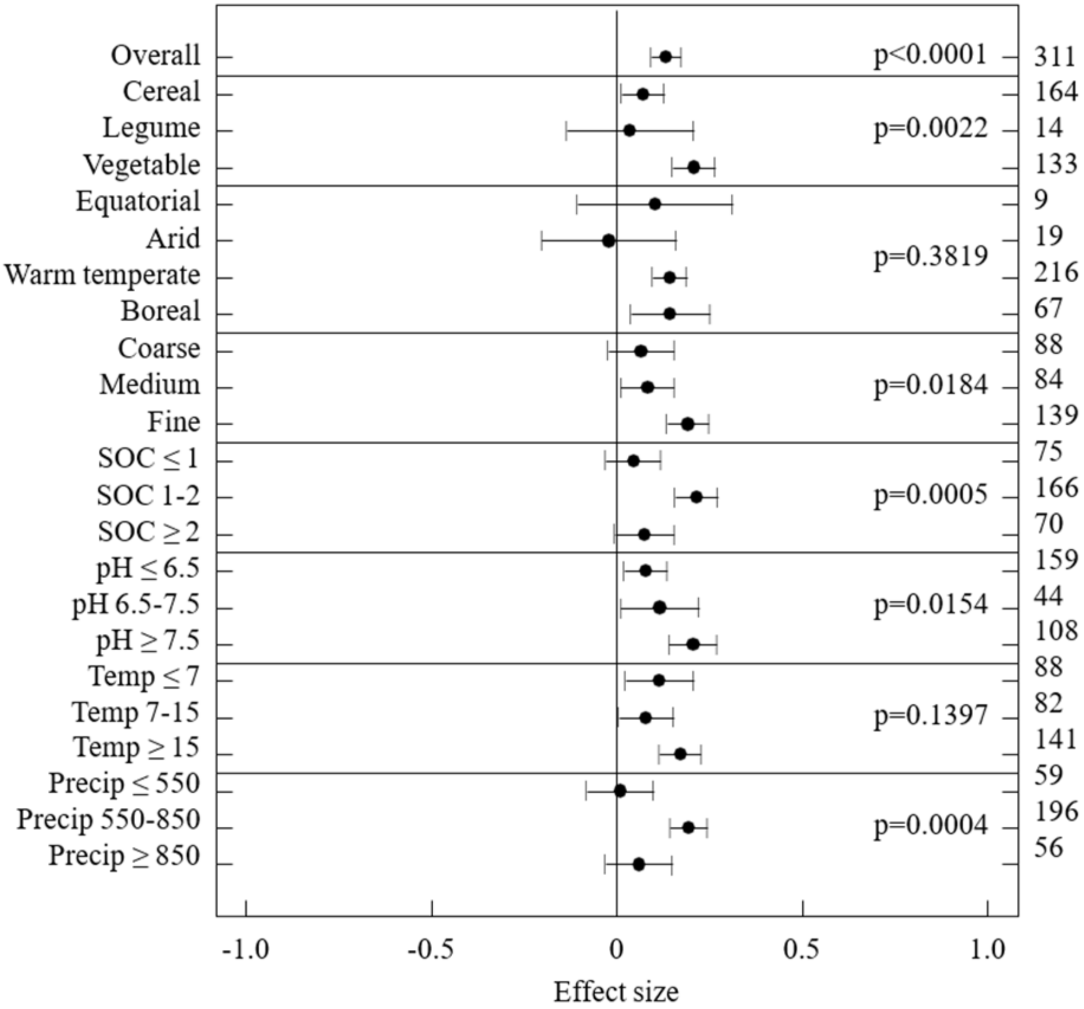

Fig. 3.2. Effect size of zinc (Zn) concentration in the edible parts of crops comparing organic with conventional agriculture, as affected by crop type, climate zone, soil factors including texture, soil organic carbon (SOC, %), pH, and environmental factors of annual mean air temperature (℃), and annual precipitation (mm). The number of observations for each category is shown next to the right axis. Data are presented as mean effect sizes with 95% confidence intervals. A significant difference in Zn concentration between organic and conventional systems is indicated when the 95% confidence interval does not overlap zero. The *p*-values denote the statistical significance of differences across categories.

3.4.2 Effect of organic agriculture on Zn concentration

Overall, crops grown under organic systems had 14.2% higher ($p < 0.0001$) Zn concentrations in edible parts, compared to conventionally systems (Fig. 3.2). This effect significantly varied with several factors including crop type, soil texture, SOC, soil pH, and annual precipitation.

Among crop types, vegetables (n = 133) exhibited the strongest response, with Zn concentrations being 23.1% higher under organic systems. Organic farming significantly increased Zn concentration in cereal grains by 7.25%, and also led to a non-significant but numerical increase of 3.66% in legumes. Regarding soil characteristics, fine-textured soils and soils with moderate SOC (1–2%) demonstrated stronger responses to organic agriculture, showing approximately 25% increase in Zn concentrations. Additionally, alkaline soils showed greater Zn concentrations under organic agriculture. For environmental factors, moderate annual precipitation levels (550–850 mm) were associated with a 21.5% increase in Zn concentration under organic agriculture. For other categories including climate and annual mean air temperature, the differences among levels were not statistically significant ($p > 0.05$).

Table 3.1. Relationships between the effect size of zinc (Zn) concentration in edible crop parts and continuous moderators including soil organic carbon (SOC), soil pH, mean air temperature and mean annual precipitation. Statistical results were reported as Q_E (residual error), Q_M (group difference), intercept, slope, and *p*-value from the mixed-effects model. A Q_M *p*-value less than 0.05 indicates a statistically significant relationship.

	Q_E	Q_M	Intercept	Slope	*p*-value (Q_M)
SOC	9109.8	1.7728	0.1591	-0.0131	0.1830
Soil pH	9098.3	9.3564	-0.233	0.0536	0.0038
Mean air temperature	9029.2	2.3817	0.0655	0.0052	0.1228
Mean annual precipitation	9007.5	0.2040	0.1146	0	0.6515

Analysis of continuous moderators revealed that soil pH was the only significant (*p* = 0.0038) factor showing a positive impact on Zn response to organic agriculture (Table 3.1, Fig. 3.3A). In contrast, although SOC and precipitation showed significant effects when analyzed as categorical moderators, they were not significant when treated as continuous moderators in the mixed effects model.

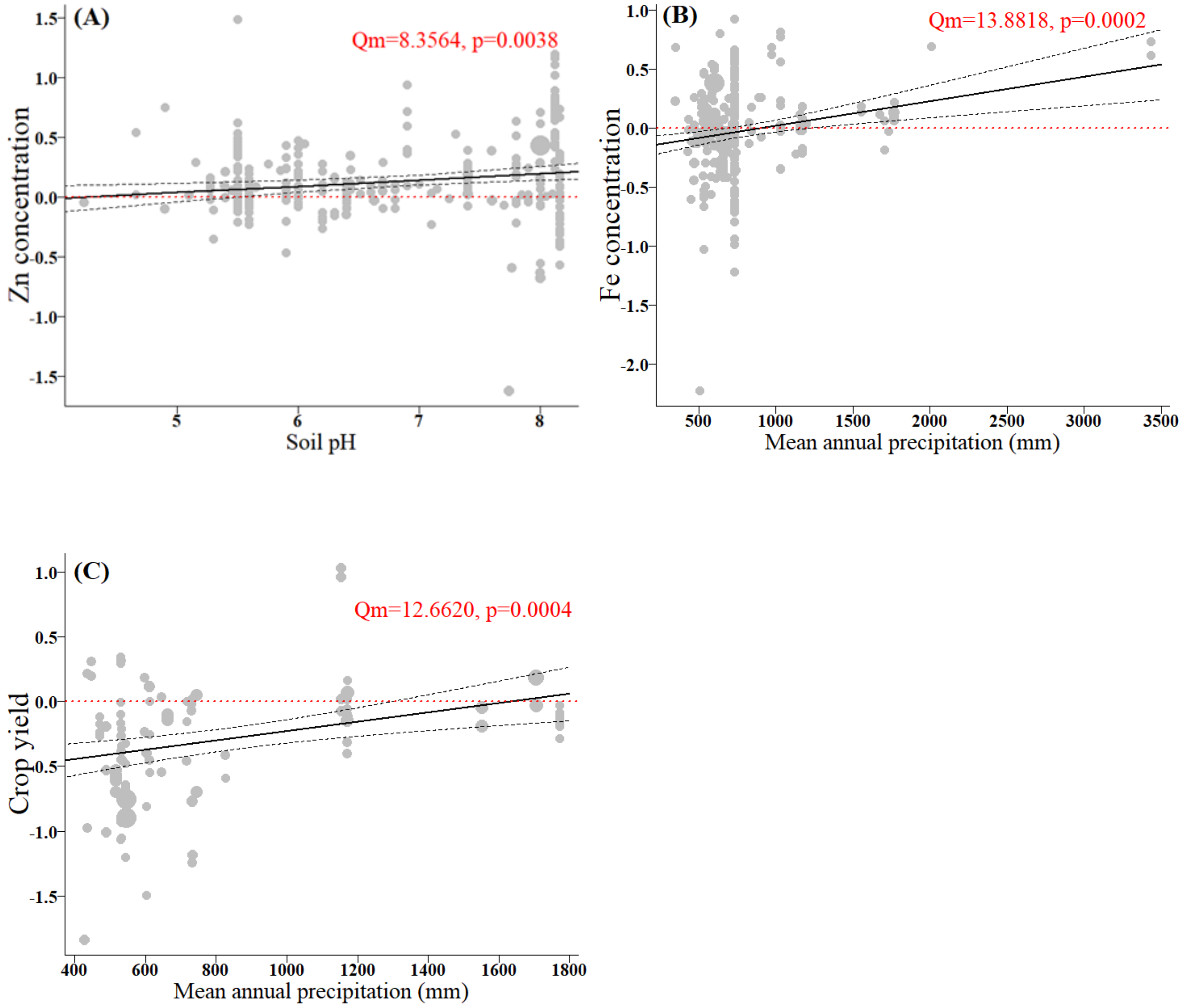

Fig. 3.3. Significant relationships between effect size of Zn concentration in crop edible parts and soil pH (A), between effect size of Fe concentration in crop edible parts and mean annual precipitation (B), and between effect size of crop yield and mean annual precipitation (C). The

solid line represents the regression model, with dashed lines indicating the 95% confidential interval. The red dotted line represents the reference line at an effect size of 0.

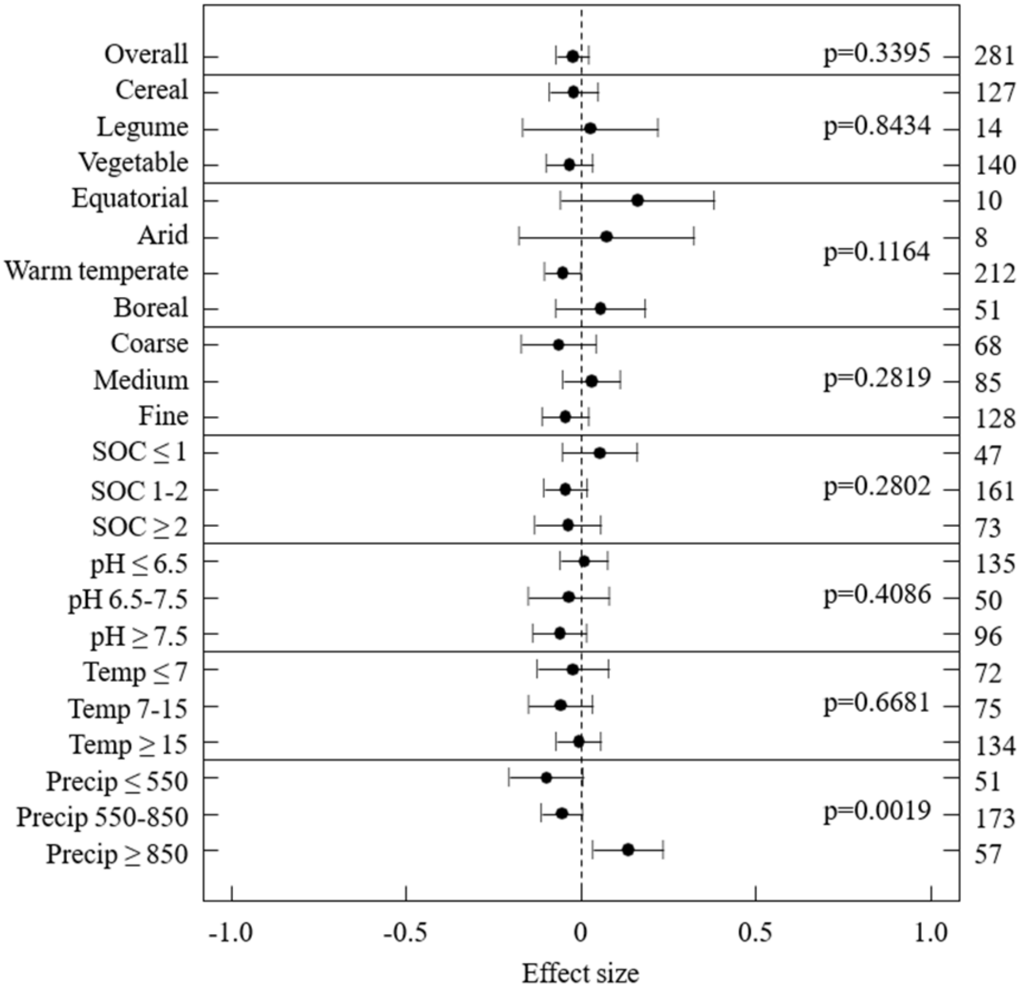

Fig. 3.4. Effect size of iron (Fe) concentration in the edible parts of crops comparing organic with conventional agriculture, as affected by crop type, climate zone, soil factors including texture, soil organic carbon (SOC, %), pH, and environmental factors of annual mean air temperature (℃), and annual precipitation (mm). The number of observations for each category is shown next to the right axis. Data are presented as mean effect sizes with 95% confidence intervals. A significant difference in Zn concentration between organic and conventional systems is indicated when the 95% confidence interval does not overlap zero. The *p*-values denote the statistical significance of differences across categories.

3.4.3 Effect of organic agriculture on Fe concentration

The overall effect size of Fe concentration in crop edible parts showed no significant difference between organic and conventional agriculture (Fig. 3.4). All factors did not affect the Fe response to farming systems, except in regions with high annual precipitation (≥ 850 mm) where organically grown crops had 14.5% higher Fe concentration. This effect was further supported by analysis of continuous moderators, where annual precipitation showed a significantly ($p = 0.0002$) positive effect on the Fe response to organic agriculture (Table 3.2, Fig 3.3B).

Table 3.2. Relationships between the effect size of iron (Fe) concentration in edible crop parts and continuous moderators including soil organic carbon (SOC), soil pH, mean air temperature and mean annual precipitation. Statistical results were reported as Q_E (residual error), Q_M (group difference), intercept, slope, and *p*-value from the mixed-effects model. A Q_M *p*-value less than 0.05 indicates a statistically significant relationship.

	Q_E	Q_M	Intercept	Slope	*p*-value (Q_M)
SOC	7164.9	3.6879	0.0207	-0.0217	0.0548
Soil pH	7491.1	0.6982	0.1019	-0.0182	0.4034
Mean air temperature	7093.3	1.2516	-0.0795	0.0043	0.2633
Mean annual precipitation	7454.3	13.8818	-0.1896	0.0002	0.0002

3.4.4 Effect of organic agriculture on crop yield

Across all studies, crop yield was 24.7% lower ($p < 0.0001$) under organic agriculture compared to conventional agriculture (Fig. 5). Such yield reductions were influenced by factors including crop type, climate zone, and annual precipitation.

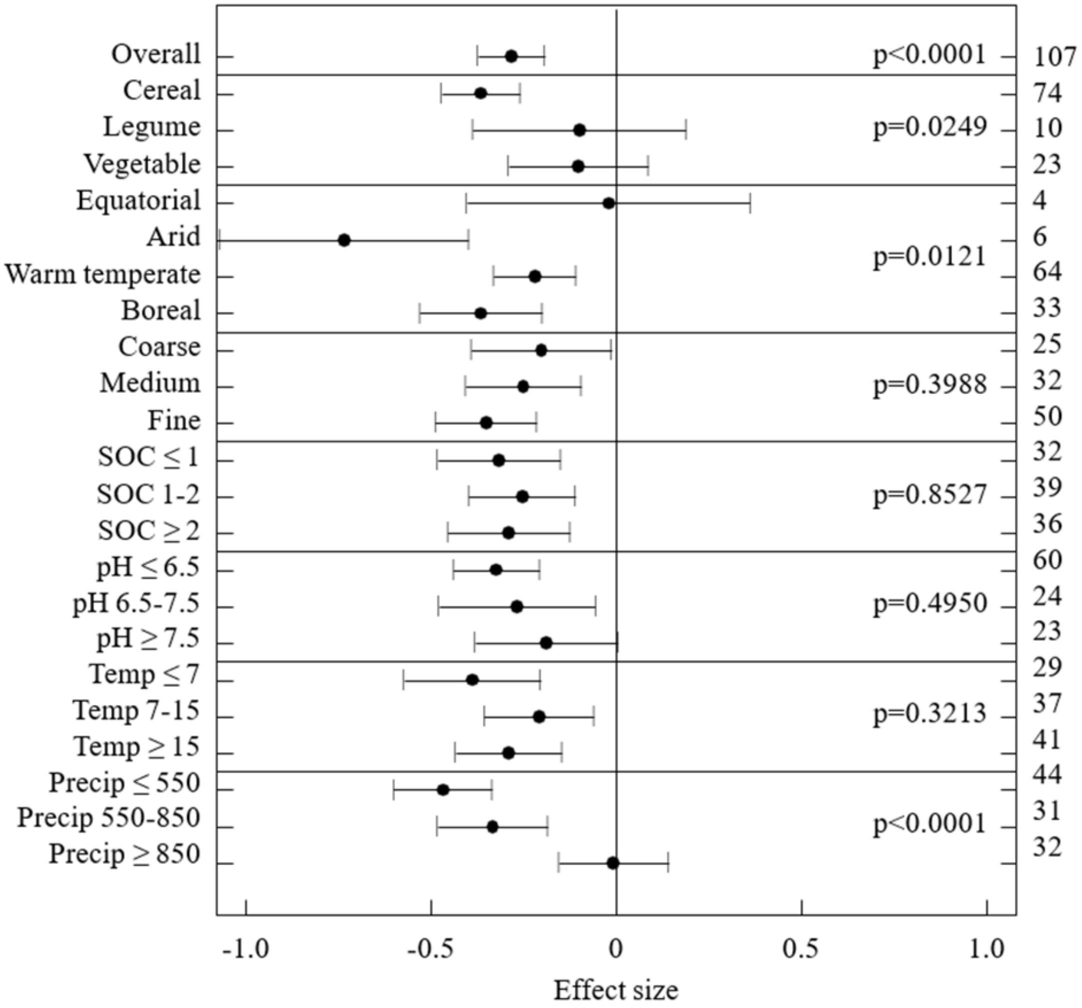

Fig. 3.5. Effect size of crop yield comparing organic with conventional agriculture, as affected by crop type, climate zone, soil factors including texture, soil organic carbon (SOC, %), pH, and environmental factors of annual mean air temperature (℃), and annual precipitation (mm). Number of observations for each category is shown next to the right axis. Data are presented as mean effect sizes with 95% confidence intervals. A significant difference in Zn concentration between organic and conventional systems is indicated when the 95% confidence interval does not overlap zero. The *p*-values denote the statistical significance of differences across categories.

Among crop types, cereals experienced the most pronounced yield reduction, with a significant 30.7% decrease in organic agriculture, while differences for legumes and vegetables were not statistically significant. Climate conditions also significantly affect crop yield response to farming systems, with yield reduction in organic agriculture being 52.1% in the arid region, 30.6% in the boreal region, and 19.8% in the warm temperate region, respectively. In contrast, yield levels were comparable between organic and conventional systems in the equatorial climate region, though this was based on a limited number of observations (n = 4).

Annual precipitation also showed a significant effect. Organic agriculture was associated with a significant 37.4% yield reduction in regions with low precipitation (< 550 mm), and 28.4% reduction in regions with moderate precipitation (550 mm–850 mm). In contrast, when annual precipitation exceeded 850 mm, yield differences between organic and conventional agriculture were not significant.

Table 3.3. Relationships between the effect size of crop yield and continuous moderators including soil organic carbon (SOC), soil pH, mean air temperature and mean annual precipitation. Statistical results were reported as Q_E (residual error), Q_M (group difference), intercept, slope, and *p*-value from the mixed-effects model. A Q_M *p*-value less than 0.05 indicates a statistically significant relationship.

	Q_E	Q_M	Intercept	Slope	*p*-value (Q_M)
SOC	694.1	3.0973	-0.1927	-0.0475	0.0784
Soil pH	756.2	0.0101	-0.3143	0.0047	0.9198
Mean air temperature	694.6	2.3085	-0.4069	0.0101	0.1287
Mean annual precipitation	589.9	12.6620	-0.5899	0.0004	0.0004

Analysis of continuous moderators confirmed a significantly linear and negative impact of annual precipitation on crop yield response (*p* = 0.0004; Table 3.3), indicating that as annual precipitation increased, the yield gap between organic and conventional agriculture decreased (Fig. 3.3C).

3.4.5 Correlation between Zn and Fe concentration in edible crop parts

Significant positive relationships between Zn and Fe concentrations were observed in both farming systems (Fig. 3.6), with a slightly stronger relationship in organic agriculture (*r* = 0.507) than conventional agriculture (*r* = 0.474).

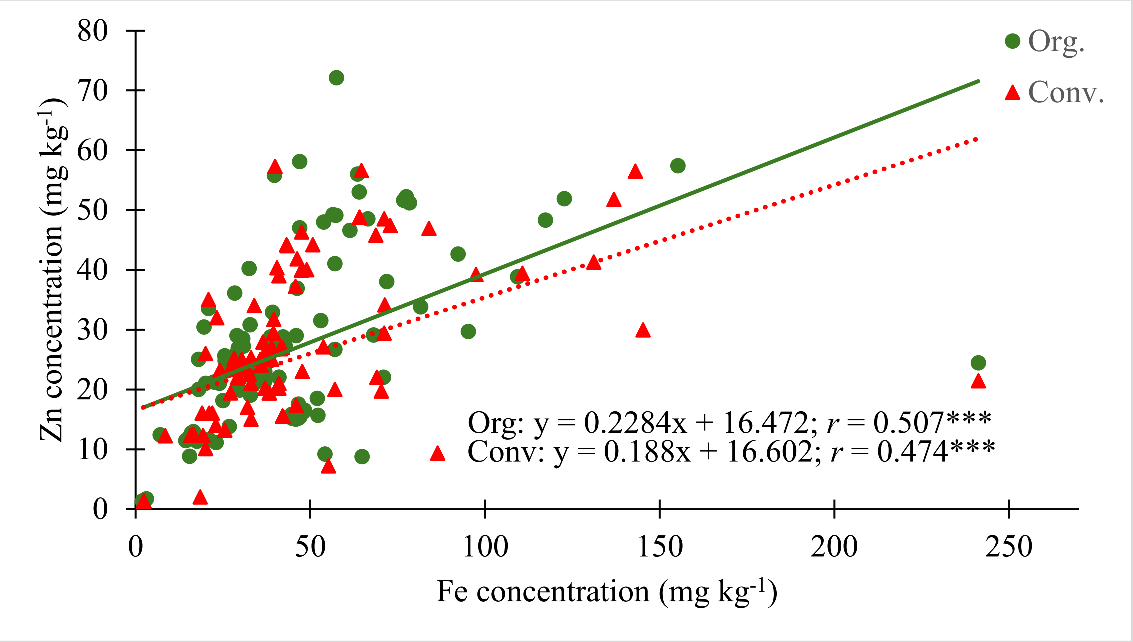

Fig. 3.6. Relationship between Zn and Fe concentrations in edible parts of crops under organic and conventional agriculture. *** indicated significance at $p < 0.001$.

3.5 Discussion

3.5.1 Organic agriculture's effect on micronutrients in crop edible parts

Our meta-analysis found that organically grown crops contain significantly higher Zn concentrations in their edible parts, with an average increase of 14.2% (95% CI: 9.7% to 19%, $p < 0.0001$). This finding of the benefits from organic agriculture on crop nutritional quality aligns with a previous meta-study, which reported a 5.7% increase in vitamins and minerals in organic foods than in conventional foods (Hunter et al., 2011). Specifically, this study reported that Zn and Fe levels were approximately 8% and 3% higher respectively in organic plant foods than their conventionally grown counterparts.

The enhanced Zn concentration in organic systems can be attributed to increased microbial abundance and activity. Also in a global meta-analysis, Lori et al. (2017) reported 32–48% greater soil microbial abundance and activity in organic than conventional cropping systems. This enhancement included a greater presence of bacteria, saprotrophic fungi and arbuscular mycorrhizal fungi (AMF) which play key roles in soil nutrient cycling and plant nutrient acquisition (Martínez-García et al., 2018). Notably, higher levels of AMF in the organic systems resulted in significant higher Zn and Fe concentration in five wheat cultivars compared to conventional systems (Nelson et al., 2011). A meta-analysis of 104 studies demonstrated the positive effect of AMF on Zn concentration and uptake across different crops and soils (Lehmann et al., 2014). In addition, organic farming systems typically rely on organic amendments such as compost and manure, which enrich the soil with essential nutrients to support crop growth. These organic inputs are conducive to the development of AMF (Mukungu et al. 2025) and other beneficial soil organisms, thereby increasing micronutrient levels in organic crops (Czech et al., 2022).

Crop type and soil properties were major moderators of Zn response to farming systems. In our analysis, vegetables exhibited the greatest increase in Zn concentration under organic management, followed by cereals, whereas legumes showed no significant difference between organic and conventional systems. These results are consistent with previous findings of elevated Zn levels in organically grown oat (Jakobsone et al., 2019), spinach (Citak and Sonmez, 2009), and *Allium* vegetables (Czech et al., 2022), reinforcing the potential of organic practices to enhance

Zn concentration across a range of vegetable crops. We also found that soils with medium to fine texture, or those with moderate SOC content (1–2%), showed stronger positive Zn response to organic farming. Such responses are likely because fine-textured soils generally have better water and nutrient retention capacities, promoting micronutrient availability (Scholberg et al., 2010), while coarse-textured soils are often less fertile due to low retention capacity (Kome et al., 2018). The observations on SOC impact are supported by earlier studies indicating moderate increases in soil organic matter enhance Zn availability, whereas excessive soil organic matter levels (> 3%) may reduce Zn availability due to increased strong binding of Zn on solid-state humic substances (Alloway, 2009; Suganya et al., 2020). Interesting, a positive impact of high soil pH (> 7.5) on Zn response to organic systems was observed. Although increased soil pH typically reduces Zn availability due to increased adsorption to soil particles and the formation of insoluble Zn species (Alloway, 2009), organic practices may still enhance Zn concentration in crop edible parts by mitigating such limitations. This effect may be attributed to enhanced microbial activity or the application of organic amendments that mobilize Zn through chelation or the production of organic acids, thereby sustaining Zn uptake in crops despite less favorable chemical conditions.

Climate conditions further influenced Zn response. Under moderate annual precipitation (550 mm–850 mm), Zn concentration in crop edible parts was significantly higher in organic compared to conventional systems. Moderate level of precipitation likely provides optimal conditions for root development, nutrient cycling, and microbial activity in organic system, thereby enhancing Zn availability and uptake. In contrast, under dry (< 550 mm) or wet (> 850 mm) conditions, differences between in Zn concentration between farming system were not significant, suggesting that extreme moisture levels may disrupt the benefits of organic management for Zn nutrition.

Unlike Zn, there was no overall difference in Fe concentration between farming system, except under wet conditions (precipitation > 850 mm), where the organic system exhibited a notable increase. This observation likely reflects Fe behavior and availability as affected by soil redox conditions. In well-aerated soils, Fe primarily exists as oxidized ferric oxides (Fe^{3+}), which are insoluble and poorly available for plants. Conversely, under waterlogged or saturated conditions, microbial respiration depletes oxygen, leading to anaerobic environments that promote the reduction of Fe^{3+} to ferrous iron (Fe^{2+}), a more soluble and plant available form (Colombo et al., 2014). Organic farming systems, with their higher levels of organic matter, further stimulate microbial activity and oxygen consumption, accelerating the redox transition. Consequently, in wet conditions, organic systems may create stronger reducing environments compared to conventional systems, facilitating greater Fe availability and uptake by crops. This enhanced Fe acquisition under high moisture aligns with observations from high-rainfall regions, where grain Fe concentrations were higher than in drier areas (Manzeke-Kangara et al., 2021). The observed positive correlations between Zn and Fe concentrations in crop edible parts under both organic and conventional systems suggest that these two micronutrients may share similar physiological pathways for uptake, translocation, and storage. This finding is consistent with earlier studies, where a positive relationship between Zn and Fe concentrations was reported in wheat grains (Nelson et al., 2011; Rawat et al., 2009). Therefore, agronomic strategies targeting Zn enhancement may simultaneously promote Fe concentration, offering a dual nutritional benefit for human health.

3.5.2 Challenges with organic agriculture

Our meta-analysis revealed an overall yield reduction of 24.7% (95% CI, 17.6%–31.2%) under organic agriculture. This finding is consistent with previous studies indicating organic yields are typically 18–25% less than conventional yields (Seufert et al., 2012; Ponisio et al., 2015; Gomiero, 2018; de la Cruz et al., 2023). Under organic agriculture, crops often experience greater biotic and abiotic stress due to increased weed pressure, higher tillage intensity, and lower soil nutrient levels, especially nitrogen (N) and P (Nelson et al., 2011; Welsh et al., 2009). Low N input has been identified as a primary constraint leading to reduced yield in organic system (Murphy et al., 2007). Similarly, P deficiency, especially in the Canadian prairies, has been linked to productivity breakdown in organic farming (Carkner et al., 2023).

Crop type, climate region and annual precipitation significantly moderated the yield gap between organic and conventional systems. Compared to legumes and vegetables, cereals exhibited the largest yield reduction of 30.7% under organic management. This disparity between crop species may reflect the historical breeding focus on high-yielding cereal varieties optimized for conventional inputs during and after the Green Revolution (Ponisio et al., 2015). Our analysis also revealed that the largest yield reduction with organic agriculture occurred in arid regions, where yields were 52.1% lower than those in conventional systems. In boreal regions, characterized by cooler temperatures and shorter growing seasons, organic yields were 30.6% lower. The yield gap was less severe in warm temperate regions at 19.8%, likely due to more favorable conditions for crop growth. In equatorial regions, where precipitation and temperature remain high year-round, no significant yield difference between farming systems was observed. This is also supported by the observation that there were no yield differences in areas receiving high precipitation (> 850 mm). While these findings suggest that strategies to improve organic productivity must account for regional environmental factors, the limited numbers of observations from the equatorial (n = 4) and arid (n = 6) regions warrant cautious interpretations. Expanded research efforts across these underrepresented climatic zones are essential to strengthen the evidence base and to inform region-specific strategies for improving organic yield performance.

Maintaining soil fertility through organic amendments are essential for sustaining crop productivity in organic systems. However, our recent research demonstrated that while compost application effectively increased yields, it simultaneously decreased grain concentrations and bioavailability of micronutrients in wheat, due to a combined influence of yield dilution and elevated phytate accumulation (Hou et al., 2025). These findings suggest that conventional manure or compost application may not be the optimal solution for achieving both high yield and improved micronutrient concentration. Future efforts could focus on selecting organic amendments that are enriched in micronutrients but low in P. Furthermore, breeding strategies could prioritize cultivars with enhanced P uptake efficiency but reduced P accumulation in edible parts, thereby improving micronutrient availability without compromising productivity. Such integrated approaches are critical for advancing the dual goals of yield sustainability and nutritional enhancement in organic agriculture.

3.5.3 Uncertainty and future implications

The reliability of this meta-analysis is influenced by the uneven distribution of available data. Over 97% of the observations included in this study originated from Europe (49.1%), Asia (33.9%), and North America (14.6%), with minimal representation from Oceania, South America and Africa. About half of the observations were from European countries, a trend consistent with previous meta-analyses on biodiversity (Rahmann, 2011), and on weed density and diversity in organic and conventional farming systems, where European studies were also predominant (Mwangi et al., 2024). This geographic imbalance restricts the broader applicability of the results, particularly to regions where organic agriculture is expanding but remains understudied.

Additionally, while this study focused on the total concentrations of Zn and Fe in crop edible parts, we were unable to assess the bioavailability of these micronutrients due to insufficient data. The presence of antinutritional factors such as phytate, which can strongly inhibit Zn and Fe adsorption in the human body, may influence the true nutritional impact of organic versus conventional agriculture.

Future research should focus on optimizing organic practices that enhance not only total micronutrient concentrations but also to improve their bioavailability in edible crop parts, while maintaining or improving productivity. Given that nutrient flow from soil to plants and ultimately to human diets is affected by complex interactions between soil conditions, agronomic practices and dietary patterns, a more integrated, systems-based approach is needed. Adopting such a comprehensive framework will enable the development of effective agricultural strategies, thereby improving food system resilience, and contributing to global efforts in alleviating micronutrient deficiencies.

3.6 Conclusion

This meta-analysis provides a comprehensive assessment of the impact of organic versus conventional agriculture on Zn and Fe concentrations in crop edible parts. Our findings indicate that organic agriculture significantly enhances Zn concentration by 14.2% but has no overall effect on Fe concentration. The observed Zn increase, particularly in vegetables, highlights the potential of organic agriculture to improve dietary Zn intake. We suggest that improved soil health is at least one of the mechanisms responsible for higher Zn concentration in organic crops. The micronutrient benefit of organic crops comes with a substantial 24.7% reduction in crop yield, with the largest yield gaps occurring in cereals and arid climate. Moreover, the effect of organic management on micronutrient bioavailability remains incomplete due to limited data on nutritional parameters such as phytate. Future research must integrate both micronutrient concentration and bioavailability to more accurately assess the contribution of organic agriculture to human nutritional health. Addressing these knowledge gaps is essential for designing agricultural strategies that enhance both food quality and system sustainability in a changing global environment.

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Chapter 4. Overall Synthesis

4.1 Summary of findings and contributions to knowledge

The Glenlea long-term crop rotation study provides crucial insights into how farming systems and crop rotation strategies affect Zn and Fe concentrations and bioavailability in wheat grain. Organic farming resulted in higher grain Zn concentrations, particularly in the diversified annual-perennial rotation involving alfalfa. This diversified crop rotation under organic management also led to a significant reduction in grain phytate content, thereby enhancing Zn and Fe bioavailability. However, these nutritional benefits came at the cost of reduced grain yields, primarily due to lower soil P availability, highlighting a trade-off between nutrient density and crop yield. Compost application in the organic annual-perennial rotation significantly alleviated P deficiency and almost doubled wheat yield. However, this yield gain was associated with reduced bioavailability of Zn and Fe in the grain (Hou et al., 2025).

The global meta-analysis of 54 peer-reviewed studies provided a complementary and broader perspective from the Glenlea field study, demonstrating an average increase of 14.2% in Zn concentration in organically grown crops compared to those grown conventionally. In contrast, Fe concentration showed no overall significant difference between organic and conventional agriculture. Additionally, this study identified a consistent yield reduction of approximately 25% under organic management. These results aligned with findings from our Glenlea study, confirming a pattern of increased micronutrient density in organic systems, while accompanied by lower yields. Furthermore, our meta-analysis showed that vegetables had the largest increase in Zn concentration under organic management compared to cereals and legumes. In regions with high precipitation (> 850 mm), organically grown crops had significantly higher Fe concentrations. We also observed that yield reduction under organic management was most pronounced in cereals compared to legumes and vegetables. Among climate regions, crops grown in arid region experienced the most severe yield reduction.

These insights gained from the Glenlea study provide a deep understanding of how organic management interacts with crop rotation and nutrient inputs, such as compost, to influence Zn and Fe bioavailability in wheat grain. Our meta-analysis further deepens those understanding by quantifying the impact at a global scale and assessing the influences of key soil properties and climatic factors. Collectively, these results provide evidence-based guidance for improving nutrient quality while minimizing yield trade-off in organic agriculture.

4.2 Limitations and uncertainty

Several limitations must be acknowledged. In the Glenlea study, the plot size was 12 m by 4 m for the organic system and 28 m by 4 m for the conventional system. These relatively small and unequal plot dimensions may have introduced edge effects. The edges of the plots usually have a different microclimate, with greater exposure to wind and sunlight, which can reduce soil moisture more rapidly. Plants near the edges may also experience different nutrient availability due to reduced root competition. Although the edge areas were excluded from the harvested samples to minimize these effects, indirect influences may still occur, limiting the potential applicability of findings to farm-scale production. Second, the seeding rates differed between organic (165 kg ha^{-1}) and conventional (125 kg ha^{-1}) farming. Although these rates were selected to reflect best practices under each system, the differences in plant density may affect plants' competition in nutrient uptake and grain filling, and thus influence both yield and grain nutrient concentration. Third, weather-related variables, such as precipitation, air/soil temperature and their seasonal variability, were not considered in this study. Variations in climatic conditions can significantly affect soil nutrient availability and stability by influencing microbial activity and associated nutrient cycling processes. For example, according to Guo et al. (2024), increased precipitation generally enhances microbial activity which leads to accelerated organic matter decomposition, thereby facilitating nutrient cycling and promoting plant growth. Incorporating these factors in future studies would provide a more holistic understanding of environmental interactions with agronomic practices.

The key limitation of the meta-analysis study is that the dataset may not be fully representative of global agricultural conditions, as most observations came from Europe, Asia, and North America, with only about 2% of the study sites being located in Oceania, South America and Africa. Tropical climates in Africa and South America typically feature highly weathered soils with low natural fertility, differing significantly from soils in temperate regions. Consequently, the findings from our study may not accurately reflect the actual agricultural conditions in these underrepresented regions. In addition, while this meta-analysis offered strong insights into influences of organic farming on Zn and Fe concentrations, it could not assess their bioavailability due to limited data availability. Very few studies reported necessary bioavailability indicators such as phytate to Zn or phytate to Fe molar ratios, or concentrations of other absorption inhibitors or enhancers. This data gap limits our ability to determine whether increased micronutrient concentrations under organic management translate into improved nutritional outcomes for human health. Given that bioavailability is often more important than total nutrient content in addressing micronutrient deficiencies, this represents a critical research need.

4.3 Implications of future research

Future research should focus on understanding and managing the trade-off between enhanced grain micronutrient concentration and reduced crop yields, as demonstrated in both the Glenlea Long-term Rotation Study and the global meta-analysis. To better address this trade-off, research efforts should emphasize optimizing soil P management practices to sustain crop yield without causing excessive grain phytate accumulation. One promising approach involves selecting organic amendments rich in micronutrients but relatively low in P. As a commonly used amendment in organic agriculture, livestock manure varies widely in nutrient composition depending on its source and processing method. Poultry manure has been reported to have the highest Zn concentration at 290 mg kg^{-1}, followed by pig manure at 207 mg kg^{-1}, while cattle manure generally contains lower Zn concentration, ranging from 89 to 129 mg kg^{-1} (Schick et al., 2013). In addition, the nutrient composition of manure is strongly affected by its processing method. For instance, solid dairy manure, especially separated solids, generally contains lower P concentrations compared to other processed forms, such as digestate, liquid, or composted manure (University of Minnesota Extension, 2024). These findings emphasize the potential of proper manure management in balancing nutrient quality and crop productivity in organic agriculture.

From a crop breeding perspective, efforts could focus on developing crop ideotypes that possesses traits facilitating enhanced P uptake under low P soil condition, meanwhile reducing P translocation from biomass into crop edible parts to enhance micronutrient bioavailability in edible crop parts (Carkner et al., 2023). In addition, recent greenhouse study showed that inoculation with arbuscular mycorrhizal fungi (AMF) enhanced root colonization and improved Fe and Zn uptake in wheat under P-deficient soil conditions (Gao and Zhang, 2025). In another field study from Glenlea, Mukungu et al. (2025) reported that fax grown organically with manure application had significantly higher AMF colonization and maintained comparable yields compared to conventional farming. These studies highlight the potential of AMF inoculation combined with organic amendments as a practical approach to improve micronutrient uptake and accumulation in organic systems.

Additional research is needed to confirm these benefits across different crops and environmental conditions, especially through more field studies in regions currently underrepresented in organic agriculture research. Furthermore, there remains a need for more research on micronutrient bioavailability, as it serves as a more direct indicator of the nutritional and health benefits of crops. In addition to wheat, more research on other cereal crops, legumes, and oilseed crops would further enrich our understanding of micronutrient dynamics in organic agriculture.

Future research should also adopt an integrated approach that considers nutrient flow from the soil, through plants, ultimately into the human diet. Such a comprehensive strategy can identify agricultural practices that effectively enhance nutrient availability for human consumption, thereby contributing to addressing the global challenge of micronutrient deficiencies.

4.4 References

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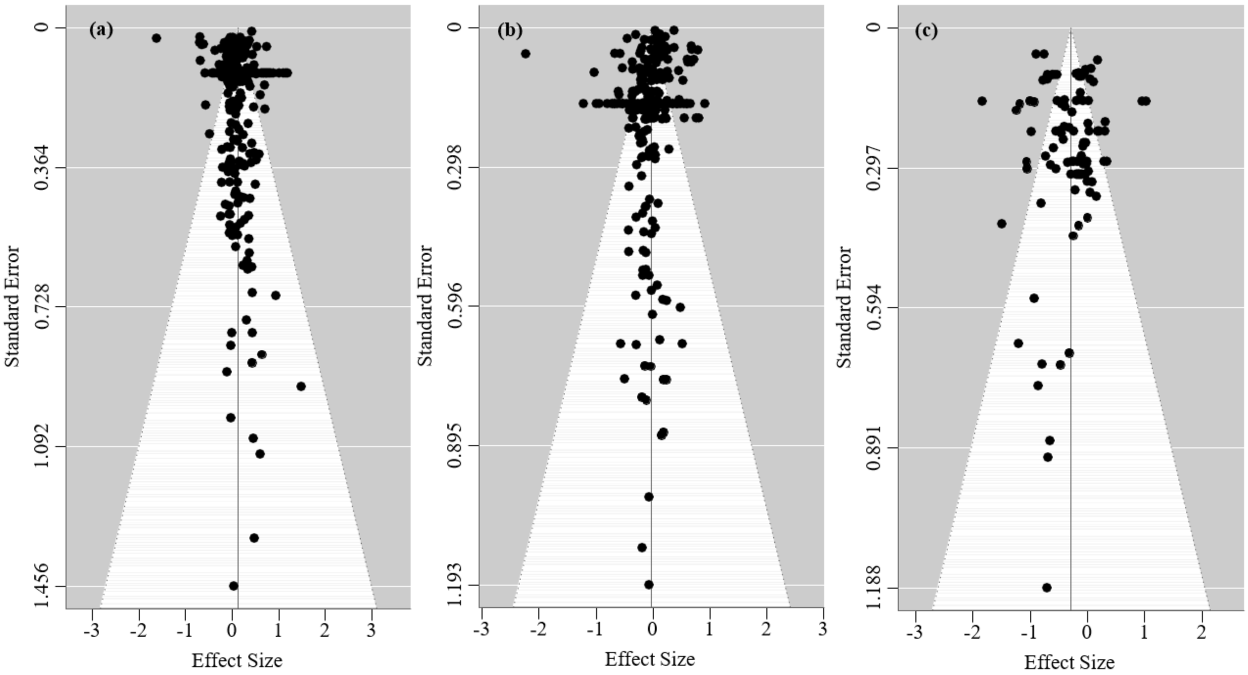
Appendices

Appendix A: Supplementary figures for Chapter 3



Supplemental Fig. 1 Funnel plots assessing potential publication bias between organic and conventional agriculture on: (a) Zn concentration, (b) Fe concentration, and (c) crop yield. The relative symmetrical distribution of points in each plot suggests no strong evidence of publication bias. The *p*-value of Egger's regression test for funnel plot asymmetry was > 0.05, indicating no statistically significant bias.

Appendix B: Dataset used in Chapter 3

Supplemental Table 1. Dataset on zinc (Zn) concentration in edible crop parts under organic and conventional agriculture

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
1	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.90	7.1	42.6	41.3
2	1	Tziouvalekas el al., 2022	legume	arid	fine	0.67	7.8	38.0	47.4
3	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.67	8.1	51.9	51.8
4	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.02	7.9	57.4	56.5
5	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.87	7.0	52.2	46.9
6	1	Tziouvalekas el al., 2022	legume	arid	fine	0.64	7.2	51.6	48.5
7	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.58	8.1	52.8	51.5
8	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.04	7.3	38.8	39.4
9	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	33.5	35.0
10	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	12.4	12.2
11	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	30.4	32.0
12	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	11.1	12.3
13	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	8.8	2.0
14	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	13.8	13.2
15	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	49.2	46.3
16	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	48.0	44.0
17	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	56.0	39.9
18	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	49.1	44.2
19	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	46.6	37.2
20	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	41.0	40.0
21	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	47.0	39.0
22	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	23.5	26.8
23	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	29.0	34.0
24	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	32.9	27.9
25	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	26.7	23.0
26	6	Golijan et al., 2022	cereal	warm temperate	medium	1.90	7.6	15.3	15.7

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
27	6	Golijan et al., 2022	cereal	warm temperate	medium	1.90	7.6	17.8	12.2
28	6	Golijan et al., 2022	legume	warm temperate	fine	2.20	7.1	19.9	25.1
29	6	Golijan et al., 2022	cereal	warm temperate	medium	3.00	7.7	14.2	15.2
30	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	26.8	22.8
31	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	22.9	20.9
32	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	18.8	17.4
33	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	18.8	17.5
34	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	22.8	18.9
35	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	15.1	15.9
36	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	17.3	18.8
37	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	19.3	19.1
38	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	16.8	17.0
39	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	11.4	12.1
40	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	16.1	11.3
41	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	14.5	13.6
42	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	22.2
43	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.7	30.5
44	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	23.2
45	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.3	20.8
46	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	22.9
47	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.7	33.7
48	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	24.1
49	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.3	24.3
50	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	20.5
51	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.7	32.3
52	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	22.0	23.6
53	8	Jākobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	26.3	23.0
54	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	29.0	22.0
55	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	22.0	20.0
56	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	22.0	21.0

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
57	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	21.0	17.0
58	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	22.0	27.0
59	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	22.0	25.0
60	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	27.0	26.0
61	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	28.0	27.0
62	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	23.0	21.0
63	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	23.0	21.0
64	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.2	20.0	15.0
65	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.9	20.0	16.0
66	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.8	21.0	16.0
67	10	Ryan et al., 2004	cereal	arid	medium	0.60	6.1	25.0	16.0
68	11	Cooper et al., 2011	cereal	warm temperate	coarse	1.91	6.4	24.1	22.9
69	11	Cooper et al., 2011	cereal	warm temperate	coarse	1.91	6.4	21.7	25.3
70	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	28.0	19.7
71	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	33.4	19.7
72	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	29.4	18.2
73	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	30.0	20.2
74	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	30.0	19.8
75	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	26.9	19.1
76	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	29.7	19.1
77	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	31.1	20.3
78	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	32.1	20.8
79	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	34.6	21.4
80	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	25.4	22.0
81	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	32.3	17.4
82	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	39.8	24.4
83	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	36.9	23.9
84	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	32.2	22.1
85	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	29.8	20.6
86	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	34.0	21.5

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
87	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	32.9	23.6
88	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	25.4	24.2
89	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	27.0	27.6
90	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	25.5	23.4
91	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	22.0	22.6
92	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	27.5	25.1
93	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	25.1	23.4
94	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	30.0	27.3
95	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	26.7	26.8
96	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	22.8	23.0
97	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	22.9	20.1
98	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	26.3	26.7
99	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	23.8	24.7
100	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	23.7	24.1
101	12	Legzdina et al., 2014	cereal	boreal	coarse	1.70	6.4	29.2	30.6
102	13	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	55.8	44.2
103	13	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	58.1	41.8
104	13	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	72.1	56.6
105	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	29.7	26.8
106	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	31.3	29.6
107	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	26.6	22.0
108	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	29.7	28.9
109	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	31.3	27.0
110	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	26.6	25.8
111	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	29.7	31.1
112	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	31.3	32.3
113	14	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	26.6	27.7
114	15	Mäder et al., 2007	cereal	warm temperate	medium	1.45	6.4	34.6	38.2
115	15	Mäder et al., 2007	cereal	warm temperate	medium	1.45	6.4	36.9	35.9
116	15	Mäder et al., 2007	cereal	warm temperate	medium	1.45	6.4	30.5	33.3

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
117	15	Mäder et al., 2007	cereal	warm temperate	medium	1.45	6.4	33.7	32.2
118	16	Murphy et al., 2008	cereal	warm temperate	medium	1.68	5.7	17.1	15.8
119	17	Al-Ghumaiz et al., 2020	cereal	arid	coarse	0.52	8.0	50.6	38.3
120	18	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	33.8	34.1
121	18	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	48.3	39.2
122	19	Singh et al., 2024	legume	warm temperate	fine	0.89	7.3	72.1	42.6
123	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	12.9	10.8
124	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	13.9	7.4
125	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	15.8	9.5
126	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	14.4	15.2
127	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	13.3	10.4
128	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	14.5	11.0
129	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	12.7	10.5
130	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	13.6	14.0
131	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	11.7	9.9
132	20	Zaccone et al., 2010	cereal	arid	fine	1.71	7.8	12.8	9.3
133	21	Zhang et al., 2020	cereal	warm temperate	medium	1.10	8.0	33.8	21.9
134	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	12.3	23.3
135	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	25.3	12.5
136	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	11.6	20.2
137	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	11.4	12.3
138	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	12.9	25.2
139	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	27.2	23.2
140	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	23.1	12.5
141	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	12.2	24.2
142	22	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	12.7	25.0
143	23	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	19.0	19.4
144	23	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	22.7	19.4
145	23	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	21.4	20.2
146	23	Laursen et al., 2011	cereal	warm temperate	coarse	2.20	5.3	19.9	20.2

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
147	23	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	53.0	48.8
148	23	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	48.5	48.8
149	23	Laursen et al., 2011	vegetable	warm temperate	coarse	1.16	5.3	11.6	10.1
150	23	Laursen et al., 2011	vegetable	warm temperate	coarse	1.16	5.3	11.3	10.1
151	24	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	36.1	40.3
152	24	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	40.2	57.3
153	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	27.9	22.5
154	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	28.5	22.2
155	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	25.6	23.3
156	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	25.6	21.9
157	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	26.9	25.3
158	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	27.2	25.0
159	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	29.1	19.7
160	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	31.5	29.4
161	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	30.8	27.1
162	25	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	36.9	31.7
163	26	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	27.4	25.8
164	26	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	28.8	25.8
165	26	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	26.7	29.4
166	26	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	28.8	29.4
167	27	Fernández-Canto et al., 2024	cereal	warm temperate	medium	5.20	4.9	19.4	21.6
168	28	Gopinath et al., 2023	legume	equatorial	coarse	0.43	6.5	25.0	21.8
169	28	Gopinath et al., 2023	legume	equatorial	coarse	0.43	6.5	29.6	28.8
170	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	24.8	25.0
171	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	21.0	26.0
172	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	23.0	24.0
173	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	18.1	14.0
174	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	9.2	7.2
175	29	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	21.2	19.4
176	30	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	1.3	1.3

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
177	30	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	1.3	1.3
178	30	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	1.3	1.3
179	30	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	1.3	1.3
180	30	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	1.7	1.3
181	31	Hattab et al., 2019	vegetable	arid	coarse	1.08	7.7	6.4	32.4
182	31	Hattab et al., 2019	vegetable	arid	coarse	1.11	7.8	1.3	2.3
183	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	23.0	15.5
184	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	42.3	16.6
185	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	30.1	27.4
186	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	41.1	37.5
187	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	24.9	13.8
188	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	18.3	12.7
189	32	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	25.1	12.3
190	33	Vaitkevičienė et al., 2020	vegetable	boreal	medium	2.40	5.4	15.8	14.4
191	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	12.2	13.2
192	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	11.9	11.7
193	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	11.5	12.0
194	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	10.9	11.2
195	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	12.9	13.2
196	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	11.7	13.2
197	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	11.0	11.7
198	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	14.8	12.0
199	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	10.3	11.2
200	34	Wierzbowska et al., 2018	vegetable	warm temperate	medium	10.30	5.5	13.8	13.2
201	35	Hajšlová et al., 2005	vegetable	warm temperate	medium	2.90	5.9	3.7	2.4
202	35	Hajšlová et al., 2005	vegetable	warm temperate	medium	2.90	5.9	2.6	3.2
203	35	Hajšlová et al., 2005	vegetable	warm temperate	medium	2.90	5.9	1.5	2.4
204	35	Hajšlová et al., 2005	vegetable	warm temperate	fine	2.30	7.4	3.7	2.8
205	35	Hajšlová et al., 2005	vegetable	warm temperate	fine	2.30	7.4	2.9	2.6
206	35	Hajšlová et al., 2005	vegetable	warm temperate	fine	2.30	7.4	2.4	2.6

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
207	36	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	51.2	45.8
208	36	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	18.5	17.3
209	36	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	29.7	29.9
210	36	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	8.7	9.3
211	36	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	24.4	21.4
212	37	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	55.1	50.4
213	37	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	50.2	44.3
214	37	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	51.4	38.7
215	37	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	48.3	53.4
216	38	Armesto et al., 2020	vegetable	warm temperate	medium	5.20	4.9	5.5	2.6
217	39	Suja et al., 2017	vegetable	equatorial	fine	0.51	5.1	84.8	83.9
218	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	121.3	40.2
219	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	80.1	40.2
220	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	84.0	40.2
221	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	68.0	40.2
222	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	54.1	40.2
223	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	85.0	40.2
224	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	79.7	40.2
225	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	90.0	40.2
226	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	133.0	40.2
227	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	61.0	40.2
228	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	111.0	40.2
229	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	69.0	40.2
230	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	98.0	40.2
231	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	69.0	40.2
232	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	82.0	40.2
233	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	93.0	40.2
234	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	76.4	40.2
235	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	87.9	44.4
236	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	92.9	44.4

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
237	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	95.7	44.4
238	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	75.4	44.4
239	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	67.8	44.4
240	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	76.1	44.4
241	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	84.8	44.4
242	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	99.2	44.4
243	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	87.0	44.4
244	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	92.8	44.4
245	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	74.5	44.4
246	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	72.4	44.4
247	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	141.2	44.4
248	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	69.6	44.4
249	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	56.1	44.4
250	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	84.6	44.4
251	40	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	95.3	44.4
252	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	48.0	40.6
253	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	23.0	40.6
254	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	33.8	40.6
255	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	40.6	40.6
256	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	41.5	40.6
257	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	37.3	40.6
258	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	58.3	40.6
259	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	34.2	40.6
260	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	32.5	40.6
261	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	46.9	40.6
262	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	57.9	40.6
263	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	43.8	40.6
264	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	58.2	40.6
265	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	47.6	40.6
266	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	44.6	40.6

Observation No.	**Study No.**	**Study**	**Crop**	**Climate**	**Texture**	**SOC (%)**	**pH**	**Zn_Org (mg kg^{-1})**	**Zn_Conv (mg kg^{-1})**
267	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	54.7	40.6
268	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	47.8	40.6
269	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	45.0	46.5
270	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	46.0	46.5
271	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	47.1	46.5
272	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	65.0	46.5
273	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	48.0	46.5
274	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	40.2	46.5
275	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	97.0	46.5
276	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	35.2	46.5
277	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	90.5	46.5
278	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	56.2	46.5
279	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	34.1	46.5
280	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	31.3	46.5
281	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	32.1	46.5
282	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	35.3	46.5
283	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	56.5	46.5
284	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	31.1	46.5
285	41	Citak and Sonmez, 2010	vegetable	warm temperate	fine	0.86	8.2	30.7	46.5
286	42	Zarzyńska and Pietraszko, 2021	vegetable	warm temperate	fine	6.60	6.7	14.1	13.5
287	43	Kunnam et al., 2022	cereal	equatorial	fine	1.37	4.7	27.7	27.3
288	43	Kunnam et al., 2022	cereal	equatorial	fine	1.37	4.7	29.0	16.9
289	44	Meagy et al., 2016	vegetable	boreal	coarse	4.70	6.6	71.0	73.0
290	45	Guilherme et al., 2020	vegetable	warm temperate	fine	0.96	6.2	19.2	25.0
291	45	Guilherme et al., 2020	vegetable	warm temperate	fine	0.96	6.2	15.7	18.6
292	46	Suja et al., 2012	vegetable	equatorial	fine	1.03	4.2	110.2	116.2
293	47	Wszelaki et al., 2005	vegetable	warm temperate	medium	0.60	6.2	30.7	29.4
294	47	Wszelaki et al., 2005	vegetable	warm temperate	medium	0.60	6.2	32.6	29.4
295	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.3	15.5
296	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.7	15.5

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Zn_Org (mg kg^{-1})	Zn_Conv (mg kg^{-1})
297	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.2	15.5
298	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	16.2	15.5
299	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.2	15.5
300	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.2	15.5
301	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.0	15.5
302	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	16.5	15.5
303	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	16.7	15.5
304	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	16.2	15.5
305	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	15.8	15.5
306	48	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	17.5	15.5
307	49	Suja et al., 2016	vegetable	equatorial	fine	1.60	5.5	77.6	73.9
308	50	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	15.1	12.2
309	50	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	7.0	4.3
310	50	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	14.6	11.1
311	50	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	5.6	3.7

Supplemental Table 2. Dataset on iron (Fe) concentration in edible crop parts under organic and conventional agriculture

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
1	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.90	7.1	92.3	131.1
2	1	Tziouvalekas el al., 2022	legume	arid	fine	0.67	7.8	71.9	72.9
3	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.67	8.1	122.7	136.9
4	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.02	7.9	155.2	143.0
5	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.87	7.0	77.5	84.0
6	1	Tziouvalekas el al., 2022	legume	arid	fine	0.64	7.2	76.7	71.1
7	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.58	8.1	266.9	487.7
8	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.04	7.3	109.3	110.7
9	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	20.9	20.9
10	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	7.0	8.5
11	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	19.6	23.2
12	2	Warman and Havard, 1998	potato	boreal	coarse	1.90	5.5	23.1	19.3
13	2	Warman and Havard, 1998	potato	boreal	coarse	1.90	5.5	15.5	18.5
14	2	Warman and Havard, 1998	potato	boreal	coarse	1.90	5.5	26.8	25.5
15	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	56.5	47.5
16	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	53.8	43.4
17	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	63.5	47.4
18	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	57.3	50.7
19	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	61.3	45.7
20	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	57.0	49.0
21	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	47.0	41.0
22	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	33.7	41.5
23	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	29.0	34.0
24	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	39.2	36.4
25	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	57.0	47.7
26	6	Golijan et al., 2022	cereal	warm temperate	medium	1.90	7.6	8.8	10.1
27	6	Golijan et al., 2022	cereal	warm temperate	medium	1.90	7.6	7.1	7.3
28	6	Golijan et al., 2022	legume	warm temperate	fine	2.20	7.1	27.3	18.6
29	6	Golijan et al., 2022	cereal	warm temperate	medium	3.00	7.7	122.6	94.3

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
30	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	13.5	13.9
31	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	10.5	10.6
32	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	14.2	13.8
33	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	16.5	17.0
34	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	13.1	18.4
35	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	17.0	14.0
36	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	14.9	6.6
37	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	26.0	20.6
38	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	31.5	18.0
39	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	10.0	9.8
40	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	16.4	7.6
41	7	Liu et al., 2020	cereal	warm temperate	medium	1.30	6.0	9.3	13.2
42	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	29.2	31.9
43	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	34.9	36.8
44	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	30.6	40.4
45	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	33.4	39.3
46	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	29.2	33.8
47	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	34.9	52.9
48	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	30.6	38.7
49	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	33.4	42.6
50	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	29.2	30.8
51	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	34.9	49.4
52	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	30.6	36.7
53	8	Jakobsone et al., 2018	cereal	warm temperate	coarse	1.60	5.6	33.4	38.3
54	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	46.0	69.0
55	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	71.0	57.0
56	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	35.0	33.0
57	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	34.0	32.0
58	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	41.0	42.0
59	9	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	41.0	39.0

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
60	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	38.0	37.0
61	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	40.0	39.0
62	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	37.0	41.0
63	9	Park et al., 2015	cereal	boreal	medium	2.80	6.6	36.0	41.0
64	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.2	29.0	33.0
65	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.9	18.0	19.0
66	10	Ryan et al., 2004	cereal	arid	medium	0.60	5.8	20.0	21.0
67	10	Ryan et al., 2004	cereal	arid	medium	0.60	6.1	18.0	22.0
68	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	55.4	65.8
69	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	68.0	69.4
70	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	54.0	61.9
71	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	52.2	61.3
72	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	56.2	63.0
73	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	46.8	52.3
74	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	52.6	63.7
75	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	50.7	53.8
76	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	50.7	77.0
77	11	Legzdina et al., 2014	cereal	boreal	coarse	1.70	5.5	45.6	48.9
78	12	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	39.7	43.2
79	12	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	47.0	46.2
80	12	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	57.5	64.6
81	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	36.5	44.2
82	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	33.5	45.2
83	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	41.2	44.0
84	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	36.5	45.8
85	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	33.5	46.5
86	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	41.2	48.7
87	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	36.5	44.5
88	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	33.5	48.0
89	13	Jakobsone et a., 2019	cereal	warm temperate	medium	1.60	5.6	41.2	48.9

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
90	14	Murphy et al., 2008	cereal	warm temperate	medium	1.68	5.7	28.6	29.2
91	15	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	81.6	71.3
92	15	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	117.3	97.4
93	16	Singh et al., 2024	legume	warm temperate	fine	0.89	7.3	212.3	106.3
94	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	16.0	31.1
95	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	26.3	16.6
96	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	14.7	41.0
97	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	14.4	15.7
98	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	16.6	28.2
99	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	30.8	24.2
100	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	26.2	16.4
101	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	15.6	28.1
102	17	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	16.0	28.3
103	18	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	32.9	38.3
104	18	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	36.4	38.3
105	18	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	37.0	37.1
106	18	Laursen et al., 2011	cereal	warm temperate	coarse	2.20	5.3	29.8	37.1
107	18	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	64.0	64.1
108	18	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	66.5	64.1
109	18	Laursen et al., 2011	potato	warm temperate	coarse	1.16	5.3	21.0	20.0
110	18	Laursen et al., 2011	potato	warm temperate	coarse	1.16	5.3	17.6	20.0
111	19	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	28.4	40.5
112	19	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	32.5	39.9
113	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	41.8	32.6
114	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	30.7	29.4
115	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	28.3	27.0
116	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	25.5	29.1
117	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	29.4	33.0

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
118	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	42.8	35.7
119	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	68.1	70.3
120	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	53.0	71.1
121	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	32.8	53.7
122	20	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	46.2	39.5
123	21	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	37.9	37.6
124	21	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	42.2	37.6
125	21	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	40.9	39.5
126	21	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	38.6	39.5
127	22	Fernández-Canto et al., 2024	cereal	warm temperate	medium	5.20	4.9	20.1	19.5
128	23	Gopinath et al., 2023	legume	equatorial	coarse	0.43	6.5	35.6	36.7
129	23	Gopinath et al., 2023	legume	equatorial	coarse	0.43	6.5	37.0	30.9
130	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	25.6	30.4
131	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	24.0	20.0
132	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	29.2	36.0
133	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	25.0	23.0
134	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	54.2	55.2
135	24	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	22.4	27.2
136	25	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	2.3	2.3
137	25	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	2.1	2.3
138	25	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	2.3	2.3
139	25	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	2.0	2.3
140	25	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	3.1	2.3
141	26	Hattab et al., 2019	vegetable	arid	coarse	1.08	7.7	46.8	23.6
142	26	Hattab et al., 2019	vegetable	arid	coarse	1.11	7.8	248.3	198.1
143	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	29.8	33.5
144	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	22.7	34.3

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
145	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	31.6	33.5
146	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	41.2	72.4
147	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	11.2	6.9
148	27	Głodowska and Krawczyk, 2017	potato	warm temperate	coarse	4.30	6.9	17.9	23.8
149	27	Głodowska and Krawczyk, 2017	vegetable	warm temperate	coarse	4.30	6.9	13.2	7.8
150	28	Vaitkevičienė et al., 2020	potato	boreal	medium	2.40	5.4	127.7	57.5
151	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	48.3	63.4
152	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	40.9	48.1
153	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	49.0	57.2
154	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	41.7	60.4
155	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	55.6	61.6
156	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	53.4	63.4
157	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	40.7	48.1
158	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	41.6	57.2
159	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	41.1	60.4
160	29	Wierzbowska et al., 2018	potato	warm temperate	medium	10.30	5.5	58.4	61.6
161	30	Hajšlová et al., 2005	potato	warm temperate	medium	2.90	5.9	3.7	3.4
162	30	Hajšlová et al., 2005	potato	warm temperate	medium	2.90	5.9	9.7	13.0
163	30	Hajšlová et al., 2005	potato	warm temperate	medium	2.90	5.9	4.3	3.4
164	30	Hajšlová et al., 2005	potato	warm temperate	fine	2.30	7.4	4.5	3.8
165	30	Hajšlová et al., 2005	potato	warm temperate	fine	2.30	7.4	11.8	10.7
166	30	Hajšlová et al., 2005	potato	warm temperate	fine	2.30	7.4	3.8	4.6
167	31	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	78.4	68.8
168	31	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	52.0	46.0
169	31	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	95.2	145.2
170	31	Maqueda et al., 2011	potato	warm temperate	medium	0.76	8.0	64.8	86.4

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
171	31	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	241.2	241.2
172	32	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	3890.0	3820.0
173	32	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	3820.0	3580.0
174	32	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	3530.0	3390.0
175	32	Sofo et al., 2016	vegetable	warm temperate	coarse	2.70	6.7	3960.0	3520.0
176	33	Armesto et al., 2020	vegetable	warm temperate	medium	5.20	4.9	12.0	12.3
177	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	374.0	634.0
178	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	311.0	634.0
179	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	377.0	634.0
180	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	342.0	634.0
181	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	188.0	634.0
182	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	248.0	634.0
183	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	313.0	634.0
184	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	377.0	634.0
185	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	436.0	634.0
186	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	236.0	634.0
187	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	322.0	634.0
188	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	286.0	634.0
189	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	465.0	634.0
190	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	452.0	634.0
191	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	373.0	634.0
192	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	371.0	634.0
193	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	326.0	634.0
194	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	516.0	500.0
195	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	916.0	500.0
196	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	724.0	500.0
197	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	663.0	500.0
198	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	903.0	500.0
199	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	917.0	500.0
200	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	938.0	500.0

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
201	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	766.0	500.0
202	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	759.0	500.0
203	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	1255.0	500.0
204	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	764.0	500.0
205	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	861.0	500.0
206	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	972.0	500.0
207	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	714.0	500.0
208	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	877.0	500.0
209	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	713.0	500.0
210	34	Citak and Sonmez, 2009	vegetable	warm temperate	fine	1.01	8.1	499.0	500.0
211	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	55.0	76.7
212	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	39.3	76.7
213	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	40.6	76.7
214	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	59.8	76.7
215	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	72.2	76.7
216	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	43.6	76.7
217	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	69.0	76.7
218	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	52.8	76.7
219	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	48.7	76.7
220	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	56.7	76.7
221	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	88.2	76.7
222	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	78.3	76.7
223	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	85.4	76.7
224	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	54.6	76.7
225	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	74.4	76.7
226	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	88.2	76.7
227	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	59.1	76.7
228	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	117.1	74.3
229	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	92.3	74.3
230	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	71.7	74.3

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
231	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	115.2	74.3
232	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	89.2	74.3
233	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	81.4	74.3
234	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	86.2	74.3
235	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	102.8	74.3
236	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	84.1	74.3
237	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	77.3	74.3
238	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	97.2	74.3
239	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	70.0	74.3
240	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	106.1	74.3
241	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	120.3	74.3
242	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	123.0	74.3
243	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	95.4	74.3
244	35	Citak and Sonmez, 2010	vegetable	warm temperate	fine	1.01	8.1	74.9	74.3
245	36	Zarzyńska and Pietraszko, 2021	potato	warm temperate	fine	6.60	6.7	4.4	40.7
246	37	Kunnam et al., 2022	cereal	equatorial	fine	1.37	4.7	41.5	22.5
247	37	Kunnam et al., 2022	cereal	equatorial	fine	1.37	4.7	40.6	19.6
248	38	Meagy et al., 2016	vegetable	boreal	coarse	4.70	6.6	314.0	392.0
249	39	Guilherme et al., 2020	vegetable	warm temperate	fine	0.96	6.2	84.1	64.7
250	39	Guilherme et al., 2020	vegetable	warm temperate	fine	0.96	6.2	68.0	73.6
251	40	Suja et al., 2012	vegetable	equatorial	fine	1.03	4.2	719.0	866.0
252	41	Wszelaki et al., 2005	potato	warm temperate	medium	0.60	6.2	102.9	51.9
253	41	Wszelaki et al., 2005	potato	warm temperate	medium	0.60	6.2	96.7	51.9
254	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	47.0	42.1
255	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	52.2	42.1
256	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	44.7	42.1
257	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	46.1	42.1
258	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	45.8	42.1
259	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	46.6	42.1

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Fe_Org (mg kg^{-1})	Fe_Conv (mg kg^{-1})
260	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	45.8	42.1
261	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	48.3	42.1
262	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	47.3	42.1
263	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	48.0	42.1
264	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	44.7	42.1
265	42	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	46.6	42.1
266	43	Suja et al., 2016	vegetable	equatorial	fine	1.60	5.5	684.0	644.0
267	44	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	81.8	61.2
268	44	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	20.0	11.7
269	44	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	45.8	35.5
270	44	Czech et al., 2022	vegetable	warm temperate	medium	1.60	6.0	14.4	12.8
271	45	L-Baeckstrom et al., 2006	cereal	boreal	medium	4.70	6.4	27.3	23.9
272	45	L-Baeckstrom et al., 2006	cereal	boreal	medium	4.70	6.2	39.5	30.6
273	45	L-Baeckstrom et al., 2006	cereal	boreal	medium	4.70	6.2	30.0	31.9
274	46	Paulauskiene et al., 2023	vegetable	boreal	medium	0.90	7.1	15.7	15.0
275	46	Paulauskiene et al., 2023	vegetable	boreal	medium	0.90	7.1	17.4	11.9
276	46	Paulauskiene et al., 2023	vegetable	boreal	medium	0.90	7.1	13.9	12.3
277	47	Lombardo et al., 2014	potato	warm temperate	coarse	0.75	7.3	21.9	16.9
278	47	Lombardo et al., 2014	potato	warm temperate	coarse	0.75	7.3	15.9	24.8
279	47	Lombardo et al., 2014	potato	warm temperate	coarse	0.75	7.3	22.8	30.6
280	48	de Lima et al., 2024	vegetable	equatorial	coarse	0.71	5.7	2.3	2.0
281	48	de Lima et al., 2024	vegetable	equatorial	coarse	0.71	5.7	0.7	0.8

Supplemental Table 3. Dataset on crop yield under organic and conventional agriculture

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Yield_Org (kg ha^{-1})	Yield_Conv (kg ha^{-1})
1	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.90	7.1	960	1660
2	1	Tziouvalekas el al., 2022	legume	arid	fine	0.67	7.8	1100	890
3	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.67	8.1	1880	1380
4	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.02	7.9	1870	1560
5	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.87	7.0	940	910
6	1	Tziouvalekas el al., 2022	legume	arid	fine	0.64	7.2	460	1220
7	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	0.58	8.1	1180	970
8	1	Tziouvalekas el al., 2022	legume	warm temperate	fine	1.04	7.3	2280	2890
9	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	4800	4730
10	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	11160	12950
11	2	Warman and Havard, 1998	cereal	boreal	coarse	1.90	5.5	5970	8920
12	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	24470	27560
13	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	14020	13330
14	2	Warman and Havard, 1998	vegetable	boreal	coarse	1.90	5.5	24490	33550
15	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	2380	4040
16	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	2650	4660
17	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	2780	5570
18	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	2800	5090
19	3	Nelson et al., 2011	cereal	boreal	medium	6.79	6.4	3110	5730
20	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	899	2198
21	4	Turmel et al., 2009	cereal	boreal	fine	4.47	7.4	1188	2518
22	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	3720	4210
23	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	4530	5110
24	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	2690	2970
25	5	Kwiatkowski et al., 2015	cereal	warm temperate	medium	1.60	6.3	1420	1640
26	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	1295	3745
27	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	5505	3905
28	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	3930	3950
29	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	5410	4035

Observation No.	**Study No.**	**Study**	**Crop**	**Climate**	**Texture**	**SOC (%)**	**pH**	**Yield_Org (kg ha^{-1})**	**Yield_Conv (kg ha^{-1})**
30	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	2560	2825
31	6	Park et al., 2015	cereal	warm temperate	medium	2.10	6.2	2560	3020
32	6	Park et al., 2015	cereal	boreal	medium	2.80	6.6	1963	2482
33	6	Park et al., 2015	cereal	boreal	medium	2.80	6.6	2174	2447
34	6	Park et al., 2015	cereal	boreal	medium	2.80	6.6	3051	3638
35	6	Park et al., 2015	cereal	boreal	medium	2.80	6.6	3114	4056
36	7	Ryan et al., 2004	cereal	arid	medium	0.60	5.2	1870	2260
37	7	Ryan et al., 2004	cereal	arid	medium	0.60	5.9	2820	7710
38	7	Ryan et al., 2004	cereal	arid	medium	0.60	5.8	3860	6530
39	7	Ryan et al., 2004	cereal	arid	medium	0.60	6.1	870	5470
40	8	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	2470	5350
41	8	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	1020	3330
42	8	Visioli et al., 2020	cereal	warm temperate	fine	1.50	5.9	860	2990
43	9	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	3990	4200
44	9	Thakur et al., 2020	cereal	equatorial	fine	0.57	5.4	4980	6040
45	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	1900	2800
46	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	2200	3100
47	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	2100	5300
48	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	1400	2900
49	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	3700	2700
50	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	1400	4000
51	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	2300	3000
52	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	1700	2100
53	10	Pandino et al., 2020	cereal	warm temperate	fine	1.20	8.0	2300	3600
54	11	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	3100	6940
55	11	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	1560	6940
56	11	Laursen et al., 2011	cereal	warm temperate	coarse	0.99	5.3	3400	5050
57	11	Laursen et al., 2011	cereal	warm temperate	coarse	2.20	5.3	3180	5050
58	11	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	2510	2510
59	11	Laursen et al., 2011	legume	warm temperate	coarse	2.20	5.3	2150	2510

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Yield_Org (kg ha^{-1})	Yield_Conv (kg ha^{-1})
60	11	Laursen et al., 2011	vegetable	warm temperate	coarse	1.16	5.3	6190	9410
61	11	Laursen et al., 2011	vegetable	warm temperate	coarse	1.16	5.3	5210	9410
62	12	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	2126	2019
63	12	Srikumar and Öckerman, 1991	cereal	warm temperate	fine	4.70	5.3	1432	2873
64	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	586	1952
65	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1521	3606
66	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1691	3266
67	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1789	2885
68	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1140	2508
69	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1675	3183
70	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1904	3775
71	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1479	2038
72	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1014	2038
73	13	Hou et al., 2025	cereal	boreal	fine	4.47	7.4	1256	3146
74	14	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	945	338
75	14	Omondi et al., 2021	cereal	warm temperate	medium	2.71	6.8	882	338
76	14	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	918	898
77	14	Omondi et al., 2021	cereal	warm temperate	medium	2.74	6.8	834	898
78	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	31010	26410
79	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	33900	31150
80	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	18860	21310
81	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	56000	52330
82	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	53040	56360
83	15	Warman and Havard, 1997	vegetable	boreal	coarse	1.90	5.5	27680	30630
84	16	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	81665	82785
85	16	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	76905	82785
86	16	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	84525	82785
87	16	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	80690	82785

Observation No.	Study No.	Study	Crop	Climate	Texture	SOC (%)	pH	Yield_Org (kg ha^{-1})	Yield_Conv (kg ha^{-1})
88	16	Polat et al., 2010	vegetable	warm temperate	coarse	1.09	7.9	77330	82785
89	17	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	7000	11000
90	17	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	11000	19000
91	17	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	67000	60000
92	17	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	33000	33000
93	17	Maqueda et al., 2011	vegetable	warm temperate	medium	0.76	8.0	14000	18000
94	18	Suja et al., 2012	vegetable	equatorial	fine	1.03	4.2	57097	47609
95	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3001	3990
96	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3468	3990
97	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3322	3990
98	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3656	3990
99	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3391	3990
100	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3566	3990
101	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3364	3990
102	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3872	3990
103	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3447	3990
104	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3614	3990
105	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3287	3990
106	19	Saha et al., 2007	cereal	warm temperate	fine	0.08	5.9	3482	3990
107	20	Suja et al., 2016	vegetable	equatorial	fine	1.60	5.5	27720	28550