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Environmental Assessments of Triticale Cultivation: Implications for Crop Rotation and Soil Health

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Abstract Triticale, a hybrid cereal, has gained attention for its potential contributions to sustainable agriculture. This study focuses on the environmental assessments of triticale cultivation, particularly its implications for crop rotation and soil health, explores the agronomic characteristics of triticale, emphasizing its historical background, suitability for crop rotations, and soil health benefits, and assesses the environmental impacts of triticale on soil structure, microbial activity, organic matter content, and erosion control. A case study was conducted to evaluate the effects of triticale cultivation on soil health indicators, offering insights into its role in enhancing soil fertility, weed suppression, and pest management within crop rotation systems. While triticale presents benefits for improving soil health and agricultural sustainability, challenges related to environmental constraints, soil management, and economic factors were identified. This study concludes with recommendations for integrating triticale into sustainable crop rotations and offers guidelines for best practices in soil health improvement. Future research should focus on optimizing triticale's role in sustainable farming practices, supporting long-term soil health and crop productivity.
Keywords Triticale cultivation; Crop rotation; Soil health; Environmental assessment; Sustainable agriculture

1 Introduction

Triticale (×*Triticosecale* Wittmack) is a hybrid cereal crop developed by crossing wheat (*Triticum* spp.) and rye (*Secale cereale* L.). This man-made species combines the high yield potential and grain quality of wheat with the vigor and resistance to diseases and abiotic stresses of rye, making it suitable for cultivation in less favorable environments (Kwiatek et al., 2023; Ma and Cai, 2024). Triticale is primarily used for forage and grain production, but it is also gaining popularity as a cover crop due to its ability to improve soil health and reduce nutrient leaching (Ayalew et al., 2018; Mergoum et al., 2019). The crop's adaptability to various environmental conditions and its potential for high biomass yield make it a valuable addition to agricultural systems (Mcgoverin et al., 2011; Faccini et al., 2023).

Environmental assessments are crucial in agriculture to ensure sustainable farming practices that do not compromise soil health or ecosystem services. These assessments help in understanding the impact of different crops and farming techniques on soil properties, nutrient cycling, and overall environmental sustainability (Dias et al., 2015). For instance, dual-purpose cover crops like triticale can provide significant ecosystem services, such as nutrient management and carbon sequestration, while also offering additional forage production (Glaze-Corcoran et al., 2023). Evaluating the environmental implications of triticale cultivation can guide farmers in making informed decisions about crop rotation and soil management practices, ultimately leading to more resilient and sustainable agricultural systems.

This study assesses the environmental impact of planting black oats, particularly its effects on crop rotation and soil health, including the evaluation of the ability of crops to improve soil properties, manage nutrients, and promote sustainable agricultural practices, aiming to provide insights to optimize the use of black oats in agricultural systems while ensuring economic and environmental benefits.

2 Triticale Cultivation and Its Agronomic Characteristics

2.1 Historical background of triticale

Triticale (×*Triticosecale Wittm.*) is a hybrid cereal derived from the cross between wheat (*Triticum* spp.) and rye (*Secale cereale* L.) (Figure 1). It was first developed in the late 19th century with the aim of combining the high yield potential and grain quality of wheat with the disease resistance and environmental tolerance of rye. Over the years, triticale has been improved through selective breeding to enhance its agronomic traits, making it a viable crop for various agricultural systems (Ketterings et al., 2015; Jańczak-Pieniążek, 2023).

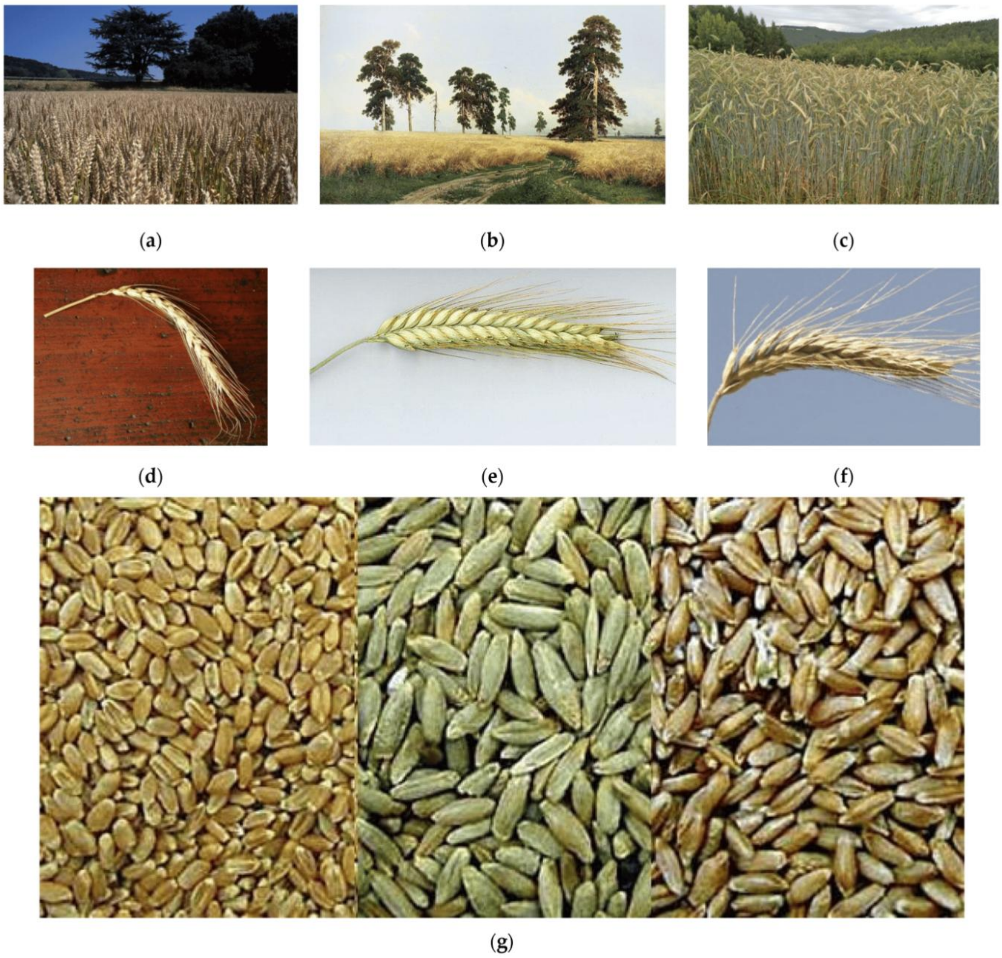

Figure 1 Phenotypes of wheat (*Triticum aestivum*; left), rye (*Secale cereale*; middle), and their hybrid, triticale (right): (a-c) cultivation fields; (d-f) single ears; and (g) seeds (Adapted from Gaviley et al., 2024)

2.2 Agronomic traits favorable for crop rotation

Triticale exhibits several agronomic traits that make it favorable for crop rotation systems. It has greater early vigor, a longer spike formation phase, reduced tillering, increased remobilization of carbohydrates to the grain, early vigorous root growth, and higher transpiration use efficiency compared to wheat (Bassu et al., 2011). These traits contribute to its ability to out-yield wheat in both favorable and unfavorable growing conditions, making it a robust option for diverse environmental conditions (Tamagno et al., 2022).

Additionally, triticale's ability to fix nitrogen when grown in rotation with legumes such as cowpea, faba bean, and pea, enhances soil nitrogen levels, which benefits subsequent crops (Oliveira et al., 2019). This nitrogen-fixing capability is particularly beneficial in Mediterranean climates where water availability can be a limiting factor. Furthermore, triticale's adaptability to saline-alkali soils and its positive impact on soil microbial communities make it an excellent candidate for improving soil health and productivity in challenging environments (Zhang et al., 2022).

2.3 Soil health benefits of triticale cultivation

Triticale cultivation offers several benefits for soil health. Its robust root system helps in alleviating soil compaction, which is crucial for maintaining soil structure and promoting water infiltration and root penetration (Calonego and Rosolem, 2010). The inclusion of triticale in crop rotations has been shown to reduce soil salinity and improve soil microbial diversity, which are essential for maintaining soil fertility and health.

Moreover, triticale's role in crop rotations can lead to increased soil organic matter and nutrient cycling, thereby enhancing soil fertility. For instance, integrating triticale with cover crops such as millet and sorghum can improve soil nitrogen levels and reduce nitrogen leaching, which is beneficial for subsequent crops like soybean. The use of triticale in organic farming systems has also demonstrated positive residual effects on soil nutrient status and crop yields, further underscoring its value in sustainable agriculture (Kayser et al., 2010).

Triticale's agronomic characteristics and its positive impact on soil health make it a valuable crop for rotation systems aimed at enhancing agricultural productivity and sustainability. Its ability to thrive in diverse environmental conditions and improve soil fertility highlights its potential as a key component in modern agricultural practices.

3 Environmental Impacts of Triticale Cultivation

3.1 Impact on soil structure and composition

Triticale cultivation has been shown to influence soil structure and composition significantly. Studies indicate that crop rotations involving triticale can affect soil air-water properties, particularly macroporosity. For instance, rotations with triticale and other crops like sugar beet and faba bean have been observed to alter the soil moisture characteristic curve, impacting water retention and macropore volume. The highest macropore volume was noted under sugar beet, which increased the volume of regular, irregular, and elongated macropores compared to triticale (Głąb et al., 2013). Additionally, triticale followed by sunn hemp in a no-till system improved soil aggregation and increased total organic carbon and nitrogen concentrations, suggesting that triticale can enhance soil structure when used in appropriate rotations (Rigon et al., 2020).

3.2 Effects on soil microbial activity

Triticale cultivation positively impacts soil microbial activity, especially when integrated into crop rotations. A study on the rotation of triticale and sweet sorghum in saline-alkali soils demonstrated a significant increase in soil microbial communities, including bacteria and Actinomycetes, which are crucial for soil health (Zhang et al., 2022). Moreover, crop rotations that include triticale have been shown to enhance soil microbial biomass carbon and nitrogen pools, which are essential for nutrient cycling and soil fertility. This is particularly evident when triticale is part of a diverse crop rotation system, which can increase microbial biomass by over 20%.

3.3 Contribution to soil organic matter

Triticale plays a vital role in contributing to soil organic matter, especially when used in crop rotations. Research indicates that rotations involving triticale can increase total soil carbon and nitrogen concentrations. For example, triticale in rotation with other crops like sunn hemp has been shown to enhance soil organic carbon and nitrogen fractions, contributing to improved soil quality. Additionally, crop rotations that include triticale can increase soil organic matter by incorporating high-quality organic inputs, which are crucial for maintaining soil health and productivity (McDaniel et al., 2014).

3.4 Implications for soil erosion control

Triticale cultivation can also aid in soil erosion control. Organic farming practices, which often include crop rotations with triticale, have been shown to enhance soil microbial abundance and activity, contributing to better soil structure and reduced erosion (Lori et al., 2017). Furthermore, the inclusion of triticale in crop rotations can improve soil cover and reduce soil salinity, which are critical factors in preventing soil erosion. For instance, high-density planting of triticale in saline soils has been associated with decreased soil salt contents and improved soil structure, thereby reducing the risk of erosion.

4 Triticale in Crop Rotation Systems

4.1 Role of triticale in diversifying crop rotations

Triticale plays a significant role in diversifying crop rotations, which is crucial for sustainable agricultural practices. Diversified crop rotations, including triticale, can reduce weed density by altering the ecological conditions that weeds are exposed to, thereby reducing their prevalence and the selection pressure for herbicide resistance (Figure 2) (Weisberger et al., 2019). Additionally, incorporating triticale into crop rotations can enhance the overall yield of subsequent crops. For instance, a study in China demonstrated that crop rotation, including triticale, increased crop yields by an average of 20% compared to continuous monoculture practices (Zhao et al., 2020). This yield benefit is attributed to the varied planting dates and crop species richness that diversified rotations bring, which disrupts pest and weed cycles and improves soil health.

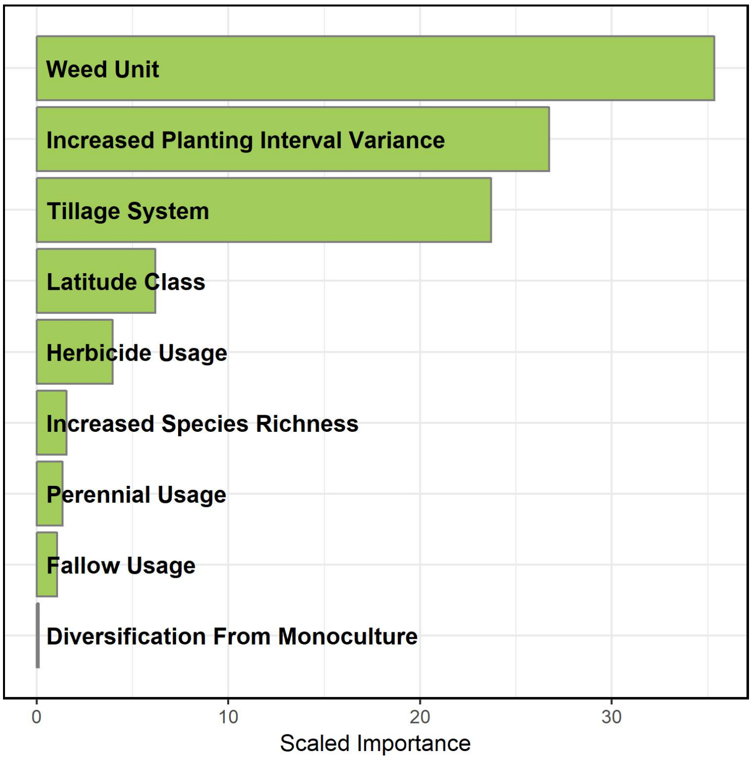

Figure 2 Scaled importance of nine predictors for weed density response to increased rotational diversity (Adopted from Weisberger et al., 2019)

Image caption: Variable importance derived from a generalized boosted regression tree (Adopted from Weisberger et al., 2019)

4.2 Enhancing soil fertility through crop rotation with triticale

Incorporating triticale into crop rotations can significantly enhance soil fertility. Triticale, when used in rotation with legumes, benefits from the nitrogen-fixing capabilities of legumes, which increase the soil's nitrogen content and improve the productivity of subsequent crops. For example, a study in a Mediterranean climate found that rotating triticale with legumes such as cowpea, faba bean, and pea improved cereal productivity by up to 59%, equivalent to the application of 153 kg of synthetic nitrogen per hectare (Oliveira et al., 2019). This improvement is due to the biologically fixed nitrogen from legumes, which remains in the soil and is available for the triticale crop, thereby reducing the need for synthetic fertilizers and promoting sustainable soil management.

4.3 Effects on weed suppression and pest management

Triticale in crop rotations has been shown to effectively suppress weeds and manage pests, contributing to healthier and more productive cropping systems (Derejko and Studnicki, 2019). A long-term study in Finland demonstrated that diversified crop rotations, including triticale, significantly reduced weed density and the severity of plant diseases such as wheat leaf blotch (Jalli et al., 2021). The study found that the most diverse crop rotations reduced weed density by 49% and decreased disease severity by 20% compared to monoculture systems.

Additionally, the use of triticale in rotation with other crops, such as vetch and rye, has been shown to achieve total winter weed suppression and reduce weed stands significantly during critical growth stages of subsequent crops (Fourie, 2016). These findings highlight the importance of triticale in integrated pest management strategies, reducing the reliance on chemical herbicides and promoting ecological balance in agricultural systems.

5 Case Study

5.1 Selection of case study location

The case study was conducted in East China, a region known for its saline-alkali soils, which pose significant challenges to agricultural productivity. This location was chosen due to its prevalent soil salinization issues, which restrict crop yield and biomass production for biofuels, making it an ideal site to assess the impact of triticale cultivation on soil health and crop rotation strategies (Zhang et al., 2022).

5.2 Methodology for assessing triticale cultivation impact

To evaluate the impact of triticale cultivation on soil health, a rotation system involving triticale and sweet sorghum was implemented. Various planting densities were tested to determine the optimal conditions for improving soil properties and crop yield. Soil samples were collected and analyzed for salt content, microbial community composition, and soil pore characteristics. Agronomic traits such as plant height, tiller number per plant, yield, and lodging rate were measured for both triticale and sweet sorghum (Głąb et al., 2013).

5.3 Results of the case study: soil health indicators

The results indicated that the rotation of triticale and sweet sorghum significantly decreased soil salt content compared to bare land plots. High-density planting of triticale (180×10^4 plants/ha) and sweet sorghum (7×10^4 plants/ha) was associated with increased counts of beneficial soil bacteria, Actinomycetes, and salt-tolerant Actinomycetes. Additionally, the soil under triticale cultivation showed improved macroporosity, which is crucial for water retention and root penetration. The highest macropore volume was observed in the Norfolk crop rotation system, which included sugar beet, spring triticale, faba bean, and winter triticale (Rigon and Calonego, 2020).

5.4 Implications for future crop rotation strategies

The findings from this case study suggest that incorporating triticale into crop rotation systems can enhance soil health by reducing salinity and improving soil structure. The increased microbial activity and improved soil porosity observed under triticale cultivation indicate that this crop can play a vital role in sustainable agricultural practices. Future crop rotation strategies should consider the inclusion of triticale, especially in regions with saline-alkali soils, to enhance soil health and maintain high crop yields. Additionally, the integration of legumes in rotation with triticale can further improve soil nitrogen levels and overall productivity, as evidenced by the positive effects of legume pre-crops on subsequent triticale yields (Kayser et al., 2010; Oliveira et al., 2019).

6 Challenges and Limitations of Triticale Cultivation

6.1 Environmental constraints

Triticale cultivation faces several environmental constraints that can impact its productivity and sustainability. Soil salinization is a significant issue, particularly in regions with saline-alkali soils. Studies have shown that rotating triticale with crops like sweet sorghum can help mitigate soil salt stress and improve soil conditions, but this requires careful management of planting densities and crop rotations (Zhang et al., 2022). Additionally, the effectiveness of crop rotations involving triticale can vary significantly based on environmental factors such as rainfall and soil texture. For instance, crop rotations in regions with moderate annual rainfall have shown less reliable yield benefits compared to those in areas with more favorable conditions (Zhao et al., 2020).

6.2 Soil management issues

Soil management is crucial for the successful cultivation of triticale. One of the primary challenges is maintaining soil structure and health. Long-term studies have indicated that different crop rotations involving triticale can influence soil air-water properties and macroporosity, which are essential for root growth and water retention. However, these effects are not always permanent and can vary depending on the specific crops used in the rotation (Głąb et al., 2013). Additionally, the choice of cover crops and their management can significantly impact soil carbon and nitrogen dynamics. For example, integrating triticale with cover crops like sunn hemp has been shown to improve soil aggregation and organic matter content, which are vital for long-term soil health (Rigon et al., 2020).

6.3 Economic and market considerations

Economic and market factors also pose challenges for triticale cultivation. While integrating triticale into crop rotations can enhance overall system productivity and provide additional forage, it can also lead to trade-offs in terms of yield and economic returns. For instance, replacing fallow periods with forage triticale in peanut monoculture systems has been shown to increase system productivity and water use efficiency but at the cost of reduced subsequent peanut yields (You et al., 2022). Moreover, the economic benefits of triticale cultivation can be influenced by the choice of cropping systems. Conventional systems tend to produce higher grain yields and better grain quality compared to integrated systems, which focus on sustainability and reduced chemical inputs (Jańczak-Pieniążek, 2023). Therefore, farmers need to carefully consider these trade-offs to optimize both economic returns and environmental sustainability (Cai, 2024).

7 Recommendations for Sustainable Triticale Cultivation

7.1 Best practices for soil health improvement

To enhance soil health in triticale cultivation, it is essential to adopt practices that improve soil structure, organic matter content, and microbial activity. One effective strategy is the use of cover crops. For instance, integrating triticale with cover crops like sunn hemp has been shown to improve soil aggregation and increase soil organic carbon (C) and nitrogen (N) fractions, which are crucial for maintaining soil fertility and structure (Rigon and Calonego, 2020). Additionally, rotating triticale with crops such as sweet sorghum can significantly reduce soil salinity, thereby improving soil conditions for subsequent crops (Zhang et al., 2022). Implementing no-till practices combined with appropriate cover cropping can further enhance soil health by reducing soil erosion and maintaining soil moisture.

7.2 Guidelines for integrating triticale into crop rotations

Integrating triticale into crop rotations can provide numerous agronomic benefits, including improved soil fertility and increased crop yields. Studies have shown that rotating triticale with legumes such as cowpea, faba bean, and pea can enhance soil nitrogen levels due to biological nitrogen fixation, which in turn benefits subsequent crops. Additionally, diversified crop rotations that include triticale can help manage weed populations and reduce the need for chemical herbicides, thus promoting a more sustainable agricultural system (Jastrzębska et al., 2023). For example, a rotation system involving triticale and sweet sorghum has been found to improve soil microbial communities and increase overall productivity in saline soils. It is recommended to design crop rotations that consider local environmental conditions, soil types, and crop compatibility to maximize the benefits of triticale integration (Zhao et al., 2020).

7.3 Policy implications for sustainable agriculture

To promote sustainable triticale cultivation, policymakers should consider supporting practices that enhance soil health and encourage diversified crop rotations. Policies could include incentives for farmers to adopt cover cropping and no-till practices, which have been shown to improve soil quality and reduce carbon emissions (Rigon et al., 2020). Additionally, providing subsidies or technical support for the integration of legumes into crop rotations can help increase soil nitrogen levels and reduce the reliance on synthetic fertilizers (Oliveira et al., 2019). Policymakers should also consider funding research and extension services to educate farmers on the benefits of sustainable practices and to develop region-specific guidelines for crop rotations that include triticale. By implementing these policies, it is possible to achieve a more sustainable and resilient agricultural system that supports long-term soil health and productivity.

8 Concluding Remarks

The cultivation of triticale within various crop rotation systems has demonstrated significant benefits for soil health and crop productivity. Studies have shown that incorporating triticale into crop rotations can enhance soil nitrogen levels, improve soil structure, and increase crop yields. For instance, the inclusion of legumes in crop rotations with triticale has been found to improve soil nitrogen availability and subsequent crop productivity, particularly under rainfed conditions. Additionally, rotating triticale with crops like sweet sorghum has been effective in reducing soil salinity and enhancing soil microbial communities, which are crucial for maintaining soil health in saline environments. Long-term studies have also indicated that crop rotations involving triticale can positively influence soil chemical properties, such as soil organic carbon and nutrient availability, thereby supporting sustainable agricultural practices.

Future research should focus on optimizing crop rotation schemes that include triticale to maximize both agronomic and environmental benefits. Investigating the long-term impacts of different crop rotations on soil health parameters, such as soil organic carbon sequestration and nitrogen mineralization, will be essential. Additionally, exploring the interactions between triticale and various cover crops, such as sunn hemp and forage sorghum, could provide insights into improving soil structure and reducing carbon emissions. Practical applications should also consider the regional variations in soil and climatic conditions to tailor crop rotation practices that enhance soil health and crop productivity. Moreover, integrating advanced soil health assessment tools, like the soil management assessment framework (SMAF), can help in monitoring and managing soil quality effectively.

Triticale plays a pivotal role in sustainable farming systems due to its adaptability and positive impact on soil health. Its inclusion in crop rotations not only boosts crop yields but also contributes to the long-term sustainability of agricultural practices by improving soil structure, enhancing nutrient cycling, and reducing soil degradation. The ability of triticale to thrive in various environmental conditions and its compatibility with other crops make it a valuable component of integrated cropping systems aimed at achieving sustainable agricultural production. As research continues to uncover the multifaceted benefits of triticale, its role in promoting sustainable farming practices will likely become even more pronounced, offering a viable solution to the challenges of modern agriculture.

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Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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