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Comparative efficacy of plant conditioners, essential oils versus fungicides in managing rust and powdery mildew diseases in winter wheat

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1 INTRODUCTION

1.1 Background of the study

Wheat has been a cornerstone of global food security for over 10,000 years, tracing its origins to the Fertile Crescent, where it was first domesticated (SHEWRY and HEY, 2015). Early agricultural societies selectively cultivated wheat for traits such as high yield and adaptability, enabling its expansion across continents through trade and migration. Over time, wheat became a staple crop in Europe and Asia before spreading to the Americas and Australia (SHEWRY and HEY, 2015). Today various wheat cultivars are grown worldwide, each adapted to specific climatic conditions. For instance, winter wheat thrives in temperate regions with cold winters, such as North America, Europe, and parts of Asia, where vernalization a prolonged cold period is necessary for flowering and optimal yield formation (SHEWRY and HEY, 2015).

According to the Food and Agriculture Organization (FAO), major wheat-producing nations, including the United States, Russia, China, and India, collectively account for over half of global wheat production (FAO, 2022). In Hungary, winter wheat has played a vital role in agriculture for centuries, deeply intertwined with the nation's agrarian history and economic development (HALMAI and VÁSÁRY, 2010). It remains the country’s most significant cereal crop, covering over one million hectares annually. The high protein content of Hungarian wheat makes it particularly valuable for breadmaking and food processing. With domestic production exceeding consumption, Hungary exports a substantial portion of its wheat, primarily to other European Union countries (HALMAI and VÁSÁRY, 2010).

On a global scale, wheat holds both economic and strategic significance as a staple food and a key export commodity (SMIL, 2000). Major wheat-exporting regions, including Russia, the United States, and the European Union, exert considerable influence over international markets, while import-dependent regions, such as parts of Africa and the Middle East, rely on global trade to meet their food demands (SMIL, 2000). However, climate change is increasingly threatening wheat production worldwide. Extreme weather events, prolonged droughts, and temperature fluctuations are affecting yields, necessitating the adoption of resilient agricultural practices and advanced breeding strategies to sustain global wheat productivity (ROSENZWEIG & TUBIELLO, 2007).

In addition to abiotic stressors, biotic factors, particularly fungal diseases, significantly constrain winter wheat yields. While a regional compendium lists 34 fungal diseases affecting wheat (GJAERUM et al., 1985), a broader global perspective identifies an even greater number (WIESE, 1977). Among the most damaging are rusts and powdery mildew, which pose a severe threat to wheat production worldwide (DEAN et al., 2012). Stem rust (*Puccinia graminis* f. sp. *tritici*) is especially devastating, while leaf rust (*Puccinia triticina*) and stripe rust (*Puccinia striiformis* f. sp. *tritici*) also cause significant economic losses. Hungary’s climate provides favorable conditions for these pathogens, necessitating robust disease management strategies. Powdery mildew (*Blumeria graminis*) is another widespread fungal disease in Hungarian wheat fields, particularly in humid conditions, further underscoring the need for effective control measures to minimize yield losses (NÉMETH, 2015).

Climate change significantly influences the dynamics of wheat rust and powdery mildew diseases through complex interactions with environmental factors. Warmer temperatures can accelerate the life cycle of these pathogens, leading to faster reproduction, earlier disease onset, and more rapid epidemic development (JIN et al., 2009). Temperature variations can also affect the expression of resistance genes in wheat, with some becoming less effective under higher temperatures, increasing the plant's susceptibility to infection (CHEN et al., 1995).

Water availability also plays a crucial role in disease development. High humidity and prolonged leaf wetness create favorable conditions for rust and powdery mildew, while changes in precipitation patterns and increased evapotranspiration may alter disease severity (TE BEEST et al., 2008). Although rust fungi typically thrive in humid environments, drought stress can weaken wheat plants, making them more vulnerable to infection (TZORTZAKIS and DHANAPALAN, 2014). Additionally, rising carbon dioxide levels can influence wheat physiology, potentially altering susceptibility to foliar pathogens such as rusts and powdery mildew. Changes in stomatal conductance, leaf structure, and carbon allocation can modify interactions between wheat and fungal pathogens, affecting disease development and severity (CHAKRABORTY et al., 2000).

Managing wheat diseases presents a significant financial burden in agriculture. Traditionally, disease control has relied on breeding resistant crop varieties, implementing sanitation measures to prevent pathogen spread through contaminated soil or seeds, and applying fungicides to eliminate fungal pathogens (BRIEN, 2017). However, concerns over fungicide residues in the agricultural ecosystem and their potential impact on food safety have led to restrictions and bans on several chemical fungicides (BRIEN, 2017). As a result, interest has grown in biological control strategies and the use of natural compounds, particularly plant-derived substances, as sustainable alternatives to conventional fungicides (CHANG et al., 2022).

Essential oils, derived from aromatic plants, have emerged as promising natural fungicidal agents due to their complex mixtures of volatile, hydrophobic, and aromatic compounds with strong antimicrobial properties (SWAMY et al., 2016). These secondary metabolites exhibit a broad range of biological activities, including insect-repellent, antibacterial, antifungal, and antiviral effects. Their efficacy against fungal pathogens is attributed to the diverse chemical constituents they contain, such as alcohols, aldehydes, phenols, terpenes, and ketones (SARTORELLI et al., 2007; SWAMY et al., 2016). Given their potential to replace synthetic fungicides, essential oils are increasingly being explored for sustainable wheat disease management, offering an environmentally friendly approach to controlling major fungal pathogens (CHANG et al., 2022).

1.2 Problem statement

Winter wheat production in Hungary is increasingly threatened by fungal diseases, particularly rusts (leaf, stem, and stripe rust) and powdery mildew. These diseases significantly reduce yields and grain quality, posing economic risks to farmers and potential threats to national food security. Conventional disease management primarily relies on fungicide applications; however, concerns over their environmental impact, the emergence of fungicide-resistant pathogen strains, and food safety issues necessitate the exploration of more sustainable alternatives. Additionally, rising input costs associated with fungicide use place a financial strain on farmers, further underscoring the need for cost-effective disease management strategies.

Given these challenges, there is a critical need to identify and evaluate environmentally friendly and economically viable alternatives for managing fungal diseases in Hungarian winter wheat production. This study aims to address this need by assessing the efficacy of plant conditioners and essential oils in comparison to conventional fungicides for controlling rust and powdery mildew infections under Hungarian growing conditions. By exploring these alternative strategies, the research seeks to contribute to the development of sustainable disease management practices that reduce reliance on synthetic fungicides while maintaining wheat productivity and quality.

1.3 Justification

Winter wheat is a key crop in Hungary, contributing significantly to the economy and food security. Protecting it from fungal diseases, particularly rusts (leaf, stem, and stripe rust) and powdery mildew, is essential for maintaining productivity and ensuring the financial well-being of farmers. These diseases are prevalent in wheat-growing regions and can severely reduce both yield and grain quality. Research has demonstrated that early-season powdery mildew infections can result in yield losses of up to 25% in susceptible wheat varieties (JEVTIC et al., 2024). Traditionally, these diseases have been controlled through the use of synthetic fungicides. However, the extensive use of these chemicals has raised concerns about their environmental impact and potential harm to human health, including links to cancer, neurological disorders, and developmental delays in children (DARIO PISELLI, 2023). Additionally, overreliance on fungicides has led to the development of resistant pathogen strains, further diminishing their effectiveness. Fungicide resistance is becoming a widespread issue globally, with nearly 200 crop-pathogen combinations showing resistance to various fungicide groups (JOHN DAMICONE, 2017).

Given the limitations of synthetic fungicides, there is a growing need to explore alternative, sustainable disease management strategies. Recent research into plant conditioners and essential oils has shown promising antifungal properties, particularly in controlling powdery mildew. Studies have demonstrated the effectiveness of certain essential oils in managing this pathogen in various plant species (HEGAZI M.A, 2010), suggesting they could offer a viable alternative to conventional fungicides. This research seeks to contribute to the development of integrated pest management strategies that reduce dependence on synthetic chemicals while maintaining or improving wheat yields. By investigating the efficacy of plant conditioners and essential oils in managing rust and powdery mildew in spring wheat under Hungarian field conditions, the study will explore their effectiveness compared to fungicides, evaluate potential differences in yield and grain quality, and assess the economic implications for farmers adopting these alternatives.

1.4 Objectives

1.4.1 Main objective

This study aimed to investigate the comparative efficacy of plant conditioners, essential oils, and fungicides in managing rust and powdery mildew diseases in winter wheat. Additionally, the study aimed to evaluate the impact of these treatments on the yield of winter wheat in Hungary.

1.4.2 Specific objectives

1. To determine the effect of fungicides, essential oils, and a plant conditioner on the incidence of fungal rusts and powdery mildew on spring wheat (cultivar MV Kikelet) in comparison to an untreated control.
2. To evaluate the yield performance of spring wheat (cultivar MV Kikelet) in response to treatments with fungicides, essential oils, and a plant conditioner, measuring grain yield (kg/ha), weight of crops in the parcels, thousand-kernel weight, and hectoliter weight, in comparison to an untreated control.

2. LITERATURE REVIEW

1.5[2.1] Types and characteristics of wheat production

Wheat is one of the most important cereal crops worldwide, cultivated in various forms to suit different climates and end uses. The most commonly grown species is common wheat (*Triticum aestivum*), primarily used for bread due to its high gluten content (SHEWRY and HEY, 2015). Durum wheat (*Triticum durum*), recognized for its dense and hard kernels, is mainly used in pasta and semolina production. Club wheat (*Triticum compactum*), with a softer grain, is suited for cakes and pastries (FELDMAN and LEVY, 2012). Spelt (Triticum spelta), an ancient hulled wheat, is prized for its nutritional qualities and popularity in health-conscious diets (DUBOIS et al., 2020). These wheat types vary in gluten strength, protein levels, and environmental adaptability, making them suitable for a wide range of food products and agroecological zones.

Wheat's adaptability is one of its most valuable traits, allowing cultivation across temperate and subtropical regions. Optimal yields, however, are typically achieved in areas with moderate rainfall and temperatures (FAO, 2022). Wheat varieties are broadly classified into winter and spring types based on sowing time, with each responding differently to environmental variables such as temperature and moisture (SHEWRY and HEY, 2015). While wheat can grow in diverse soil types, well-drained loamy soils rich in nutrients and offering balanced aeration and moisture retention are ideal for maximizing productivity (BRADY and WEIL, 2017; TROEH and FOTH, 2012; MENGEL and KIRKBY, 2001). The modernization of wheat production has led to the widespread adoption of advanced practices including the use of improved cultivars, precision irrigation, mechanized harvesting, and integrated pest and nutrient management strategies, all contributing to higher yields and efficient resource use (PINGALI, 2006; GLOVER et al., 2017).

1.5.1[2.1.1] Global trends in wheat production and consumption

Wheat occupies a dominant position in global agriculture, with around 217 million hectares cultivated in 2018, making it the most extensively grown crop worldwide (Figure 1) (ERENSTEIN et al., 2022). It plays a pivotal role in global food systems, with major producers including China, India, Russia, the United States, and the European Union (FAOSTAT, 2024). The estimated global wheat production for the 2024/2025 season is approximately 793 million metric tons. Among the top producers, China and the European Union each contribute around 136 million metric tons, followed by India (110 MMT), Russia (91 MMT), and the United States (49 MMT) (STATISTA, 2025).

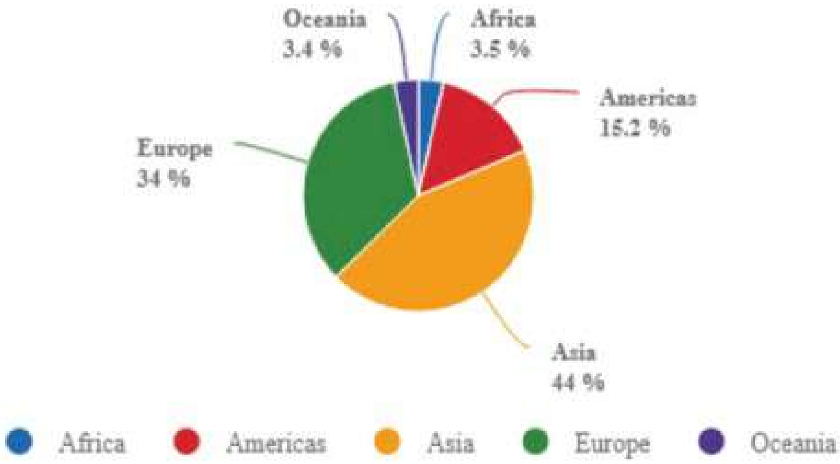


***Figure 1*: Production shares of wheat by region.**

Wheat is cultivated across more than 120 countries, in both developed and developing regions. Its exceptional frost tolerance enables it to grow in areas unsuitable for most other crops, especially in regions where temperatures fall below freezing during the growing season. Roughly 150 million hectares of wheat are planted in such cold environments (ERENSTEIn et al., 2022). Only a limited number of other crops, including rye, triticale, barley, and certain legumes, share this capability. The global wheat production system is influenced by diverse factors such as climate variability, economic shifts, technological progress, and geopolitical tensions (USDA, 2024; International Grains Council, 2024).

Wheat also plays a major role in international trade, with exports from surplus regions ensuring food access in deficit areas (WTO, 2023). The market is affected by price volatility, driven by supply-demand imbalances and speculative trading (OECD-FAO, 2023). Furthermore, wheat production impacts global sustainability through its association with land use, water consumption, and greenhouse gas emissions (IPCC, 2022). Globally, wheat is a dietary staple, with an average consumption of 65.6 kg per person annually, accounting for 37% of total cereal intake. It is consumed in 173 countries, with per capita consumption exceeding 50 kg in 102 nations. Consumption is highest in North Africa, West/Central Asia, and Europe, with Asia being the largest overall consumer (ERENSTEIN et al., 2022).

Although global per capita wheat consumption has slightly declined in recent years, it rose significantly between the 1960s and 1990s. This growth was particularly strong in Africa and Asia, where annual per capita consumption increased from 30 kg to 49 kg and 29 kg to 63 kg, respectively. Countries like China and India have driven much of this growth, although regional preferences persist for example, wheat dominates in Northwest India, while rice is favored in the Southeast. Similar dietary patterns are observed in China and Pakistan (ERENSTEIN et al., 2022).

1.5.2[2.1.2] Hungarian wheat production

Wheat cultivation in Hungary forms a vital part of the country's agricultural framework (Figure 2), supported by favorable natural conditions such as fertile soils and a continental climate with adequate rainfall (HCSO, 2023). Hungary combines traditional farming techniques with modern agricultural technologies, including sustainable practices and precision farming tools (MATE, 2022). The country has experienced generally increasing average yields, although interannual variability is influenced by climatic and agronomic factors (EUROSTAT, 2024).

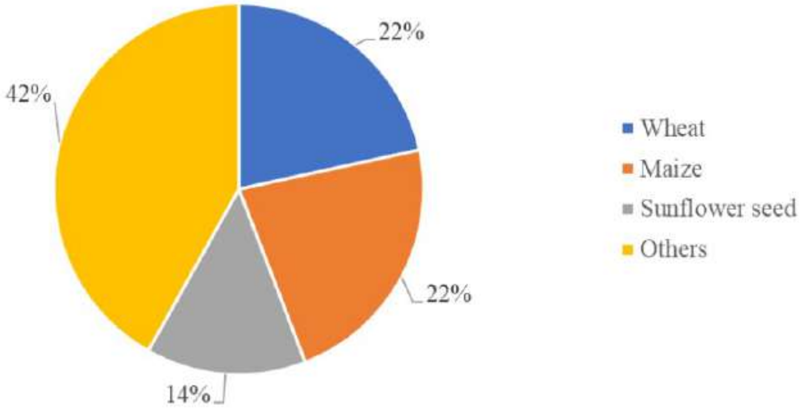


***Figure 2*: Hungary's top inland crops for year 2020.**

In 2023, Hungary produced approximately 1.2 million tonnes of wheat from around 220,000 hectares of farmland, with an average yield of 5.5 tonnes per hectare (Eurostat, 2024). Beyond satisfying domestic consumption, Hungarian wheat contributes to regional and international markets (Ministry of Agriculture, 2023). Continued efforts in research and breeding programs aim to develop higher-yielding, disease-resistant wheat varieties suited to local conditions (NAIK, 2021).

The importance of wheat in Hungary is underscored by its role in both domestic consumption and exports. Hungarian wheat supports diverse uses, including human food, animal feed, ethanol production, and starch processing. The long-standing expertise of Hungarian farmers, combined with suitable agroecological conditions, supports a robust wheat industry. Fluctuations in production over the past decade (figure 3) reflect changes in cultivated area and yield levels, as evidenced in national statistics (HCSO, 2021a).

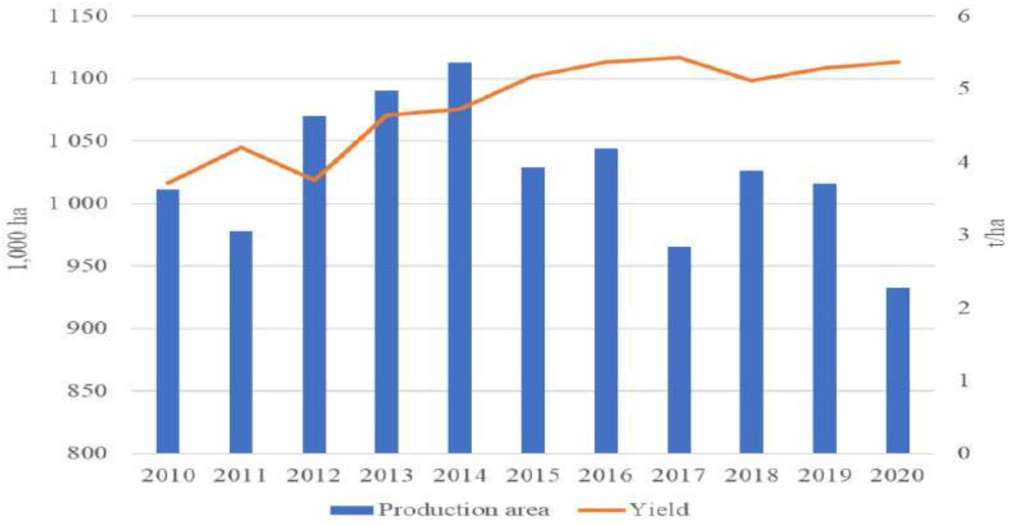


***Figure 3*: Wheat production area and yield from 2010 to 2020.**

1.5.3[2.1.3] Hungarian wheat usage

Production volumes, annual consumption patterns, and carryover stocks from previous years shape Hungarian wheat usage. In 2019, Hungary utilized approximately 9.14 million tonnes of wheat. The largest share was allocated to storage, followed by exports (Figure 4). Substantial amounts were also used for industrial purposes and animal feed, while smaller portions went toward seed and direct human consumption. Post-harvest losses were minimal (HCSO, 2021b).

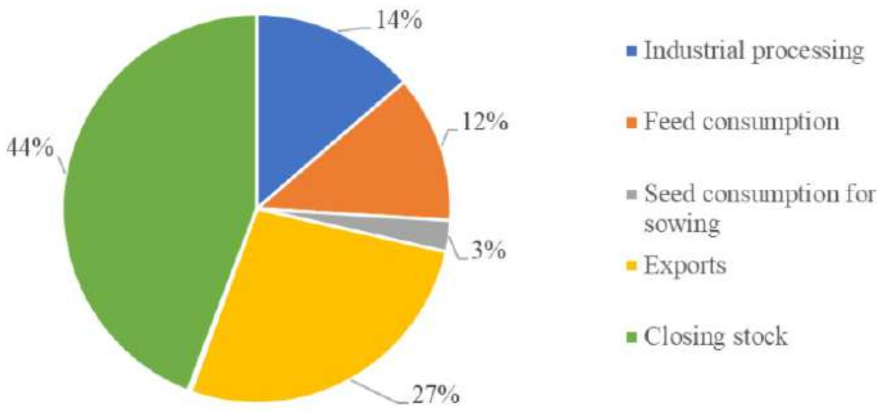


***Figure 4*: Wheat usage in Hungary.**

Figure 3 presents a breakdown of wheat utilization across categories in 2019. The multifunctional use of wheat in Hungary reflects its integral role in food systems and industrial applications. The efficient allocation of wheat resources enhances food security and economic stability while supporting the broader agri-food supply chain (MIZIK AND RÁDAI, 2021).

1.6[2.2] The main diseases affecting wheat crops

Wheat crops are susceptible to a variety of diseases that significantly affect yield and quality. Among the most critical are fungal pathogens, particularly rust and powdery mildew diseases, which continue to challenge global wheat production despite advancements in breeding and disease management. This section provides an overview of major rust and powdery mildew diseases, their biological characteristics, historical significance, and impact on crop productivity.

1.6.1[2.2.1] Wheat rusts and their impact on productivity

Wheat rusts are among the most destructive diseases affecting wheat crops globally. The three primary rusts stem rust, stripe rust, and leaf rust are caused by different species of the *Puccinia* fung*us* species.: *Puccinia graminis* f. sp. *tritici* (stem rust), *Puccinia striiformis* f. sp. *tritici* (stripe rust), and *Puccinia triticina* (leaf rust), all within the Basidiomycota phylum (SINGH et al., 2016).

These rust fungi are obligate biotrophic parasites and belong to a group of more than 7,000 known Puccinia species that pose considerable economic and agricultural threats worldwide (AIME et al., 2018). The genus *Puccinia*, under the order Pucciniales, has an evolutionary history spanning approximately 235 million years and possesses relatively large genomes, estimated at about 380 Mb (TAVARES et al., 2014).

Historically, wheat rust diseases have had a profound impact on agriculture, with evidence of rust spores dating back to 700 BC. Ancient Roman farmers even offered sacrifices to Robigus, the deity of rust, to protect their crops. These pathogens thrive under specific environmental conditions. Stem rust favors warm and humid climates, thriving at temperatures up to 30°C; leaf rust prefers slightly cooler, moist conditions (20–24°C), while stripe rust is most prevalent in cool, moist environments (12–20°C) (FIGUEROA et al., 2018; PRETORIUS et al., 2020; SINGH et al., 2011). Recent years have witnessed the emergence of more virulent and climate-adapted rust strains. For example, heat-tolerant stripe rust variants originating in the Himalayan region are now spreading across Europe and Asia. This dynamic evolution, combined with the rust fungi's ability to overcome resistance genes in wheat, contributes to recurrent regional epidemics and heightened risks to food security (SINGH et al., 2016).

Rust fungi have a complex heteroecious life cycle involving five spore stages spermatia, aeciospores, urediniospores, teliospores, and basidiospores (MONEY, 2016). While wheat serves as the primary host, alternate hosts are crucial to completing their sexual cycles. For example, Berberis and Mahonia species support the sexual phase of *P. graminis* and *P. striiformis*, while *Thalictrum, Anchusa, Isopyrum*, and *Clemati*s serve as alternate hosts for *P. triticina* (JIN et al., 2010; WANG et al., 2015).

As wheat matures, uredinia give way to telia, which produce thick-walled teliospores capable of surviving winter on crop residues. In spring, teliospores germinate and produce basidiospores, which infect barberry leaves, leading to the formation of spermagonia and eventually dikaryotic aeciospores. These aeciospores infect wheat by penetrating stomata, establishing haustoria that extract nutrients without disrupting the host plasma membrane (MONEY, 2016). A single infected plant can release millions of urediniospores within a week, leading to explosive disease spread (AIME et al., 2018). In regions like India, where alternate hosts are less prevalent, the fungus relies on urediniospores surviving on off-season wheat or grasses to reinitiate infection cycles (BHARDWAJ et al., 2019).

1.6.1.1[2.2.1.1] Stem Rust and Its Historical Significance

Stem rust, also known as black rust, is caused by Puccinia graminis f. sp. tritici, which also infects barley and rye. It is regarded as the most destructive rust disease, necessitating the continuous development of alternative and sustainable control strategies. Integrated disease management approaches such as deploying resistant cultivars, biological control agents, and precision agriculture tools have gained prominence over traditional reliance on fungicides (SAUNDERS et al., 2019; STEFFENSON, 2021).

Historically, stem rust has caused widespread yield losses globally, including devastating outbreaks in Africa, the Americas, Europe, and Australia. In the United States, severe epidemics in the early to mid-20th century led to yield losses of 19.3–28.4%. The introduction of resistant wheat varieties and the eradication of barberry in 1954 significantly curbed the disease (SINGH et al., 2016). However, it persisted in warmer regions of Central and Eastern Europe. A significant turning point occurred in 1999 with the emergence of the Ug99 race in Uganda, which overcame the widely deployed Sr31 resistance gene (PRETORIUS et al., 2000; SINGH et al., 2011). The appearance of additional virulent races, such as TKTTF, led to major losses, including the collapse of Ethiopia's 'Digalu' wheat crop in 2013 (OLIVERA et al., 2015). Stem rust poses the greatest threat when susceptible varieties are grown across large areas, allowing early infections to rapidly escalate into epidemics (BHAVANI et al., 2019).

Severe stem rust infections hinder wheat development by suppressing tillering, reducing photosynthetic efficiency, and impairing nutrient and water transport, leading to reduced grain filling and shriveled kernels. Notable historical epidemics include those in Scandinavia in 1951 (20–33% losses) and Central Europe in 1932 (OLIVER et al., 2022; SINGH et al., 2021). More recently, outbreaks occurred in Germany (2013), Denmark, Sweden, and the UK, and a major epidemic in Sicily (2016) affected thousands of hectares of bread and durum wheat (OLIVERA FIRPO et al., 2017; LEWIS et al., 2018;

BHATTACHARYA, 2017). The Sicilian strain, TTRTF (or TTTTF), exhibited virulence against Sr13b, particularly affecting durum wheat (PATPOUR et al., 2020).

In Sweden, rust was observed on late-maturing wheat and barley during the cool, wet summer of 2017 and has been detected annually since. Research indicates both asexual reproduction on cereals and sexual reproduction on Berberis vulgaris (KJELLSTRÖM, 2021; BERLIN et al., 2012). These findings underscore the importance of monitoring alternate hosts and implementing early-warning systems. The RustWatch project, launched in 2018, supports coordinated surveillance and breeding across Europe, building on the work of the Global Rust Reference Center and the Borlaug Global Rust Initiative (MCINTOSH and PRETORIUS, 2011; SAUNDERS et al., 2019). The resurgence of stem rust highlights the economic risks posed by pathogen evolution and emphasizes the need for sustained, multi-pronged disease management strategies.

1.6.1.1.1[2.2.1.1.1] Symptoms of stem rust

Stem rust exhibits distinct symptoms on various wheat plant parts, most notably the stems. The hallmark symptom is the formation of elongated, reddish-brown pustules (uredinia) that rupture the epidermis and release masses of urediniospores (Figure 5) (SINGH et al., 2016). These lesions can coalesce to form large areas of infection, significantly weakening plant structure and compromising water and nutrient transport.

Although pustules may also appear on leaves and leaf sheaths, they are generally less abundant. Leaf infections can accelerate senescence and diminish photosynthetic efficiency. As plants mature, the uredinia are succeeded by black telia, which house the fungus’s overwintering teliospores. Severe infections often result in shriveled grains and substantial yield reductions, marking the disease as one of the most damaging threats to wheat cultivation (STEFFENSON, 2021; WANYERA et al., 2019).

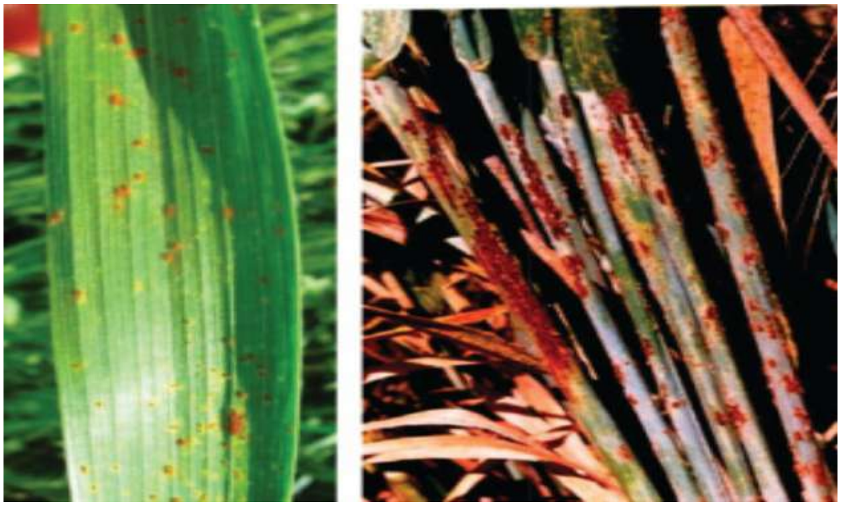


***Figure 5*: Urediopustules of stem rust.**

1.6.1.1.2[2.2.1.1.2] Lifecycle of *Puccinia graminis*

The heteroecious rust fungus Puccinia graminis completes its complex life cycle by producing thick-walled teliospores on gramineous hosts, particularly in temperate climates (Figures 6, 7 and 8). These teliospores, formed through karyogamy, remain dormant over winter and germinate in spring on alternate hosts such as Berberis or Mahonia species. Meiosis, initiated prior to dormancy, resumes upon germination, leading to the development of haploid basidiospores. These basidiospores, each containing a single haploid nucleus, are dispersed by wind and infect the upper surface of Berberis leaves, resulting in the formation of pycnia. Pycniospores, exuded in nectar, are transmitted by insects and rain, facilitating fusion with flexuous hyphae of the opposite mating type. This plasmogamy event initiates dikaryotic growth, culminating in the formation of aecia on the underside of barberry leaves. Aeciospores, released from the aecia, are dispersed by wind and infect gramineous hosts, leading to the production of urediniospores within uredinia. These urediniospores enable repeated cycles of infection on gramineous tissues especially stems and leaf sheaths eventually resulting in the formation of telia.

In regions such as the central United States, where Berberis has been extensively eradicated, P. graminis survives via urediniospores on volunteer wheat, exploiting these plants as a “green bridge” to persist between growing seasons. Similar survival mechanisms have been observed in Australia and India. However, in Europe, stem rust occurs less frequently, and the precise mechanisms of overwintering or oversummering remain incompletely understood (STEFFENSON, 2021; FIGUEROA et al., 2018; CUMMINS and HIRATSUKA, 2003).

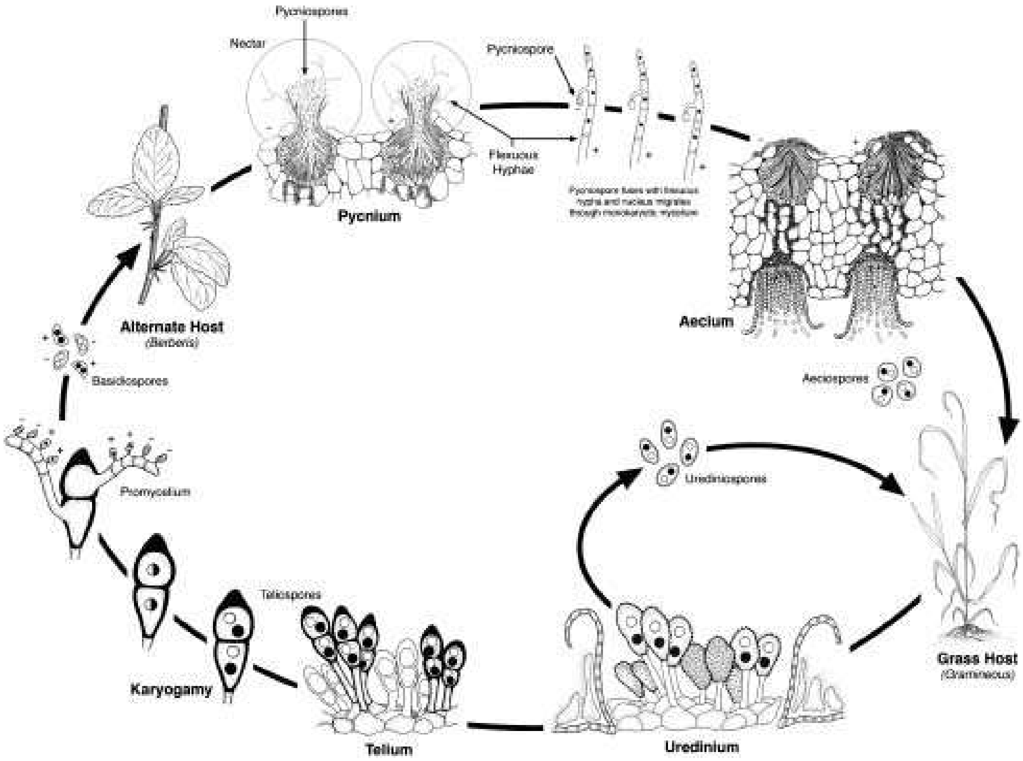


Figure 6: **Lifecycle of *Puccinia graminis***

Figure 6 illustrates the life cycle of *Puccinia graminis*, highlighting the asexual uredinial stage, characterized by dikaryotic urediniospores that can rapidly reproduce on the grass host every 14–20 days under optimal conditions. Toward the end of the grass host's growing season typically in late summer or autumn the fungus transitions to the sexual stage by forming teliospores. Karyogamy occurs within these maturing teliospores, and meiosis of the resulting diploid nucleus initiates prior to dormancy. In spring, meiosis completes and teliospores germinate, producing four haploid basidiospores of opposite mating types (+ and –). These basidiospores infect the alternate host (Berberis), leading to the production of haploid pycnia. Fertilization occurs via fusion between pycniospores and flexuous hyphae of the opposite mating type, initiating dikaryotic development and the subsequent formation of aecia. The aecia produce dikaryotic aeciospores, which infect the grass host and thereby complete the life cycle. In regions with mild winters and sufficient summer moisture, *P. graminis* can persist in the uredinial stage on autumn-sown cereals, volunteer cereal plants, or susceptible wild grasses, effectively bypassing the need for the alternate host (STEFFENSON, 2021; FIGUEROA et al., 2018; CUMMINS and HIRATSUKA, 2003).

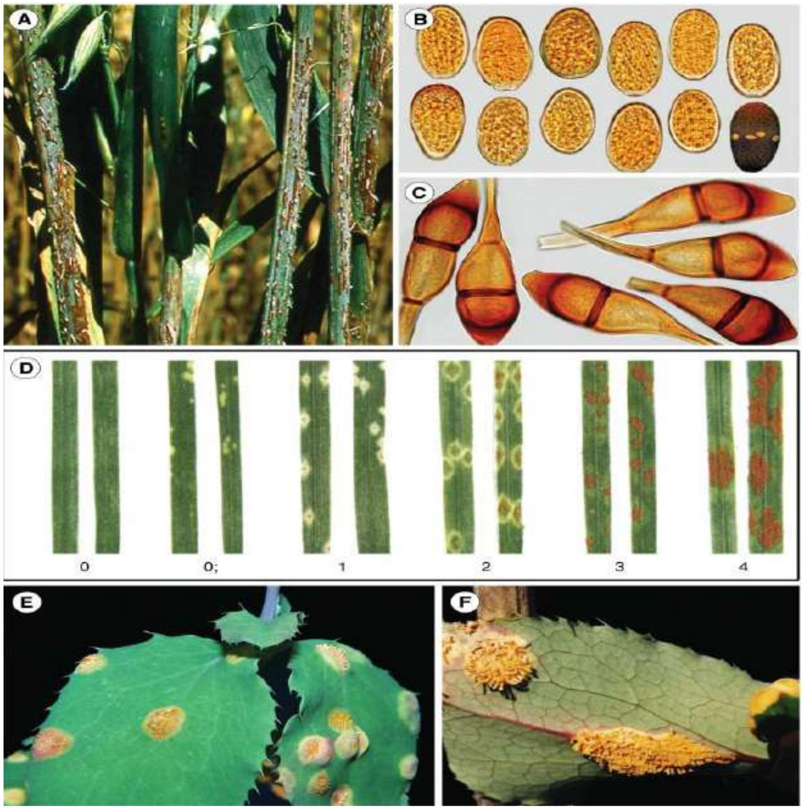


Figure 7: Symptoms of _Puccinia graminis_

Symptoms of *Puccinia graminis* on both its primary and alternate hosts, along with the morphology of urediniospores and teliospores. **(A)** Uredinia of *P. graminis* f. sp. *avenae* on oat plants. **(B)** Urediniospores of *P. graminis* under magnification, with one stained spore highlighting the characteristic equatorial positioning of germ pores. **(C)** Teliospores of *P. graminis* under magnification. **(D)** Infection types of *P. graminis* f. sp. *tritici* on seedlings of differential wheat cultivars; infection types 0–2 are considered resistant, while types 3 and 4 indicate susceptibility (adapted from STAKMAN et al., 1962). **(E)** Clusters of pycnia of *P. graminis* on the upper surface of *Berberis vulgaris* leaves. **(F)** Clusters of aecia of *P. graminis* on the lower surface of a *B. vulgaris* leaf (Source: LEONARD and SZABO, 2005).

***Figure 8*: Uredinia of *Puccinia triticina* on flag leaves of wheat.**

1.6.1.2[2.2.1.2] Wheat leaf rust

Wheat leaf rust, caused by *Puccinia triticina*, is the most widespread rust disease affecting wheat globally, surpassing both stem and stripe rust in prevalence. This heteroecious fungus requires two hosts wheat and alternate species such as Thalictrum speciosissimum or Isopyrum fumarioides to complete its life cycle. The Fertile Crescent, where these hosts coexist, is hypothesized as the center of origin for *P. triticina* (BOLTON et al., 2008). Wheat rusts, including leaf rust, have threatened wheat production for millennia, with mentions in historical accounts from classical Greece, Rome, and the Bible.

P. triticina was introduced to North America in the 17th century with the expansion of wheat cultivation (KOLMER, 2018; LONG and PARK, 2020). Initially, leaf rust was underestimated compared to diseases such as stem rust (LEONARD and SZABO, 2005) and Fusarium head blight (GOSWAMI and KISTLER, 2004). However, it significantly reduces wheat yield by decreasing both kernel number and weight. Today, *P. triticina* is a globally recognized wheat pathogen, causing considerable losses in yield across multiple continents (KOLMER, 2005; MARASAS et al., 2004).

Wheat leaf rust affects crops throughout the Americas, Europe, Asia, Africa, and Australia, with damage severity varying by region (MCCALLUM et al., 2012). For example, in 2007, leaf rust caused a 14% reduction in winter wheat yield in Kansas, a major wheat-producing state in the U.S. (Kansas Department of Agriculture). Between 2000 and 2004, economic losses in the U.S. from leaf rust were estimated at USD 350 million. In China, annual yield losses due to leaf rust are estimated at 3 million tons.

In recent decades, the use of wheat cultivars incorporating slow-rusting resistance genes has significantly mitigated the impact of leaf rust in many regions (HUERTA-ESPINO et al., 2011). Although *P. triticina* is globally distributed, its sexual cycle is rarely completed due to the limited availability of compatible alternate hosts. Notably, native North American species of Thalictrum and Isopyrum exhibit resistance to infection by basidiospores of the leaf rust pathogen (KOLMER, 2018; LONG and PARK, 2020).

1.6.1.2.1[2.2.1.2.1] Taxonomic history of *Puccinia triticina*

The classification of wheat leaf rust, caused by a fungus in the Basidiomycete order Uredinales, has evolved significantly over time. Initially, the disease was often confused with wheat stem rust. However, in 1815, AUGUSTIN DE CANDOLLE distinguished it as a separate entity and identified the causal organism as Uredo rubigo-vera (DC) (BOLTON et al., 2008). LATER, WINTER (1884) classified it within the Puccinia rubigo-vera complex, and Eriksson (1899) subsequently redefined it as *Puccinia triticina*, reflecting its host specificity to wheat.

Despite this, the pathogen was later subsumed under the broader *Puccinia recondita* complex as *P. recondita* f. sp. *tritici*, due to morphological similarities in spores and telial hosts. However, advances in research including studies on alternate host specificity, ribosomal DNA sequencing, spore morphology, and infection structure have provided strong evidence supporting the distinction of leaf rust pathogens based on their alternate hosts. Specifically, leaf rusts utilizing *Thalictrum speciosissimum* as the alternate host differ genetically and biologically from those associated with *Anchusa* species. This distinction is reinforced by observed sexual incompatibility between the groups.

As a result, the pathogen responsible for leaf rust on both common wheat (*Triticum aestivum* L.) and durum wheat (*T. turgidum* L. var. *durum*) is now formally recognized as *Puccinia triticina* Eriksson (KOLMER, 2018; BOLTON ET AL., 2008).

1.6.1.2.2[2.2.1.2.2] Symptoms and identification of wheat leaf rust

The fungal pathogen *Puccinia triticina* is responsible for leaf rust in wheat, which manifests through a progression of distinct symptoms (Figure 9) (SINGH 2017). In highly susceptible wheat cultivars, large uredinia develop without accompanying signs of chlorosis or necrosis in host tissues (BOLTON et al., 2008). Symptom expression typically follows a color gradient, beginning as yellow lesions, turning orange, and eventually becoming dark brown as the disease progresses. Ultimately, the infected leaf tissue desiccates. Interestingly, different symptom stages may be simultaneously visible on various parts of the same leaf (ROBERT et al., 2005).

***Figure 9*: Symptoms of leaf rust of wheat.**

Leaf rust is most commonly identified during its uredinial stage, which is marked by small, eruptive, round to oval pustules uredinia measuring up to 1.5 mm in diameter. These structures, which appear scattered across both the upper and lower leaf surfaces, range in color from orange to brown. The uredinia release nearly spherical, orange-brown urediniospores, approximately 20 µm in diameter. These spores possess thick, spiny walls and typically contain up to eight equatorially positioned germ pores (KOLMER, 2018).

1.6.1.2.3[2.2.1.2.3] Host range of *Puccinia triticina*

Globally, hexaploid common wheat (*Triticum aestivum* L.) serves as the primary host for *Puccinia triticina* (LONG and PARK, 2020). However, this rust pathogen also affects other wheat types, including tetraploid durum wheat (*T. turgidum* ssp. *durum*), wild and domesticated emmer wheat (*T. dicoccoides* and *T. dicoccum*), and triticale. In Israel, a form of *P. triticina* distinct from those infecting wheat has been identified on the diploid species Aegilops speltoides in restricted localities (YEHUDA et al., 2004). In the southern United States, *P. triticina* has also been found infecting *A. cylindrica* (common goatgrass).

The pathogen exhibits a high degree of host specificity, with only certain races of *P. triticina* capable of infecting non-hexaploid hosts. Genetic differentiation and host-range divergence suggest that *P. triticina* populations on durum wheat and *A. speltoides* likely represent separate formae speciales distinct from those infecting common wheat (GOYEAU et al., 2006; ORDOÑEZ and KOLMER, 2007). Although natural infections of *P. triticina* on wild wheat relatives such as *Ae. sharonensis, Ae. tauschii, Ae. bicornis, Ae. longissima, Ae. ovata, Ae. variabilis, T. timopheevi,* and *T. urartu* are rare, these species can be artificially infected with virulent rust strains under controlled conditions (KOLMER, 2018).

The sexual stage of *P. triticina* is seldom observed on *Thalictrum* species in North America (LEVINE and HILDRETH, 1957), but has been reported on *T. speciosissimum* in southern Europe (CASULLI and SINISCALCO, 1987; D'OLIVEIRA, 1940; D'OLIVEIRA and SAMBORSKI, 1966; YOUNG and D'OLIVEIRA, 1982). Infections on *Isopyrum fumaroides* appear to be geographically restricted to a region in Siberia (CHESTER, 1946).

1.6.1.2.4[2.2.1.2.4] Lifecycle of *Puccinia triticina*

Puccinia triticina is a macrocyclic and heteroecious rust fungus, completing a complex life cycle that requires two taxonomically unrelated host species and involves five distinct spore stages (Figure 10) (BOLTON et al., 2008). On wheat, the pathogen produces dikaryotic urediniospores globose to oval spores approximately 20 µm in diameter that facilitate repeated asexual infection cycles under favorable conditions, particularly in the presence of free moisture and temperatures between 10–25 °C (ANIKSTER et al., 2005a). As the wheat matures and the infection progresses, the uredinia give rise to dikaryotic, thick-walled, two-celled brown-black teliospores (~16 µm in width). These teliospores play a key role in the survival of the fungus during the hot, dry Mediterranean summers and initiate the sexual cycle upon infection of alternate hosts in the autumn. Early in their development, teliospores undergo karyogamy, where the two haploid nuclei fuse to form a diploid nucleus (MONEY, 2016).

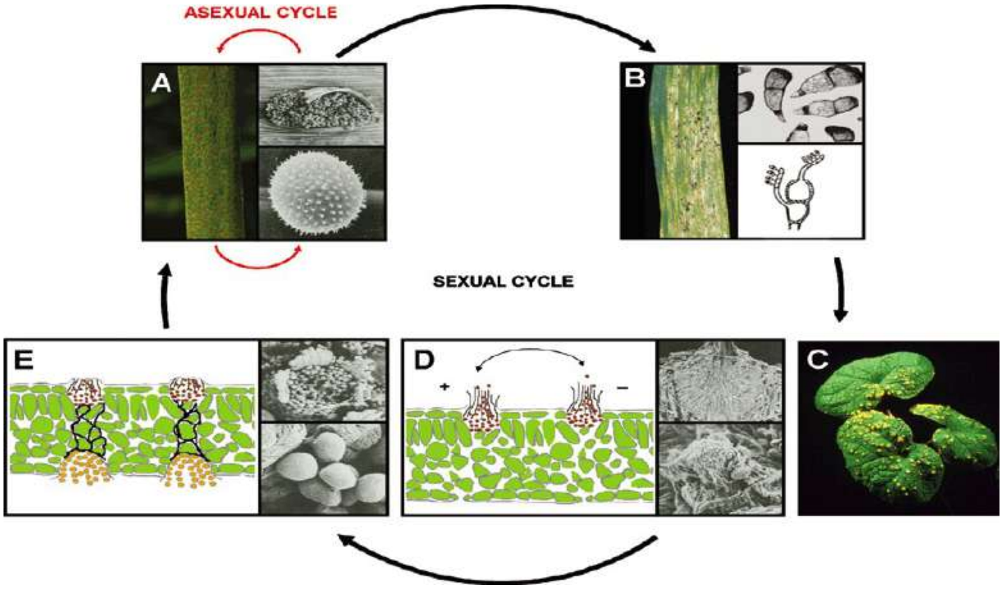


Figure 10: **Lifecycle of wheat leaf rust (*Puccinia triticina*).**

(A) Shows uredinia on wheat leaves, each containing dikaryotic urediniospores originating from aeciospores or urediniospores. This asexual stage can repeat multiple times under favorable conditions. Top inset: a surface view of a uredinium (×100); bottom inset: high-magnification view of the spiny surface of a single urediniospore (×3000).

(B) Depicts the development of telia near the end of the growing season, appearing as black, erupting structures comparable in size to uredinia. Top inset: mature teliospores; bottom inset: karyogamy and meiosis within the teliospore produce four haploid basidiospores, with two of each mating type (+ and –).

(C) Displays basidiospore infection on *Thalictrum* leaves, resulting in yellow-orange pycnia on the upper leaf surface.

(D) Provides a cross-sectional view of *Thalictrum* leaf tissue with pycnia. Top inset: infection by basidiospores leads to haploid pycnia formation (×400); bottom inset: production of pycniospores and flexuous hyphae in a nectar-like exudate (×500), enabling plasmogamy between compatible mating types.

(E) Illustrates a cross-section of *Thalictrum* bearing both pycnia and aecia. Top inset: development of dikaryotic aecia following successful fertilization (×200); bottom inset: chains of dikaryotic aeciospores produced by the aecium (×1250).

Under conducive conditions, teliospores germinate to form a promycelium (basidium), within which meiosis occurs, producing four haploid nuclei that are partitioned into individual cells. Each cell generates a sterigma, into which a haploid nucleus migrates, forming a basidiospore (Fig. 10B). These basidiospores, each bearing a single haploid nucleus, are dispersed by wind and infect alternate hosts such as *Thalictrum* spp. (Fig. 10C) . Basidiospore penetration into epidermal cells induces the formation of flask-shaped pycnia, which produce pycniospores and flexuous hyphae (Fig. 10D). Although the precise origin of flexuous hyphae remains debated, they are essential for sexual reproduction through the fusion with compatible pycniospores. The resulting dikaryotic mycelium gives rise to aecia on the lower leaf surface (Fig. 10E), which produce wind-dispersed aeciospores that re-infect the telial host (e.g., wheat), completing the cycle with the production of urediniospores.

While the full sexual cycle is rarely completed in many regions due to limited availability of alternate hosts, *P. triticina* can persist asexually through uredinial infections. In the southern United States, for example, the pathogen survives on volunteer wheat plants, acting as a primary inoculum source for autumn-sown winter wheat. The fungus can also overwinter as mycelium or urediniospores within infected winter wheat plants when environmental conditions permit (LONG and PARK, 2020).

1.6.1.3[2.2.1.3] **Wheat stripe rust**

Wheat stripe rust, also known as yellow rust due to the characteristic color of its spores during asexual infection, has been a significant disease affecting wheat, barley, rye, triticale, and certain graminaceous hosts for centuries. It is caused by the obligate biotrophic fungus *Puccinia striiformis* f. sp. *tritici* (Pst). This pathogen poses a major threat to global agriculture due to its high genetic diversity primarily arising from sexual recombination in the Himalayan region combined with its ability for long-distance dispersal across continents through both natural and anthropogenic means. Furthermore, its rapid local adaptation via stepwise evolution enables it to overcome resistance genes one at a time (HOVMØLLER et al., 2011).

Stripe rust is currently the most significant biological constraint on wheat production and presents a serious challenge to global food security. Approximately 88% of the global wheat cultivation area is vulnerable to this disease, with annual losses exceeding 5 million tons, translating to a market value of over USD 1 billion (WELLINGS, 2011; BEDDOW et al., 2015). A global survey of pathologists and breeders working directly on stripe rust confirms that Pst remains a persistent threat to wheat production. Regional yield losses commonly range between 0.1% and 5%, with occasional severe outbreaks causing losses of 5% to 25%. High-risk regions include the Pacific Northwest of the USA, northwest and southwest China, Nepal, Australia, and Kenya (WELLINGS, 2011).

1.6.1.3.1[2.2.1.3.1] Disease symptoms, development, and signs of the pathogen

Stripe rust infects living tissues of cereal crops and grasses throughout the plant's growth stages. Under favorable temperatures, symptoms typically appear within a week of infection, followed by sporulation around two weeks later. The fungus produces small yellow-to-orange pustules called uredia, which are filled with masses of microscopic spores. These spores form a visible, powdery layer on leaf surfaces.

Young seedlings do not exhibit the distinctive stripe pattern or necrosis; these symptoms emerge later as the plant enters stem elongation. The extent of damage including chlorosis, necrosis, and spore production depends on the plant’s resistance level and ambient temperature. The linear stripes and pustule formations caused by stripe rust are distinct from symptoms of other rust diseases. Over time, the pathogen weakens the host plant by extracting water and nutrients, compromising growth and yield (CHEN, 2005).

1.6.1.3.2[2.2.1.3.2] Taxonomy, biology of the pathogen, and host Range

Stripe rust is caused by different forms of *Puccinia striiformis*, a basidiomycete fungus in the order Uredinales. The species' taxonomy has evolved over time, with the current name established in 1953. Its life cycle includes dikaryotic uredial and telial spore stages.

Although teliospores produce haploid basidiospores, Pst does not exhibit pycnial or aecial stages in nature, in contrast to stem and leaf rust pathogens (CHEN, 2005).

Primary hosts include various wheat species such as common wheat (*Triticum aestivum L.*), durum wheat (*T. turgidum var. durum L.*), cultivated emmer (*T. dicoccum Schrank*), wild emmer (*T. dicoccoides Korn*), and triticale (×Triticosecale). While barley (*Hordeum vulgare L.*) and rye (*Secale cereale L.*) may become infected, they rarely suffer major outbreaks. Pst also infects several pasture grasses, including *Elymus canadensis L*., *Leymus secalinus Hochst, Agropyron* spp., *Hordeum* spp., *Phalaris* spp., and *Bromus unioloides Kunth.*

Though Pst was long thought to lack alternate hosts, recent findings confirm that barberry species (*Berberis chinensis*, *B. koreana*, *B. holstii*, *B. vulgaris*, *B. shensiana*, *B. potaninii*, *B. dolichobotrys*, *B. heteropoda*) and Oregon grape (*Mahonia aquifolium*) can serve as alternate hosts necessary for completing the sexual cycle (CHEN, 2013).

1.6.1.3.3[2.2.1.3.3] **Historical impact of wheat stripe rust and status in European countries**

Stripe rust has threatened cereal crops since ancient times, with references appearing in the Old Testament and early historical writings. Documented outbreaks include occurrences in England (1725) and Sweden (1794). Its primary impact is the reduction of grain yield and quality. Early greenhouse studies by BEVER (1937) reported yield reductions of up to 65% in susceptible spring wheat due to decreased dry matter, root mass, plant height, spike formation, and grain number. The damage was particularly severe when infection began during the seedling stage.

Spike infection, while less studied, is especially detrimental. PURDY and ALLAN (1963) observed 20% yield loss from spike infections in cultivars resistant to foliar rust. Field studies in New Zealand by CROMEY (1989) reported an average 11% reduction in grain weight, with the severity linked to infection timing and the duration of moist conditions during flowering (WELLINGS, 2011).

In Europe, stripe rust has posed a major threat for over a century, especially in northern countries like France, the Netherlands, Germany, Denmark, and the UK. These areas have seen frequent emergence of new virulent pathotypes, largely due to intensive resistance breeding. While outbreaks are less frequent in southern Europe, they still occur under favorable conditions. Data from the 1960s–1970s indicated an average annual yield loss of around 10% in Europe (HOVMØLLER and JUSTESEN, 2007; DE VALLAVIEILLE-POPE et al., 2011).

Despite conducive environments, effective resistance deployment and fungicide use led to a significant reduction in stripe rust prevalence from the late 1980s onward (SCHMITS, 2003, CITED IN HOVMØLLER and JUSTESEN, 2007). However, the breakdown of resistance genes remains a concern. For instance, virulence against the widely used Yr17 gene was first detected in the UK in 1994, followed by its spread to Denmark, France, and other countries indicating a shared epidemiological zone across northern Europe (JUSTESEN et al., 2002; HOVMØLLER et al., 2002; HOVMØLLER and JUSTESEN, 2007).

In France, the disease is most prevalent in the north. Severe epidemics occurred in the 1980s (MBOUP ET AL., 2012; DE VALLAVIEILLE-POPE ET AL., 2011). In 2009, a newly emerged pathotype caused substantial grain yield losses in Danish triticale fields, reaching up to 7.5 t/ha.

1.6.1.3.4[2.2.1.3.4] Lifecycle of wheat stripe rust fungus *Puccinia striiformis* f. sp. *Tritici*

The sexual cycle of *Puccinia striiformis* f. sp. *tritici* (Pst) begins in spring with the release of short-lived, binucleate basidiospores (2N), which infect barberry plants (Figure 11). Successful infections lead to the formation of pycnia on the upper leaf surface, where haploid pycniospores (N) of specific mating types are produced. These pycniospores, upon fusion with receptive hyphae from compatible pycnia, initiate dikaryotization and aecium development on the lower leaf surface, resulting in genetically diverse aecia. The resulting aeciospores (N+N′) are capable of infecting wheat, the primary host, and thus initiate the asexual phase of the life cycle.

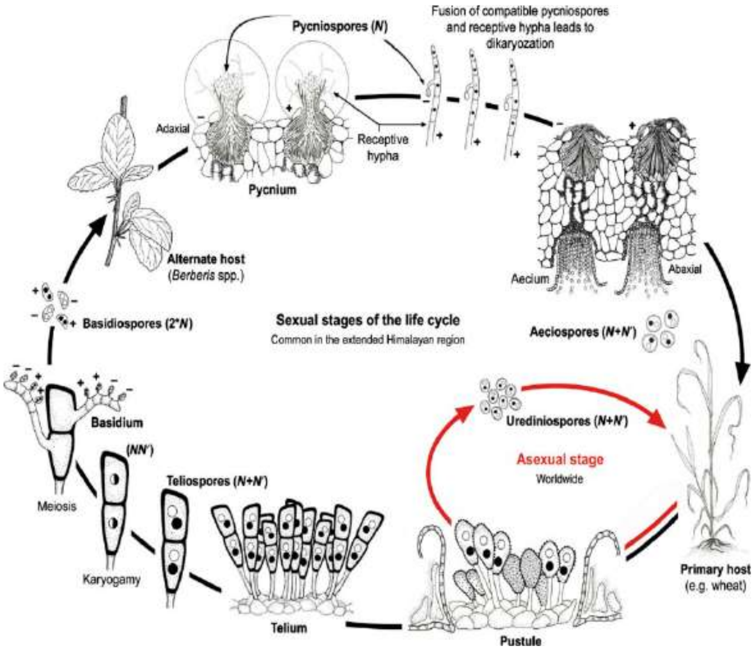


***Figure 11*: Lifecycle of wheat stripe rust fungus *Puccinia striformis* f. sp. *tritici*.**

On wheat, infection manifests as yellow pustules on both leaf surfaces, which release numerous dikaryotic urediniospores (N+N′). These urediniospores are capable of causing approximately 15 reinfection cycles during a single growing season. As the season ends, the pathogen transitions to telia formation, producing thick-walled, long-lived teliospores (N+N′). In spring, teliospores undergo nuclear fusion (karyogamy, NN′) and meiosis, generating new genetic diversity. Germination of the teliospores leads to basidium formation and the production of binucleated basidiospores (2N), which are ready to infect barberry again, completing the cycle (LITTLEFIELD, 1981; HOVMØLLER and JUSTESEN, 2007; CHEN et al., 2014; RODRIGUEZ-ALGABA et al., 2014).

1.6.2[2.2.2] Powdery mildew of wheat

Powdery mildew, caused by *Blumeria graminis* f. sp. *tritici*, is a globally prevalent disease affecting cereals and grasses (COWGER et al., 2012). Specifically, *Blumeria graminis* is widespread across Europe, North America, Central Asia, and China. It is also found in African countries, the higher-rainfall regions of Western Australia, and parts of Latin America, including southern Brazil (COWGER and BROWN, 2019). Powdery mildew ranks as the fourth most significant wheat disease, following the three rusts. Yield losses can range from 13% to 34% under low to moderate infection and escalate to 50% to 100%

in severe infestations. Effective control of this disease requires a comprehensive understanding of its damaging impact, etiology, virulence patterns, host resistance mechanisms, and appropriate fungicidal management (BASANDRAI, 2017).

1.6.2.1[2.2.2.1] Symptoms of powdery mildew disease on wheat

Powdery mildew affects cereals and grasses, manifesting as white to grey-tan patches on leaves, stems, and ears, with leaves being the most frequently infected (Figure 12) (COWGER and BROWN, 2019; SINGH, 2017). Initially, subtle yellow spots appear, quickly followed by the development of powdery, spore-producing patches. These patches release visible clouds of spores when disturbed. Late in the season, small, dark fruiting bodies (ascomata) may appear within these patches (COWGER and BROWN, 2019).

Figure 12**: Symptoms of powdery mildew on wheat leaves indicated by A & C and spikes indicated by B.**

1.6.2.2[2.2.2.2] Impact of powdery mildew in Europe

Powdery mildew is a significant threat to cereal crops globally, with yield losses potentially reaching up to 60%, depending on the disease severity and timing (COWGER et al., 2012; FONES and GURR, 2015). While present worldwide, its impact is most pronounced in temperate regions, particularly the northern hemisphere, where wheat and barley are extensively cultivated (COWGER et al., 2012). It also poses a risk in subtropical and tropical areas.

In Europe, powdery mildew significantly reduces cereal yields. In the UK, while considered a moderate risk to wheat with 13-17% crop impact, yield losses typically remain below 10% (AHDB, 2016). However, susceptible barley varieties in Scotland have seen an increased incidence (FAS, 2019). In northern and central Europe, it is regarded as a major wheat disease, and it also affects barley production (MIEDANER and FLATH, 2007; DREISEITL, 2011). These findings highlight the potential severity of powdery mildew on wheat yields. Modern research continues to emphasize the importance of effective disease management strategies to mitigate yield losses and improve crop health.

1.7[2.3] Intergrated methods of control against rusts and powdery mildew disease of wheat

1.7.1[2.3.1] Agrotechnical strategies

Contemporary management of wheat rusts and powdery mildew emphasizes integrated approaches. Key strategies include crop rotation, the removal of volunteer wheat plants, and the destruction of infected crop residues to reduce pathogen inoculum levels. Utilizing resistant wheat cultivars and engaging in resistance breeding programs are fundamental strategies. Additionally, optimizing nutrient management and promoting early crop maturation can mitigate disease epidemics, as fully ripened wheat exhibits decreased susceptibility to these pathogens (OLIVER et al., 2022; SINGH et al., 2021).

1.7.2[2.3.2] Chemical control application

Modern strategies for managing wheat rusts and powdery mildew often necessitate the application of fungicides. When disease pressure is high, specific fungicides such as ACANTO, ALERT, AMISTAR, FOLICUR SOLO, MILSTAR, and TANGO STAR are utilized to protect wheat crops. The strategic use of these fungicides, in conjunction with other integrated management practices, is crucial for minimizing yield losses (FRAAIJE et al., 2020; LUCAS et al.,2015). Seed treatments, such as BIOSILD BD, DIVIDEND 030 FS, and SIGNAL 200 FS, are applied to seeds to provide early protection against these diseases, establishing a foundation for healthy crop development. This preventative approach is a key component of integrated management for these diseases in contemporary agriculture (MUNKVOLD, 2020; PÉREZ-GARCÍA et al., 2019).

1.7.3[2.3.3] Alternative Control Strategies

Due to the overuse of synthetic fungicides and concerns about their environmental impact including high residues, resistance development, and adverse effects on ecosystems there is growing interest in biopesticides. The use of essential oils, extracted from plants with known antifungal properties, offers an eco-friendly alternative for managing fungal rust diseases in wheat. This approach, which is the main focus of this research study, aims to reduce reliance on synthetic fungicides and provide sustainable solutions for controlling wheat diseases.

1.8[2.4] Application of essential oils as a biocontrol method

Essential oils (EOs) represent a promising biocontrol alternative for managing fungal diseases in wheat, appreciated for their safety, bioactivity, biodegradability, environmental compatibility, and economic feasibility. The increasing market demand for natural and sustainable agricultural inputs further underscores the potential of EO-based technologies. Nevertheless, widespread implementation remains limited due to a lack of comprehensive scientific data regarding their efficacy, application scope, and detailed mechanisms of action (PAVELA, 2021; SINGH and SHARMA, 2022).

Derived from various plant organs particularly flowers EOs are complex, volatile, aromatic, and hydrophobic secondary metabolites. These compounds are typically obtained via physical extraction methods such as steam distillation or cold pressing, which preserve their chemical integrity for subsequent use. Traditionally valued for their fragrance and medicinal properties, essential oils from aromatic plants such as thyme, savory, cinnamon, cumin, rosemary, and clove have been utilized globally as culinary flavorings. Beyond their sensory attributes, essential oils demonstrate broad-spectrum antimicrobial activities, including insecticidal, antibacterial, antifungal, and antiviral effects. These biological properties are attributed to functional chemical groups such as alcohols, aldehydes, phenolics, terpenes, ketones, and other bioactive constituents (RÍOS and RECIO, 2005; SWAMY et al., 2016).

1.8.1[2.4.1] Mechanism of action of essential oils against fungal diseases in wheat

Essential oils exert antifungal activity through multiple, complementary mechanisms that compromise fungal viability. Primarily, EO components disrupt fungal cell membrane integrity, leading to cytoplasmic leakage and impaired cellular function. They also interfere with ergosterol biosynthesis, a key component of fungal cell membranes, thereby weakening structural stability. In addition, some EO constituents inhibit fungal respiratory pathways and enzymatic activity, resulting in metabolic dysfunction and cell death.

Moreover, several essential oils are known to induce systemic plant defense mechanisms. By triggering the plant's immune response, they enhance wheat's resistance to fungal pathogens. These combined direct and indirect actions render essential oils a compelling option within integrated disease management frameworks (SHARMA et al., 2021; TRIPATHI et al., 2020). This study explores the efficacy of essential oils as an alternative to chemical fungicides in controlling wheat rusts and powdery mildew, assessing their effectiveness in real agricultural conditions.

1.8.2[2.4.2] Application and mechanisms of plant conditioners in managing fungal diseases of wheat

Plant conditioners encompassing a diverse range of substances that promote plant health and resilience are increasingly recognized for their role in managing fungal diseases in wheat. These agents operate through several mechanisms, including the activation of systemic acquired resistance (SAR), reinforcement of plant cell walls, and enhancement of nutrient uptake, all of which contribute to improved plant vigor and stress tolerance. For example, silicon-based conditioners enhance structural defenses by promoting the deposition of silica in epidermal cell walls, creating a physical barrier that restricts fungal entry. In parallel, biochemical pathways are activated, leading to the production of phenolic compounds and pathogenesis-related proteins. Similarly, biostimulants such as humic substances and seaweed extracts prime wheat plants for a more rapid and robust response to pathogen invasion.

By reducing dependency on synthetic fungicides and contributing to sustainable farming practices, plant conditioners represent a valuable component of integrated pest management. This study aims to assess the comparative effectiveness of plant conditioners and conventional chemical fungicides in controlling wheat rusts and powdery mildew under field-relevant scenarios (ROMERO et al., 2021; YAKHIN et al., 2017).

3 MATERIALS AND METHODS

1.9[3.1] Study site details

The research for this study took place at the experimental farm of the Faculty of Agricultural and Food Sciences and Environmental Management at the University of Debrecen, situated in Debrecen, Hungary. This location is 121 meters above sea level, positioned at latitude 47° 33′7.080"N and longitude 21° 36′7.488"E. The soil in the experimental area is characteristic of Rich, dark hue, a soil type known for its silty composition which contributes to a significant capacity to retain water.

3.2. Design of the experiment.

A field experiment was set using a completely Randomized Design (CRD) with four replicates and four treatments. Spring wheat varieties known as MV Kikelet, moderately susceptible to diseases, were sown on 12/03/2024 at the recommended rate into plots measuring 5 meters by 3 meters, with rows spaced 15 centimeters apart, each plot containing 20 rows. The layout of the 0.5-meter separated plots and the 2-meter separated replications is depicted in Figure 13.

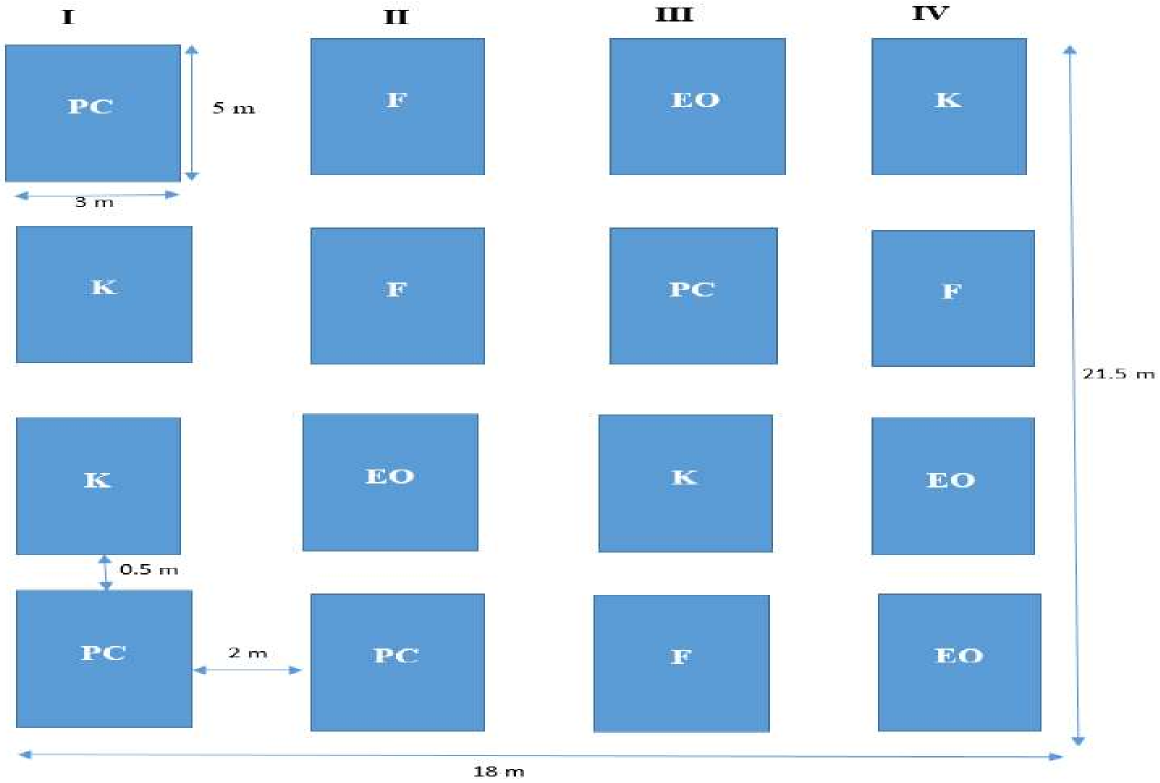


Figure 13: **Field Layout**

Where: PC- Plant conditioners
F- Fungicides
EO- Essential Oils
K- Control

1.10[3.2] Weather conditions

During the research study, weather conditions were monitored by the aid of the agrometeorological station at the DE AKIT DTTI Practical Garden, which is run by the Precision Research and Development Service Center at the University of Debrecen, Faculty of Agricultural and Food Sciences and Environmental Management. A Campbell Scientific CR1000 instrument collected data every 10 minutes with a sampling rate of 100Hz. The recorded parameters included minimum, maximum, and average temperatures (in °C), humidity (in %), and precipitation (in mm). The specific sensors used were an ARG-100 for precipitation and a HygroVUE10 for temperature and humidity.

3.3 Experimental materials used.

In this study, four (4) treatments were evaluated for their effectiveness in managing rust and powdery mildew diseases on spring wheat. First treatment , Genium plant conditioner were applied at a rate of 4 liters per hectare (equivalent to 60 ml per 15 square meter plot) combined with Solvitis Mikrokomplex plant conditioner at 1 liter per hectare (15 ml per 15 square meter plot were applied on 12.06.2024 with a back sprayer, second treatment involving fungicide Amistar (active ingredient azoxystrobin) at 1 liter per hectare (15 ml per 15 square meter plot), was applied on 27.05.2024, with a back sprayer, third treatment was peppermint essential oil which was applied on 12.06.2024 and 25.06.2024, with a back sprayer and the fourth treatment was control.

1.10.1[3.2.1] Genium plant conditioner.

Genium contain a blend of humic and fulvic acids**;** this is organic compounds derived from the decomposition of plant matter. Seaweed extracts**;** rich in trace elements, amino acids, and plant growth regulators (like auxins, cytokinins, and gibberellins). Amino Acids**,** The building blocks of proteins, which can aid in plant growth and stress tolerance. Vitamins**;** such as B vitamins, which can play roles in metabolic processes. Microbial Inoculants**:**

Beneficial bacteria and fungi that can improve nutrient availability and soil health. Wetting Agents/Surfactants; to improve the spread and absorption of the product on plant surfaces. The primary function was to improving soil health; enhancing soil structure, water retention, and nutrient availability. To stimulating plant growth; Promoting root development, shoot growth, and overall vigor.To enhancing nutrient uptake; making it easier for plants to absorb essential nutrients from the soil or foliar applications. To increasing stress tolerance; helping plants better withstand environmental stresses like drought, temperature extremes, and potentially disease pressure

3.3.2 Mikrokomplex plant conditioner.

This contains essential micronutrients; Such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). These are vital for various plant metabolic processes. Macronutrients; in smaller quantities (nitrogen, phosphorus, potassium). Chelating agents; substances that bind to micronutrients, keeping them soluble and available for plant uptake, especially in alkaline soils. Some Bio stimulants; like humic/fulvic acids or amino acids to aid absorption and utilization of the micronutrients. The primary function of Solvitis Mikrokomplex was to supply essential micronutrients; correcting deficiencies and ensuring plants have the necessary trace elements for optimal growth and development. To Improve nutrient balance, helping plants utilize other nutrients more effectively. To enhance physiological processes, micronutrients are crucial for photosynthesis, enzyme activity and other vital functions. To boost plant health and resilience; by ensuring all nutritional needs are met.

1.10.3[3.2.3] Amistar application.

Amistar products contain the active ingredient azoxystrobin with chemical group: Strobilurin (QoI inhibitor - Quinone outside Inhibitor). The mode of action are Systemic (It can be absorbed by the plant and transported within the xylem, offering protection to new growth), translaminar(can move through the leaf tissue, providing protection to both the upper and lower surfaces, even if only one side is sprayed), protectant (highly effective at preventing fungal infections by inhibiting spore germination and the early stages of fungal growth) with some curative properties (exhibits some curative activity by killing fungal mycelium (the vegetative part of the fungus) and inhibiting the development of fruiting bodies within the leaf tissue, especially during the early stages of infection). Primary mechanism of Azoxystrobin was to disrupt the energy production within fungal cells. It specifically inhibits electron transport at the quinone outside (Qo) site of the cytochrome bc1 complex in the fungal mitochondria. This blockage prevents the fungus from producing adenosine triphosphate (ATP), which is essential for its growth and survival. Azoxystrobin is effective against a wide range of fungal pathogens, including Powdery mildew (Ascomycetes) and rusts (Basidiomycetes).

3.3.4 Essential oil (Peppermint)

Peppermint essential oil is a highly concentrated volatile liquid extracted from the leaves and flowering tops of the peppermint plant (*Mentha piperita*). It is characterized by strong, cool, and refreshing minty aroma, primarily due to its main chemical components: menthol which is potential antifungal and menthone has antimicrobial activity.

3.3.5 Seeds used.

The moderately susceptible spring wheat cultivar used in this study was MV Kikelet, which was obtained from the Centre for Agricultural Research in Martonvásár, Hungary.

1.4[3.4] Data collection and calculation

Diseases assessment was done, disease incedense for both rust and powdery mildew from 100 randomly chosen plants within each plot. was assessed visually on the spring wheat plants. The number of diseased plants in each plot where recorded. After harvest other parameters that were measured and recorded include growth parameters such as yield and yield components (kg).

3.5 Statistical analysis.

The collected data pertaining to leaf rust and powdery mildew including disease incidense, yield, and yield components, were subjected to statistical analysis using Analysis of Variance (ANOVA) with Genistat 18th edition software. To determine significant differences between treatment means, the Least Significant Difference (LSD) method was applied. Furthermore, Regression Modeling, encompassing correlation and regression coefficients, was utilized to evaluate the relationships between epidemiological disease parameters, yield components, and weather variables.

2[4] RESULTS AND DISCUSSION

2.1[4.1] Effects of treatments (essential oils, Plant Conditioners,Fungicides and Control) on grain yield and quality (test weight, hectoliter weight).

The findings revealed no statistically significant differences ($p>0.05$), which indicates clearly that the treatments applied in the study did not lead to markedly different results in terms of overall yield and other associated parameters (refer to table 1 for details). Nevertheless, the average total yield for a 15 square meter area, when extrapolated to a larger scale of one hectare, approximates about 2.4 tons. This yields a concerning gap of approximately 3.2 tons when contrasted with the current potential average wheat yields per hectare in Hungary. Notably, the Hungarian Central Statistical Office (2024) reports the average yield to be around 5.6 tons per hectare, which can vary significantly depending on changing weather conditions throughout the growing season.

***Table 1:* Effects of treatments on Yield, test weight and hectoliter weight of winter wheat variety MV.**

Source of Variation	Weight/Plot (g)	1000g Weight	Hectoliter Weight
Plant Conditioner	3918 ^{a}	55.00 ^{a}	74975 ^{a}
Fungicides	3268 ^{a}	46.55 ^{a}	75432 ^{a}
Essential Oils	3784 ^{a}	40.80 ^{a}	76050 ^{a}
Control	3571 ^{a}	46.95 ^{a}	76638 ^{a}
Mean	3635.25	47.325	75773.75
CV	15.6	23.5	1.4
$LSD_{0.05}$	873.660	17.133	1640.744

Throughout the research period, the occurrence of various fungal rusts, along with the infection caused by powdery mildew, can serve as a major contributing factor to the significant yield loss that has been highlighted above. Furthermore, the established correlation relationship indicates a relatively negative relationship between the prevalence of the fungal diseases and the overall yield obtained ($r = -0.34$). This is particularly concerning when it comes to the rust fungi (table 2). This notably negative correlation underscores the critical importance of managing these fungal infections in an effective manner to mitigate their detrimental impact on agricultural productivity and ensure better yields for farmers. By addressing these issues strategically, stakeholders can work to enhance the health of crops and improve productivity in the agricultural sector overall.

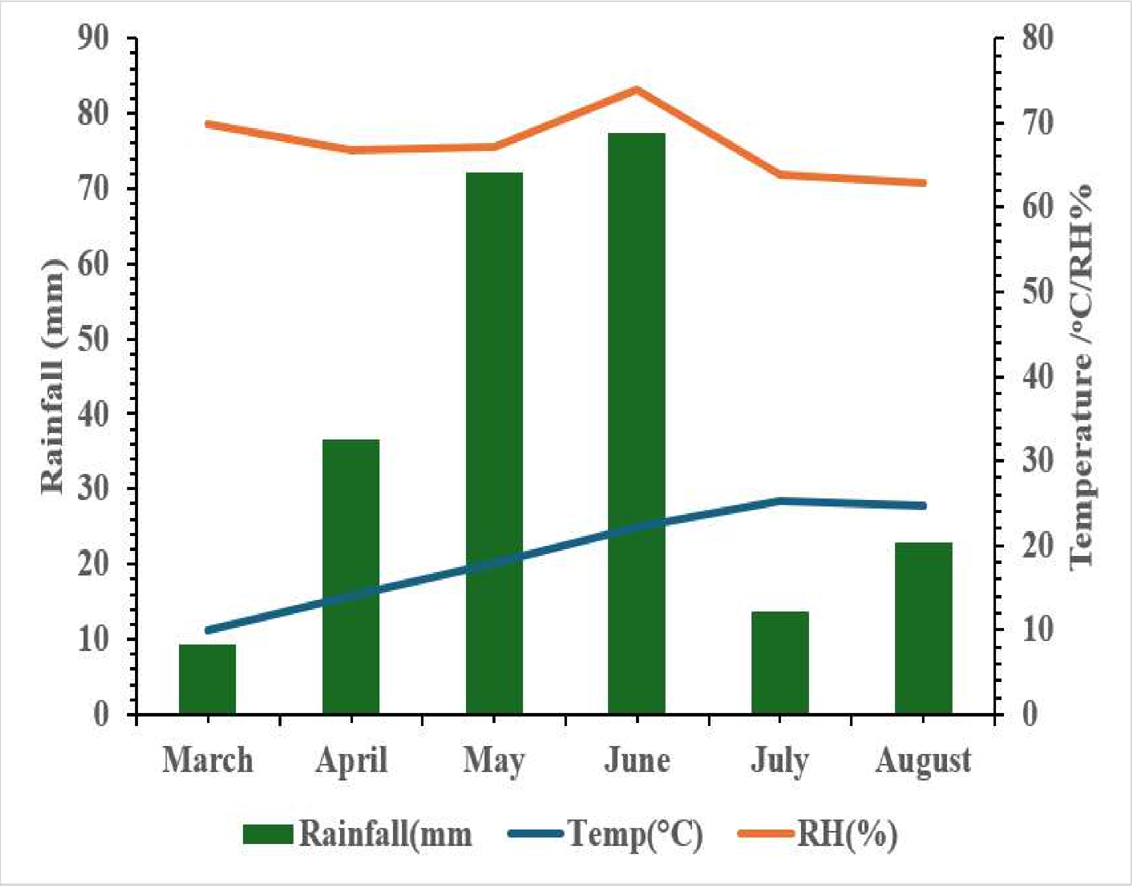
Table 2 **Pearson correlation coefficient showing the relationship between yield and fungal diseasases under various treatment**

	Weight/ plot	*1000gW*	*Hectoliter Weight*	*RF*	*PM*	*RF+PM*
Weight/plot	1					
1000gW	0.340	1				
Hectoliter Weight	0.142	-0.167	1			
RF	-0.337	0.143	-0.014	1		
PM	-0.078	-0.125	-0.143	-0.546	1	
RF+PM	0.311	-0.151	0.089	-0.877	0.239	1

2.2[4.2] Weather conditions on the on the incidence of diseases

The growth dynamics of various fungi and the overall productivity of agricultural crops are significantly influenced by various meteorological and environmental factors. Figure 14 illustrates in detail the specific weather conditions that have been observed at the designated experimental station throughout the study. The source of the meteorological data at DE AKIT DTTI Practical Garden operated by Precision Research and Development Service Center, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen. The data were recoreded by Campbell Scientific CR1000 at the basic resolution of the data is 10 minutes and sampling is 100Hz. The type of sensors involved involved were ARG-100 for precipitation while temperature and Relative humidity used HygroVUE10.

Figure 14: **Weather conditions at the experimental station during the research**



The development and spread of both Rust Fungi and Powdery Mildew are significantly influenced by various environmental factors that are crucial for their growth. According to AGRIOS (2005), the incidence of Rust-related fungal diseases affecting wheat is particularly dependent on particular climatic conditions, which require not only elevated humidity but also prolonged leaf wetness for the effective facilitation of spore germination and subsequent infection. These types of fungi generally flourish within moderate temperature ranges, specifically between 15°C and 25°C (59°F to 77°F), where conditions are optimal for their life cycle. On the other hand, Powdery Mildew also prefers similar moderate temperatures, specifically within the range of approximately 15°C to 22°C (59°F to 72°F). However, it exhibits a greater tolerance for relatively lower humidity levels when compared to Rust Fungi. Consequently, it can be said that increased humidity significantly enhances the proliferation and growth of Powdery Mildew, which aligns perfectly with the weather conditions that were recorded at the experimental station, as clearly depicted in figure 14. These interactions illustrate the nuanced relationship between environmental conditions and fungal disease dynamics, providing essential insights into the management of these diseases in agricultural practices.

2.3[4.3] Effects of Treatments on the Incidences of Rust Fungi and Powdery Mildew

The presented data in figures 15 to 17 illustrate the effectiveness of the treatments in mitigating the prevalence of fungal rust and powdery mildew.

Figure 15: **Effects of treatments against Rust fungi occurrences**

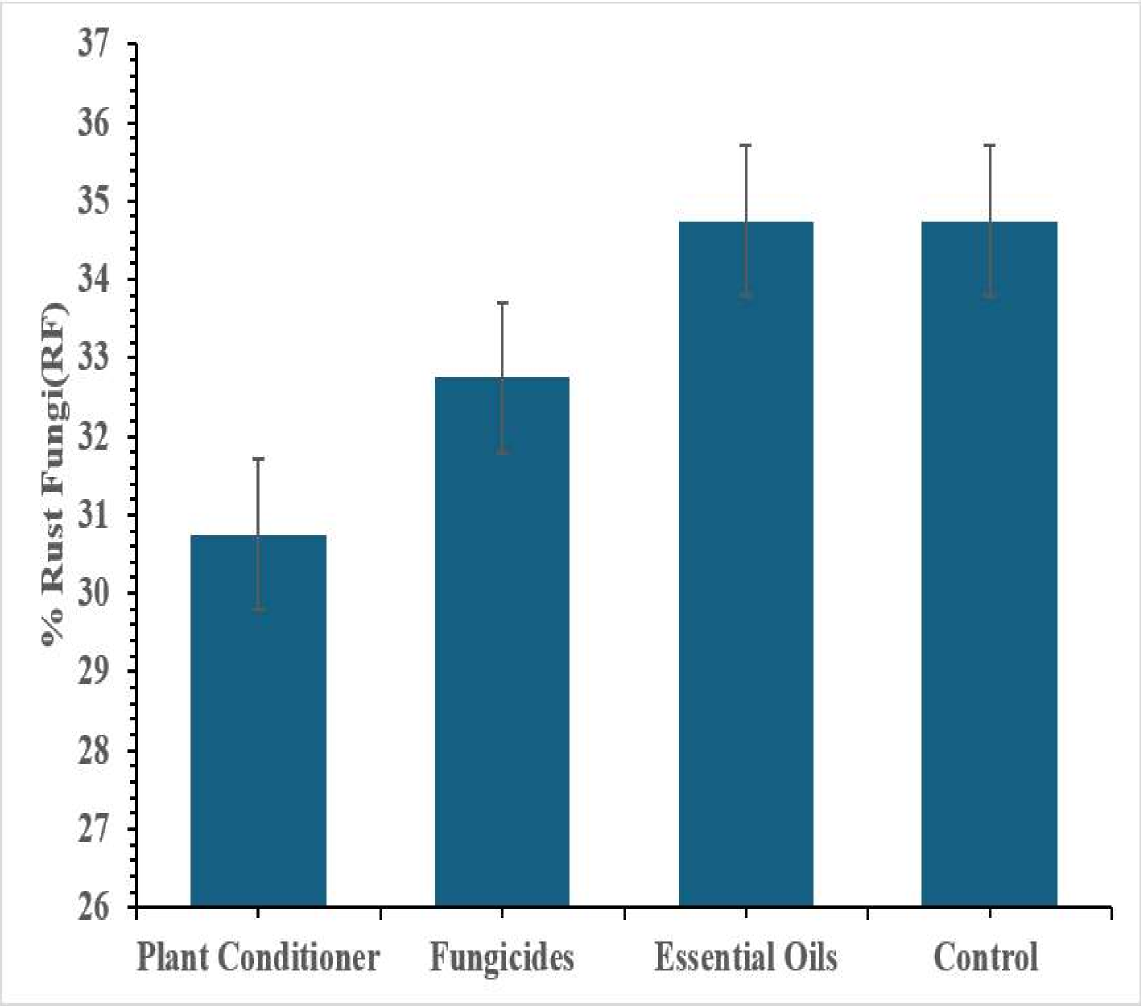


Figure 16: **Effects of treatments against powdery mildew occurrences**

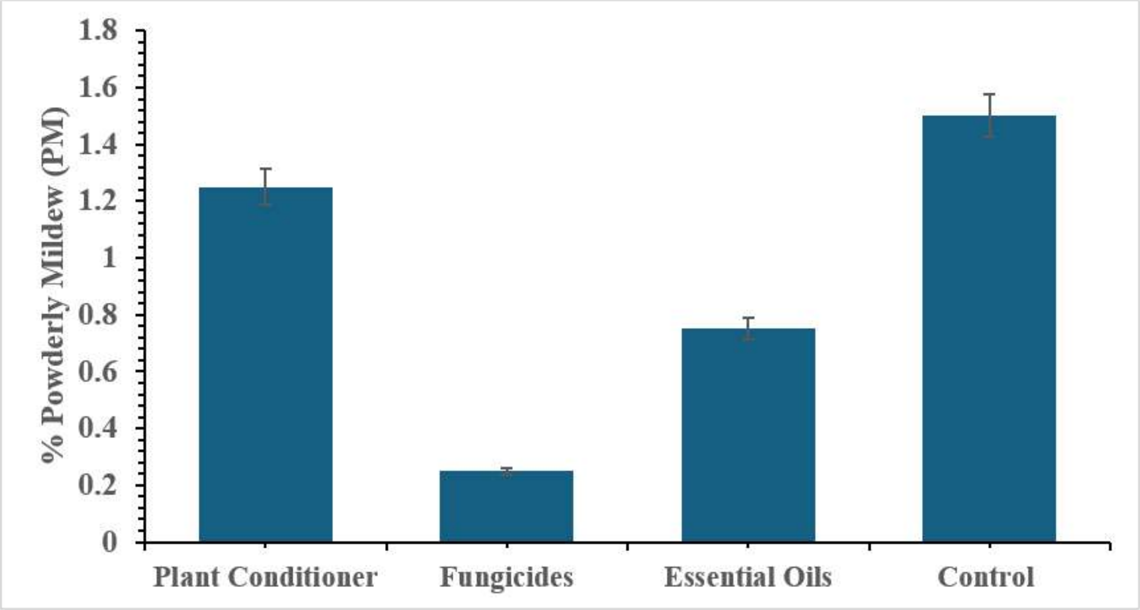
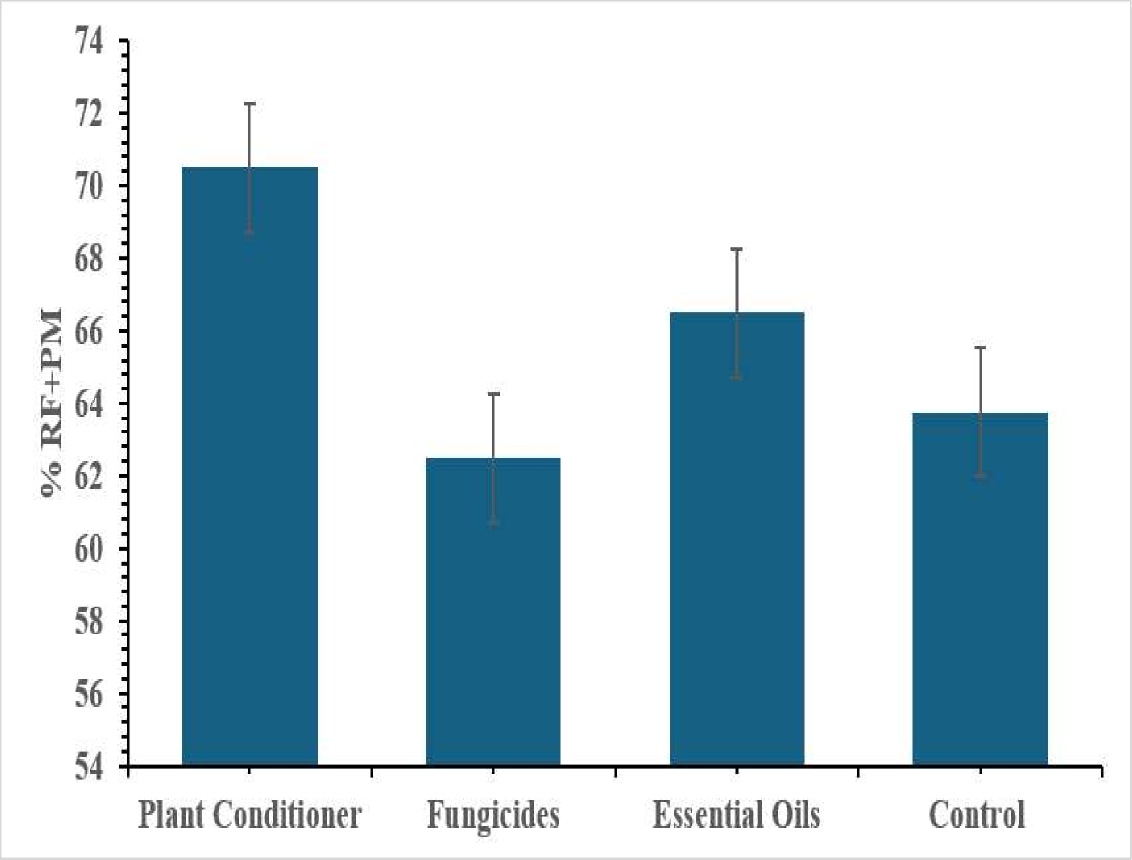


Figure 17: **Effects of treatments against Fungi rust and powdery mildew occurrences**



The treatments appied in the study demonstrated significant impacts on the development of rust fungi (RF) and powdery mildew (PM). The use of the plant conditioner was found to be particularly effective in managing and controlling the rust fungi. The occurrence of rust fungi is linked directly to the favorable climatic conditions that were observed throughout the entire duration of the research study, as illustrated in (Figure 14). On the other hand, the plant conditioner demonstrated to be notably ineffective in controlling and managing the powdery mildew disease.

The results of the study indicated that the fungicides employed showed a significant level of effectiveness, ($p<0.05$) for the control of powdery mildew (figure 16). Furthermore, these fungicides were also effective for the dual management of both rust fungi and powdery mildew diseases combined (figure 17). Additionally, while essential oils performed poorly and were not effective in the control of rust fungi diseases, they did exhibit a moderate level of efficacy in managing both powdery mildew and the combined effects of rust fungi and powdery mildew diseases. These results are indicative of a compelling opportunity to develop an effective approach, especially when taking into account the notable differences in efficacy between the plant conditioner and essential oils compared to the synthetic fungicides that were used in the study.

2.4[4.4] The association of the weather conditions at the experimental station with the occurance and progression of fungal rust and powdery mildew

The weather conditions recorded at the experimental station were conducive to the sporulation and proliferation of rust fungi (RF) as well as to powdery mildew (PM). Table (2) presents a two-tailed Pearson correlation that was performed to thoroughly investigate the relationships between various weather conditions at the experimental station throughout the entire cultivation season and the sporulation and development of fungal rust and powdery mildew. This statistical analysis aims to provide a deeper understanding of how environmental factors can be associated and influence the progression of the fungi species under study.

***Table 3*: Correlation coefficient values showing a relationship of agrometeorological conditions on, fungal diseases development**

	Temp(°C)	*RH %*	*Rainfall(mm*	*RF %*	*PM %*	*RF+PM%*
Temp (°C)	1.000					
RH (%)	-0.374	1.000				
Rainfall (mm)	0.113	0.534	1.000			
RF %	0.943	0.188	0.994	1.000		
PM %	0.289	0.890	0.146	0.039	1.000	
RF+PM %	-0.597	-0.013	-0.551	-0.596	0.416	1.000

Correlation analysis indicated significant ($p<0.05$) strong positive and negative relationships existing between various variables that were meticulously examined. Firstly, temperature exhibited a strong and positive influence on the development and proliferation of rust fungi, which was confirmed by the Pearson correlation coefficient ($r=0.943$), underscoring the crucial role that temperature plays in fungal growth dynamics. Similarly, rainfall demonstrated a strong and positive correlation with the development of rust fungi ($r= 0.994$), highlighting the importance of adequate moisture in fostering these organisms.

The temperature at the research station during the growing season consistently ranged between 10 to 24 °C, with an average temperature calculated at 19.8 °C. These compelling results align with the findings of AGRIOS (2005), who reported that the optimum temperature range of 15 to 25 °C is particularly facilitative for the sporulation and development of rust fungi, alongside heightened relative humidity levels that are conducive to their growth.

On the other hand, the results also indicated a strong positive association between relative humidity and the incidence of powdery mildew. This observation strongly depicts that the higher relative humidity recorded at the experimental site during the growing season, which averaged 67.5% is highly indicative of conditions favoring the progression of powdery mildew, allowing it to thrive under such environmental circumstances.

2.5[4.5] Discussion

Many essential oils have shown *in vitro* antifungal activity against wheat fungal pathogens like rust and powdery mildew (e.g., SINGH et al., 2016; BEN AMOR et al., 2017). The effectiveness of these oils (such as thyme, oregano, peppermint, tea tree oil, lavender, clove, cinnamon, rosemary, lemongrass) is highly variable, depending on the specific oil, its concentration, and the targeted fungal species (DAFERERA et al., 2003). Contrary to my research, essential oils did not demonstrate a significant effect on rust and powdery mildew control. This could be attributed to either the application rates or the timing of application being incorrect.

One study evaluated lavender (*Lavandula angustifolia*), tea tree (*Melaleuca alternifolia*), and peppermint (*Mentha piperita*) oils against wheat rust diseases in a field experiment, comparing them to commercial fungicides (MASHILIMU, 2024.). The findings indicated that while fungicides significantly reduced disease severity, there was no significant difference observed between the tested essential oils and the untreated control group regarding their ability to suppress rust development. The study also assessed the impact of these treatments on various yield components of the wheat crop (MASHILIMU, 2024.) This study is closely linked to my investigation, and the findings demonstrate a similar trend.

Studies on the impact of essential oils on wheat yield are less abundant and show variable results (TOHAMEY and EL-SHARKAWY, 2014). Some research suggests that effective disease control with essential oils can lead to improved yields by reducing disease-related losses (HAGGAG et al., 2015). However, if the essential oil doesn't provide sufficient disease control (MASHILIMU, 2024). or if it causes any phytotoxicity at effective concentrations (JOP et al., 2021), it may not positively impact or could even reduce yield. Compared to this research, the yield impact was lower than the potential wheat yield projected for a one-hectare area under ideal conditions.

The impact of plant conditioners on wheat yield is often linked to improved nutrient availability and plant health, leading to better growth and potentially higher yields, especially under suboptimal growing conditions (HAMDY and SFEIR, 2002; EL-HADIDI and ABO EL-EZZ, 2021). Their effect on yield specifically through disease management is usually indirect, by enhancing the plant's natural defense mechanisms rather than directly targeting the pathogen (UT INSTITUTE OF AGRICULTURE, 2023.).

This study implies that plant conditioners alone may not be sufficient to control severe outbreaks of highly virulent fungal diseases like rust and powdery mildew. They are often seen as a component of an integrated approach. The effectiveness of both plant conditioners and essential oils can be highly dependent on the specific wheat variety, the prevalent fungal pathogen races, environmental conditions (temperature, humidity), application methods, and the timing of application.

3[5] CONCLUSIONS AND RECOMMENDATIONS

3.1[5.1] Conclusions

Despite the results indicating that there were no statistically significant differences in yield between the applied treatments, the use of plant conditioner led to an increase in yield by 16.5%, 3.4%, and 8.9% when compared to fungicides, essential oils, and the control group, respectively. Furthermore, the plant conditioner exhibited a greater efficacy in controlling rust fungi than the other treatments. This observation underscores the potential of utilizing plant conditioner not only in enhancing the yield of wheat crops but also in effectively managing the challenges posed by fungal rust diseases. However, it is important to highlight that the performance of plant conditioner in managing powdery mildew was not as effective when compared to the results observed with fungicides and essential oils. On the other hand, essential oils showed moderate efficacy in the management of powdery mildew. The disparity observed in the effectiveness of these treatments offers a compelling opportunity for developing an integrated approach to efficiently manage both fungal rust and powdery mildew in wheat crops through the blending of these applications. Such a strategy could significantly reduce the reliance on fungicides, which are most commonly used to combat these diseases, thereby promoting more sustainable agricultural practices.

3.2[5.2] Recommendations

Based on the findings of this research, the following recommendations are made:

1. Conducting further studies on testing the combined efficacy of plant conditioners and essential oils in managing rust fungi and powdery mildew to enhance yield of wheat, through optimizizing application rates and timing, the objective is to explore different concentrations and application schedules of the plant conditioners and essential oils, both individually and in combination, to identify the most effective and economical regimes.
2. To Conduct further research to understand the potential synergistic mechanisms between the plant conditioners and essential oils that might be contributing to disease management. This could involve analyzing plant defense responses or direct pathogen inhibition, and potentially reduce the overall chemical load.

3. Explore the efficacy of other essential oils known for their antifungal properties, either alone or in combination with plant conditioners, to broaden the spectrum of control or enhance effectiveness.
4. To continue research in breeding wheat, with the aim of evaluating the performance of wheat varieties specifically bred for tolerance to abiotic and biotic stress conditions.
5. To conduct multi-year trials to evaluate the sustainability and long-term impact of these treatments on disease management, soil health, and beneficial microbial communities.
6. To Conduct a thorough economic analysis comparing the cost of essential oil and plant conditioner treatments (including application) with the cost and benefits of traditional fungicide programs for winter wheat in Hungary.
7. To Highlight the potential environmental advantages of using essential oils and plant conditioners as alternatives or supplements to synthetic fungicides, focusing on reduced chemical residues and potential benefits to beneficial organisms.

4[6] SUMMARY

This research investigated the comparative efficacy of plant conditioners, essential oils (peppermint), and a conventional fungicide (Amistar) in managing rust fungi and powdery mildew diseases in spring wheat (cultivar MV Kikelet) under field conditions at the University of Debrecen, Hungary. The study also evaluated the impact of these treatments on wheat yield and quality parameters. A Randomized Complete Block Design (CRD) with four replicates and four treatments (plant conditioner mix, fungicide, essential oil, and untreated control) was employed. Disease incidence was visually assessed, and yield components were measured after harvest. Statistical analysis, including ANOVA and correlation, was performed using Genistat 18th edition.

The findings revealed no statistically significant differences between the treatments in terms of overall yield, test weight, and hectoliter weight. However, the extrapolated average yield (2.4 tons/hectare) was significantly lower than the potential average yield in Hungary (5.6 tons/hectare), highlighting a substantial yield gap potentially attributable to fungal diseases. Correlation analysis indicated a negative relationship between fungal disease prevalence and yield.

Regarding disease management, the plant conditioner showed effectiveness in controlling rust fungi but was ineffective against powdery mildew. The fungicide (Amistar) demonstrated significant control of powdery mildew and also managed both rust fungi and powdery mildew combined. Essential oils (peppermint) showed poor control of rust fungi but exhibited moderate efficacy against powdery mildew and the combined diseases.

Weather conditions at the experimental station (temperature ranging from 10 to 24 °C, average 19.8 °C; average relative humidity of 67.5%; and rainfall) were found to be conducive to the development and proliferation of both rust fungi and powdery mildew, aligning with established literature on their preferred environmental conditions. Correlation analysis confirmed a strong positive relationship between temperature and rainfall with rust fungi development, and a strong positive association between relative humidity and powdery mildew incidence.

In conclusion, while the tested treatments did not significantly impact overall yield parameters in this specific study, they exhibited varying levels of efficacy in controlling rust and powdery mildew. The fungicide proved most effective against powdery mildew and the combined diseases. The plant conditioner showed potential against rust, while essential oils had limited impact on rust but some effect on powdery mildew. The study underscores the significant influence of favorable weather conditions on fungal disease development and the potential for substantial yield losses. Further research is needed to optimize the application rates and timing of alternative treatments like plant conditioners and essential oils, potentially within integrated pest management strategies, to provide sustainable and effective disease control in Hungarian wheat production.

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DECLARATIONS

I, Christopher Costas Msigwa (HQ56QU), aware of my criminal and disciplinary liability, hereby declare and confirm with my signature that the thesis/dissertation is the result of my work. I have handled the literature used appropriately, I have learned the correct method for handling literary sources from the relevant regulations, and I have complied with the legal requirements related to the thesis. I acknowledge that if I violate these requirements, my thesis will be rejected.

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