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REVIEW

Managing fungal pathogens of field crops in sustainable agriculture and AgroVariety internet application as a case study

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Abstract

Effective management of plant fungal pathogens is crucial for minimizing economic and environmental impacts of crop diseases in agricultural production. It plays a major role in providing healthy and nutritious food, maintaining human and animal well-being, and maintaining an environmental balance in agroecosystems. These goals agree with agroecology and Integrated Pest Management (IPM). Agroecology integrates ecological principles with agriculture and offers a holistic and environmentally friendly approach to fungal disease management. IPM focuses on prevention and protection against pests and diseases, involving environmentally safe agricultural practices, cultivating resistant plant varieties, and promoting agrobiodiversity. The authors aimed to provide a comprehensive and concise overview of the key components of IPM in sustainable agriculture including recent developments in electronic tools helping farmers to make optimal economic and environmental decisions. While maintaining agroecology principles there is a particular focus on the significance of plant resistance to major pathogens, breeding technologies, effective crop management practices, and non-chemical fungal management. Agroecological approaches to fungal plant pathogen management prioritize the long-term health of agricultural ecosystems, contributing to the overall biodiversity and sustainability of farming systems. To illustrate the practical application of these principles, the AgroVariety application (app), developed for farmers, was used to discuss the role of specialized applications in decision-making for environmentally friendly and cost-effective plant production. This tool emphasizes combining different IPM techniques, with specific emphasis on methods that are least harmful to the environment and tailored to control particular pathogens.

Keywords: agroecology, agricultural applications, climate change, Integrated fungal Plant Pathogens Management, sustainable agriculture, variety choice

Introduction

On November 15, 2022 the global human population reached the milestone of 8 billion (Dawson and Zhang 2024) and, it became more evident that plant health is crucial for humankind for numerous reasons, including food security and safety, and the promotion of a healthy environment (Delabre *et al.* 2021; Rizzo *et al.* 2021). The world's population is expected to continue growing for another 50 or 60 years, reaching a peak of around 10.3 billion people in the mid-2080s, up from 8.2 billion in 2024. Although plants play a vital role in supporting public health, their significance is often overlooked. Plant health can be affected by a wide range of abiotic and biotrophic factors, including plant pathogens. In recognition of this fact, the United Nations declared 2020 to be the International Year of Plant Health (IYPH). Healthy plants are crucial in the "One Health" concept, which benefits both humans and animals (Banerjee and van der Heijden 2023). Growing public awareness of risks to human health and environmental safety has contributed significantly to ramping up risk mitigation activities in this area. In the realm of plant protection most control measures address the risks associated with the widespread use of synthetic chemicals. Such use of synthetic chemicals in plant protection has many drawbacks, including environmental contamination, human health hazards, pest resistance, and high costs. Effective ma nagement of fungal plant pathogens is of major importance due to its direct impact on the development of sustainable agricultural production (Sharma *et al.* 2019; Al-Agele *et al.* 2021; Bouri *et al.* 2023; Singh *et al.* 2023). The mitigation of these pathogens plays a crucial role in achieving optimal economic performance, social inclusion, and environmental sustainability. These aspects are fundamental in a holistic approach to sustainable and responsible agricultural practices (Hatt *et al.* 2019). Integrated Pest Management (IPM) strategies, which the EU promotes, focus on pest prevention and alternative control methods that do not harm beneficial organisms such as pollinators, human practitioners, or crop-dependent animals. The EU's "Farm-to-Fork" and "Biodiversity" strategies highlight the need to transition to a fair, healthy, and environmentally-friendly food system. Recently the European Commission has also adopted a proposal for new regulation of the Sustainable Use of Plant Protection Products. Under this regulation, the EC has set EU-wide targets to halve the use of synthetic chemical pesticides by 2030. IPM can be used to achieve optimal fungal plant pathogen management while minimizing risks and impacts on human health and the environment (Fenibo *et al.* 2021; Lázaro *et al.* 2020, 2021; Kalogiannidis *et al.* 2022; Erekalo *et al.* 2024).

When implementing IPM strategies to manage plant diseases, it is essential to consider the disease triangle. The disease triangle illustrates the three critical components necessary for disease development: a susceptible host plant, a pathogen, and suitable environmental conditions (Delabre *et al.* 2021; Richard *et al.* 2022; Singh *et al.* 2023). Environmental change and human activities affect the soil, and thus the microorganisms found there, through agrotechnology, fertilization and crop rotation. As a result the evolution of the pathogen has generally increased disease threats to global crops. Environmentally friendly farming practices involve varieties from advanced breeding programs, integrating biotechnology and genetic engineering (Lamichhane *et al.* 2018; Li and Yan 2020; Scossa *et al.* 2021). They also include diverse farming practices, careful pesticide use, water conservation, and enhancing soil health through agronomic and innovative fertilizer strategies (Al-Agele *et al.* 2021; Delabre *et al.* 2021; Andrés *et al.* 2021; Banerjee and van der Heijden 2023). The role of plant resistance breeding in ecosystem stability varies. It is essential to approach plant resistance breeding with a holistic understanding of ecosystem dynamics and potential long-term consequences of cultivated varieties. A balanced and sustainable approach involves incorporating resistance traits that benefit both crop productivity and ecosystem health. Additionally, monitoring ecological impacts and promoting practices that enhance overall ecosystem stability are crucial elements of responsible plant resistance breeding. These components are integrated into a new disease triangle (Singh *et al.* 2023). By understanding the interactions between all these elements, farmers and agricultural experts can effectively develop comprehensive strategies of IPM to manage plant diseases. In sustainable agriculture, the components involved in the pre-infection process are distinguished from those associated with post-infection strategies under climate change conditions (Kebe *et al.* 2023). Key components of IPM in sustainable agriculture are shown in Figure 1.

Agroecology plays a crucial role in sustainable agriculture, contributing to overall environmental conservation, resource efficiency, community engagement, and the overall resilience of farming systems (Wezel *et al.* 2014; Tamburini *et al.* 2020; Deguine *et al.* 2023; Joshi *et al.* 2023; Le Provost *et al.* 2023). In the face of current agricultural challenges, a mere return to practices of the last century has proven to be inadequate due primarily to the resulting decline in crop yields in a rapidly changing environment, and a growing demand for healthier and safer food of the highest quality. In addition, the economic impact of many fungal and other pest species has evolved, while last century's crop protection practices continue to generate yields of insufficient quality and volume. Thorough research on agricultural pests in the changing climate and their consistent monitoring are critical to ensure that farmers are equipped with the pest control knowledge they need to produce healthy crops. Numerous field studies offer insights into optimal land use for resilient agroecosystems. Farmers must apply this knowledge for cost-effective disease control, ensuring environmentally sound, large-scale plant production. To support informed and eco-friendly decisions, effective information management for farmers is essential. Specifically designed internet applications (apps) can play a vital role by consolidating diverse agricultural data into a unified web service, analyzing and presenting integrated data in a user-friendly format and enabling users to access real-time information about their fields

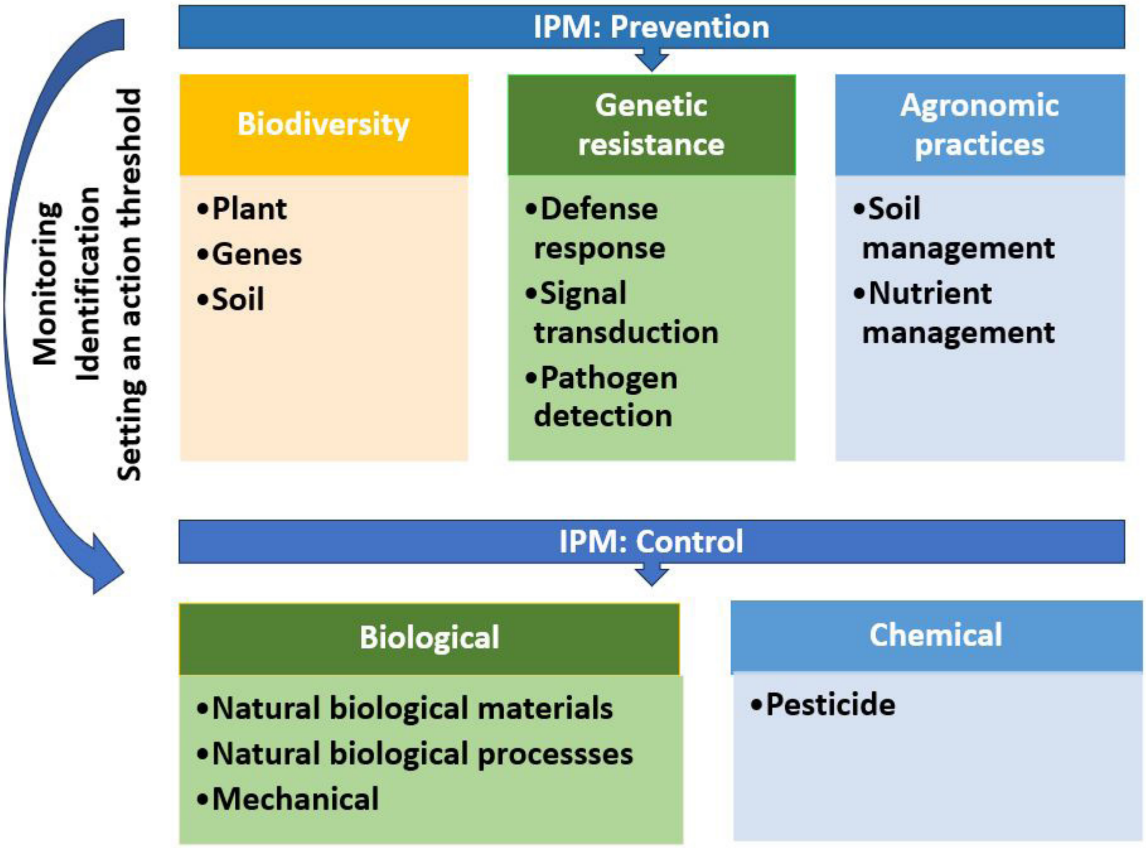

Fig. 1. Key components of Integrated Pest Management (IPM) in sustainable agriculture

(Bonke *et al.* 2018; Lamichhane *et al.* 2018; Eichler Inwood and Dale 2019; Oteyo *et al.* 2021). These apps empower farmers to boost productivity, operational efficiency, and adapt cropping systems to evolving socioeconomic contexts. Furthermore, these apps act as catalysts, actively promoting the enhancement of agroecosystem diversity. They are crucial in addressing a range of environmental issues, such as soil, water, and air quality. Recently many innovations have been introduced into agricultural production through remote sensors, sensor networks, weather forecasting services, machine visions and image analyses, as well as other technologies such as Information Technology (IT), satellite technology, Geographical Information System (GIS), Big Data Technology (BDT), and Machine Learning (ML). These innovations have positive economic and environmental impacts on all aspects of the agriculture sector, including disease management (Boursianis *et al.* 2022; Ali *et al.* 2023; Balaska *et al.* 2023; Gokulakrishnaa and Thirunavukkarasu 2023; Chojnacka 2024;; Kasera *et al.* 2024). A critical challenge is making the benefits of these apps available to a wide range of participants and end users within the agriculture sector. It is important to consider the fact that farmers are primarily focused not on (big) data, but on knowledge generated from this data. This proactive approach significantly contributes to the broader goal of advancing sustainable agricultural practices. In effect, it helps to establish a harmonious balance between agricultural activities and environmental preservation (Khanal *et al.* 2017; Bonke *et al.* 2018; Lamichhane *et al.* 2018; Eichler Inwood and Dale 2019; Oteyo *et al.* 2021).

In this mini-review the focus was on non-chemical IPM components provided by biotic interactions, namely: plant resistance as host management, improvements in agricultural practices and environmental pathogen management as well as biological control of fungal plant pathogens. The identified benefits set a clear program that can be adapted to develop apps supporting decision-making for environmentally friendly and profitable crop production. Furthermore, this subject will be discussed by using the example of the AgroVariety app developed for Polish farmers. The AgroVariety app is designed for farmers as a practical app of IPM components for sustainable agriculture. This example shows the benefits of modern technologies, such as drones or satellites, that enable monitoring the condition of plantations. The utilization of climate change data from 1970 to 2010 serves as a compelling example of how these technologies can significantly enhance their efficacy in developed apps.

Prevention in sustainable fungal plant pathogen management

Plant resistance and breeding technologies for sustainable fungal pathogen management

Cultivars better adapted to an environment characterized by rapid climate change and current agriculture challenges ensure sustainable agriculture and play an important role in IPM. The high-yielding crop varieties introduced during the Green Revolution often had limited genetic diversity. This relative genetic uniformity can make crops more susceptible to specific pathogens, leading to potential large-scale epidemics if a pathogen overcomes the limited resistance present in these crops. Genetic resistance and tolerance to fungal pathogens play important roles in the transition toward more sustainable and lower-input agriculture (Ansaldi *et al.* 2018; Milner *et al.* 2018; Sakellariou and Mylona 2020; Zetzsche *et al.* 2020; Singh *et al.* 2023).

Disease-resistant crop varieties align with principles of sustainable agriculture by promoting practices that are economically viable, environmentally sound, and socially responsible. These varieties contribute to the long-term sustainability of crop production systems, because of their resilience against disease outbreaks and provide a lack of harmful influence on non-target organisms. Developing crops with inherent resistance can reduce the reliance on chemical pesticides. This underlines the role of internet apps in disseminating information and facilitating decision-making, which potentially can minimize the negative impacts of pesticides on non-target organisms, such as beneficial insects, soil microorganisms, birds, and aquatic life, contributing to ecosystem stability (Wada *et al.* 2020; Zetzsche *et al.* 2020; Varshney *et al.* 2021b).

Healthy soils support diverse microbial communities and nutrient cycling, which are essential components of ecological stability. Disease-resistant varieties contribute to stable crop yields by minimizing losses due to diseases. For example, this stability in wheat production supports food security and economic stability for farmers, contributing to the overall resilience of agricultural systems. Resilient plants with improved resistance traits can contribute to overall ecosystem health. When plants resist diseases, they are less likely to succumb to stress, contributing to the maintenance of nutrient-cycling processes in the soil. By reducing the need for broad-spectrum pesticides, plant resistance breeding can help preserve biodiversity (Miedaner and Juroszek 2021; Bouri *et al.* 2023). Pesticides can have detrimental effects on non-target species, and minimizing their use underscores the role of internet apps in information exchange and awareness. As a result, the diversity of flora and fauna in and around agricultural ecosystems may be better maintained. While breeding for resistance, it is important to maintain genetic diversity within plant populations. This diversity can be a key component of ecosystem stability, allowing plants to adapt to changing environmental conditions and evolving pest and disease pressures. Crop varieties resistant to specific pests or diseases can contribute to the stability of agricultural systems. Such resistance can prevent devastating outbreaks that might otherwise lead to the widespread loss of crops, ensuring more consistent food production. While plant resistance breeding primarily targets specific pests or diseases, it is important to consider its potential impact on non-target organisms. For instance, the development of genetically modified crops may have indirect effects on certain organisms, and careful assessment is required to minimize unintended consequences (Wada *et al.* 2020; Varshney *et al.* 2021b).

Climate shifts alter pathogen populations and contribute to the emergence of new pathogens, making it difficult for breeders to meet the requirements of sustainable agriculture (Ansaldi *et al.* 2018; Miller *et al.* 2022). In disease resistance breeding, the disease triangle directs programs to identify genetic factors associated with host susceptibility and interactions with pathogens. By focusing on these components, breeders strategically introduce or enhance resistance traits, creating plant varieties resilient to specific diseases. The disease triangle serves as a bridge between resistance breeding and IPM, guiding the development of effective and sustainable solutions. This integrated approach recognizes the importance of understanding ecological interactions within the triangle to inform both management practices and genetic improvements for enhanced disease resistance (Ansaldi *et al.* 2018).

A plant's genetic makeup significantly determines its resistance to pathogens. Specific genes code for proteins involved in defense mechanisms, including recognition receptors and compounds that regulate defense compound production. Pathogen resistance in plants involves various organelles and classes of both proteins and non-protein compounds, each of which is crucial for regulating the defense response. The factors influencing these roles also impact other signaling systems, such as growth and responses to abiotic stress (Andersen *et al.* 2018; Sharma *et al.* 2019). Plant resistance to pathogens is influenced by genetic and environmental factors and involves components like secondary metabolites (alkaloids, flavonoids, terpenoids) with antimicrobial properties. Physical barriers, such as cell walls and trichomes, prevent pathogen entry. Induced defense mechanisms, like systemic acquired resistance (SAR) and hypersensitive response (HR), involve activating defense genes and rapid localized cell death, which limits the spread of pathogens (Balint-Kurti 2019; Li *et al.* 2022b). Resistance breeding relies chiefly on the incorporation of new genes resistant to fungal pathogens into crop varieties. Numerous studies show that this breeding method is the most effective and environmentally safest way to control economically important diseases (Zetzsche *et al.* 2020). Effective resistance not only protects crop varieties but also reduces the production of inoculum and the spread of pathogens over larger areas, leading to epiphytosis. However, fungal pathogens tend to display high levels of genetic variability, with new races emerging rapidly and spreading across long distances. This rapid emergence reduces the number of resistance genes that effectively control pathogen distribution, limiting options for breeders. Additionally, many modern crop cultivars grown across large areas lack partial host resistance due to being bred for race-specific resistance in most modern breeding programs (John and Babu 2021; Laidig *et al*. 2021). The loss of such resistance during the breeding process has long been recognized by plant pathologists and breeders. Several strategies to increase the durability of race-specific resistance genes in crop cultivars have been proposed and implemented, including the use of multiline cultivars, the 'pyramiding' of multiple resistance genes into a single variety, and the deployment of multiple cultivars with a range of resistance genes across specific areas or over time (e.g., cultivar mixtures, winter versus spring crop varieties). Introducing new effective sources of resistance into breeding material is essential for these genetic control strategies to be effective (Lamichhane *et al*. 2018; John and Babu 2021; Miedaner and Juroszek 2021).

The establishment of gene banks in the 20th century addressed genetic crop erosion caused by increasing homogeneity in new crop varieties. Gene banks, created to preserve vital plant genetic resources for current and future food demand, play a major role in breeding for resistance. Integrated into breeding programs, they contribute to the biological progress of crops and their direct production (Nguyen and Norton 2020; Thudi *et al.* 2020; Volk *et al.* 2021). To maximize their effectiveness, data from major gene banks, especially those relevant to fungal pathogen resistance, must undergo proper phenotyping and genotyping. Gene banks serve as crucial repositories of genetic diversity, offering a diverse pool of genetic material for identifying and introducing resistance traits to combat specific pathogens. Resistant plants within these collections provide valuable genes for incorporation into breeding programs, enhancing crop resistance (Thudi *et al.* 2020; Riaz *et al.* 2021; Volk *et al.* 2021). Researchers benefit from the genetic information stored in gene banks, helping them understand specific resistance genes and mechanisms. This knowledge aids in the targeted integration of traits for resistance. These gene banks also play a vital role in addressing genetic erosion, preventing the loss of crop genetic diversity over time. By preserving various plant varieties, they maintain a reservoir of traits essential for developing resistance in crops facing emerging pathogens and changing environmental conditions. Breeders access gene bank collections to introduce new sources of resistance, thereby infusing genetic diversity to create robust, resilient crop varieties that resist pathogens, contributing to sustainable agriculture. To harness the genetic resources in gene banks effectively, proper phenotyping and genotyping of stored plant material are essential. Phenotyping evaluates observable characteristics while genotyping analyzes the genetic makeup, guiding breeders in selecting and incorporating specific resistance traits into their programs (Milner *et al.* 2018; Thudi *et al.* 2020; Volk *et al.* 2021).

Breeding techniques play a key role in effective improvement of plant genetics, making production more sustainable environmentally, economically, and socially (Varshney *et al.* 2021a). Both plant breeders and geneticists are under constant pressure to sustain and increase food production by employing both innovative breeding strategies and minor crops that are well adapted to marginal lands and capable of providing a source of nutrition through increased tolerance to abiotic and biotic stress (Bailey-Serres *et al.* 2019; Laidig *et al.* 2021; Varshney *et al.* 2021a, b). While conventional breeding methods, including crosses and backcrosses, have proven effective, they are also time-consuming and labor-intensive. Genetic-engineering-based breeding techniques (NBTs) provide a quicker and more effective alternative to conventional breeding to improve plant resistance against fungal pathogens (Wada *et al.* 2020; Paul *et al.* 2021; Xu *et al.* 2022). Breeders began to use mutagenesis in the 1960s, followed by the emergence of in vitro cultures in the mid-1970s, genetic transformation (GMO) in the mid-1980s, marker-assisted selection (MAS) and transgenesis in the mid-1990s, and transcriptomic, and next genomic selection, GWAS, RNA-seq and gene editing in the early 21st century (Rasheed *et al.* 2017; Anwar and Kim 2020; Gangurde *et al.* 2022; Wei *et al.* 2023). Such DNA marker-based solutions as marker-assisted backcrossing (MABC) have improved plant traits by facilitating the transfer of QTL with strong effects. However, the potential of MABC for improving genetic gain is limited by the number of loci that can be addressed. The extensive presence of minor-effect QTL may explain the 'diminishing returns' of current crop breeding practices. Therefore, the success of future crop improvements hinges on harnessing variations attributable to minor-effect loci given that experimental populations with the segregation of such loci could be developed when most major-effect loci have been identified (Xu *et al.* 2022; Riaz *et al.* 2021).

Modern methods, such as genomic selection (NGS) and Diversity Arrays Technology (DArT), are deployed to improve complex traits such as disease resistance (Thudi *et al.* 2020; Varshney *et al.* 2021a, b). They reduce cost and enable high-throughputs and cost-effective genotyping. Analysis of the genetic architecture of resistance to main fungal pathogens by means of a genome-wide association study (GWAS) enables the identification of MTAs relevant for marker-assisted selection. Breeding transgenic plants involves transferring a gene from one organism to another to introduce a desirable trait, such as fungi or environmental stress resistance, into a plant that lacks this particular trait. This method has given rise to new biotechnological tools (NBTs), allowing for the development of elite cultivars with novel agronomic features (Anwar and Kim 2020; Gangurde *et al.* 2022; Wei *et al.* 2023). Genome-edited crops with new effective types of resistance can be grown quickly with the use of CRISPR/Cas9. The advantage of such new genome editing techniques as CRISPR-Cas9 is that they allow scientists to either modify or delete specific genes and DNA sequences associated with disease resistance and disease susceptibility, without introducing foreign DNA. This technique has also contributed to significant resistance with rapid multiplication potentials, producing genome-edited crops that are well-suited for quick adoption and use in the field. Examples of such genome editing tools include CRISPR-Cas9, TALENs, ZFNs, and meganucleases (Paul *et al.* 2021). Several genome-edited crops are in various stages of development and production. Some genome-edited crops are in production or close to commercialization. Genome editing has been employed to develop crops with improved tolerance to specific herbicides, allowing for more targeted and effective weed control. Researchers are using genome editing to enhance the drought tolerance of various crops, including maize and rice, to address the challenges associated with water scarcity (Wada *et al.* 2020; Paul *et al.* 2021; Xu *et al.* 2022)

However, in many countries, concerns are growing over the unintended effects of genome-edited crops on the environment and human health. These concerns are not aligned with sustainable farming practices, which are methods of agriculture aiming to conserve natural resources, reduce environmental impacts, enhance social and economic benefits, and ensure food security and quality (Wada *et al.* 2020). Especially in this context, apps play an important role in advancing genome editing techniques for breeding cultivars and promoting sustainable agriculture practices. They are indispensable for navigating the complex landscape of genome editing, breeding cultivars, and sustainable agriculture. Apps empower stakeholders with the information and collaborative tools needed to ensure that advancements in genetic technologies are aligned with the principles of environmental conservation, economic viability, and food security. They serve as essential tools in disseminating knowledge, fostering collaboration, and ensuring transparency in the development and implementation of genetic modifications. Apps facilitate the sharing of research findings, best practices, and regulatory guidelines related to genome editing in agriculture. Scientists, researchers, and policymakers can collaborate across borders, enabling the global community to work collectively on developing safe and environmentally friendly breeding cultivars (Richard *et al.* 2022; Xu *et al.* 2022; Bouri *et al.* 2023; Czembor *et al.* 2023).

Online platforms provide easy access to a vast repository of research articles, educational materials, and case studies related to genome editing and sustainable agriculture. This accessibility empowers scientists and farmers to stay informed about the latest advancements, ensuring that genetic modifications align with sustainable farming practices (Xu *et al.* 2022; Czembor *et al.* 2023). Apps enable the efficient sharing and analysis of data related to genome-edited crops. This is crucial for monitoring and assessing the environmental and health impacts of genetically modified cultivars, helping to identify and address any unintended effects. Apps can aid in monitoring and ensuring regulatory compliance for genome-edited crops. Online platforms can be used for real-time reporting, data submission, and tracking of genetically modified cultivars, helping regulatory bodies to enforce guidelines and mitigate potential risks. In this regard, genomic selection (GS) has been considered the most promising method of genetically improving complex traits controlled by multiple genes, each of which is associated with minor effects (Varshney *et al.* 2021a, b; Riaz *et al.* 2021). Large-scale GS applications in plants can be developed at a significantly reduced cost by refining field management to improve heritability estimation and prediction accuracy and by developing optimum GS models for genotype-environment interaction and non-additive effects (Varshney *et al.* 2021a, b). Moreover, it would be more effective to integrate GS with other breeding tools and platforms for accelerated breeding to further enhance genetic gains in plant resistance to fungal pathogens. In addition, establishing an open-source breeding network and developing transdisciplinary approaches would be essential for enhancing breeding efficiency for small- and medium-sized enterprises and agricultural research systems in developing countries (Watson-Haigh *et al.* 2018; König *et al.* 2020; Wang *et al.* 2020; Xu *et al.* 2022; Czembor *et al.* 2023).

Omics knowledge and new emerging technologies hold many opportunities (Zhang *et al.* 2022). While increased disease prevalence is an often ignored effect of interactions between fungal species, several opportunities also arise from advancements in omics technologies. For instance, high-quality reference genomes are now available for thousands of species which can improve the understanding of crop domestication and crop improvement. Omics data is generated at various levels, including genome, epigenome, transcriptome, epi transcriptome, and proteome, and can now be acquired for any species at a reasonable cost. Matching IT tools are also being developed to analyze the biological significance of such data (Tong and Nikoloski 2021; Zhang *et al.* 2022).

Apps play a significant role in advancing genomic selection for the development of fungal-resistant cultivars in sustainable agriculture. They enhance the efficiency and effectiveness of genomic selection for developing fungal-resistant cultivars by facilitating data management, collaboration, accessibility to genomic resources, and communication. These applications contribute to ongoing efforts to address fungal threats in crop cultivation while promoting environmentally friendly and sustainable agricultural practices. Apps facilitate the storage, retrieval, and analysis of vast genomic datasets, enabling researchers and breeders to efficiently manage genetic information related to fungal resistance. This aids in the identification of key genomic markers associated with resistance traits (Xu *et al.* 2022; Czembor *et al.* 2023).

Internet platforms provide a collaborative environment for researchers, scientists, and agricultural experts globally, fostering the exchange of knowledge, research findings, and best practices related to genomic selection for fungal-resistant cultivars. Collaboration across borders accelerates progress in developing effective and sustainable solutions. Online platforms offer easy access to genomic resources, including genomic databases, reference genomes, and bioinformatics tools (Xu *et al.* 2022; Czembor *et al.* 2023). This accessibility empowers researchers to explore diverse genetic information, enhancing the precision of genomic selection for fungal resistance. Apps play a crucial role in fostering communication among stakeholders involved in the development and adoption of fungal-resistant cultivars, including researchers, breeders, farmers, policymakers, and industry experts. Effective communication ensures that advancements in genomic selection align with the practical needs of agriculture. Online platforms provide educational materials and resources related to genomic selection and fungal resistance, supplying researchers, breeders, and farmers with the knowledge needed to understand and implement genomic technologies in their agricultural practices. Internet apps contribute to ensuring regulatory compliance by providing platforms for transparent reporting and data sharing. This is crucial for obtaining regulatory approvals and building trust among consumers, regulators, and other stakeholders in the sustainable agriculture sector. Genomic selection relies on precise breeding strategies, and internet apps assist in designing and implementing these strategies. Through online platforms, breeders can access cutting-edge tools for marker-assisted selection, genomic prediction, and other advanced breeding techniques to develop cultivars with enhanced fungal resistance (Watson-Haigh *et al.* 2018; Konig *et al.* 2020; Wang *et al.* 2020; Xu *et al.* 2022; Czembor *et al.* 2023).

In summary, breeding for resistance is crucial in IPM because it offers a sustainable, long-term, and environmentally friendly strategy for managing pests in agriculture. It aligns with the principles of ecological balance, economic efficiency, and reduced environmental impact, making it a key component of modern and responsible pest management practices. Apps enhance the efficiency and effectiveness of breeding for developing fungal-resistant cultivars in sustainable agriculture. Apps should provide the user with easy access to information regarding a variety's resistance to pathogens that are most harmful in the environmental conditions indicated by them. By facilitating data management, collaboration, accessibility to genomic resources, and communication, these applications contribute to the ongoing efforts to address fungal threats in crop cultivation while promoting environmentally friendly and sustainable agricultural practices (Wang *et al.* 2020; Xu *et al.* 2022; Belmain *et al.* 2022; Czembor *et al.* 2023).

Agricultural practices for sustainable fungal plant pathogen management

Soil management

While the Green Revolution had many positive impacts, such as increased crop yields, it had certain effects on fungal pathogens in agricultural systems (Feiziene *et al.* 2018; Barros-Rodriguez *et al.* 2021; John and Babu 2021; Makiola *et al.* 2022; Çakmakçı *et al.* 2023). The appropriate agricultural practices that are agroecosystem-friendly are one of the major principles of sustainable agriculture and play an important role in IPM (Wezel *et al.* 2014; Al-Agele *et al.* 2021; Andres *et al.* 2021; Banerjee and van der Heijden 2023). Such agricultural practices reduce plant susceptibility to abiotic stress, and next-to-biotic stress, reduce the buildup of fungal pathogens and integrate biodiversity and production goals (Larkin and Lynch 2018; Panth *et al.* 2020). Internet apps facilitate the dissemination of these practices, aiding farmers in adopting IPM strategies. These applications contribute to soil microbial community management, including beneficial fungi crucial for plant health. By ensuring proper agricultural practices, internet apps help maintain a balance between pathogenic and beneficial fungi in the soil, preventing disruptions that may lead to increased pathogen prevalence (Larkin and Lynch 2018).

Soilborne necrotrophic plant pathogenic fungi represent a diverse group of pathogens that can significantly impact field crops, influencing plant growth, yield, and overall crop health. The specific pathogens involved vary, depending on such factors as the type of crop, prevailing climate, and soil conditions (Panth *et al.* 2020; Deguine *et al.* 2023). This group of soilborne pathogens is characterized by its ability to kill host plant cells and derive nutrients from dead tissue. Adding to the challenge, these pathogens produce resilient structures known as sclerotia – hard, black formations capable of enduring in the soil for extended periods. When conditions are favorable, these sclerotia germinate, leading to the infection of additional plants. The resilience of soilborne fungi poses difficulties in control due to their broad range of hosts, prolonged survival capabilities, and resistance to many fungicides (Panth *et al.* 2020). Therefore, it should be emphasized that the most effective method of combating these fungi is through diversification of crop species as a central agroecological principle, The cultivation of diverse crop plant species in sustainable agriculture (especially small–farming) involves growing a variety of different crops within a given farming system. This approach contrasts with monoculture, where a single crop is grown over a large area (Ratnadass *et al.* 2012; Dong *et al.* 2021; Deguine *et al.* 2023; Erekalo *et al.* 2024)

The broad and harmful nature of soilborne fungi, exemplified by *Fusarium* spp., *Pythium* spp., *Verticillium* spp., *Rhizoctonia solani*, *Alternaria* spp., *Aspergillus* spp., *Penicillium* spp., *Sclerotinia sclerotiorum*, *Cochiobolus sativus*, and *Phoma* spp., underscores the importance of comprehensive fungal management. Apps contribute by providing information on specific fungi, their impact on crops, and effective control measures. Among the most harmful group is *Fusarium* spp., which affects different crops such as cereals, vegetables, and legumes. It causes various diseases on crops, such as Fusarium head blight, Fusarium wilt, Fusarium root rot, and vascular wilts (Meyer-Wolfarth *et al.* 2021; Suproniené *et al.* 2023). *Fusarium* spp. is capable of transiting from a biotrophic to a necrotrophic lifestyle, thereby earning the classification of hemibiotrophic pathogens. This adaptive trait underscores the versatility and complexity of its pathogenicity (Barros-Rodriguez *et al.* 2021). Some of the most important soilborne necrotrophic fungi, including *Fusarium*, *Alternaria*, *Aspergillus*, or *Penicillium*, are responsible for some of the most significant crop diseases worldwide, produce mycotoxins, and threaten human and animal health. *Fusarium* species produce mycotoxins, such as deoxynivalenol (DON), that can harm both plants and animals. *Aspergillus* is a genus of fungi that can cause various types of pulmonary aspergillosis, which are lung infections or allergic reactions caused by inhaling *Aspergillus* spores. *Aspergillus* and *Penicillium* are a genus of fungi that can be found in various environments, including soil. Soilborne *Aspergillus* and *Penicillium* species can have different roles and impacts on plants, animals, and humans. Some of them are beneficial, some are harmful, and some are both. Apps help in addressing the threat posed by mycotoxins produced by certain fungi, safeguarding both human and animal health (Meyer-Wolfarth *et al.* 2021; Richard *et al.* 2022; Bouri *et al.* 2023; Nji *et al.* 2023; Suproniené *et al.* 2023).

Similarly, *Pythium* spp. affects various crops, particularly those cultivated under wet or waterlogged conditions, contributing to damping-off, seed rot, and root rot. *Verticillium* spp., which produces sclerotia, targets field crops like potatoes, tomatoes, and strawberries, and affects the vascular system, leading to wilting and stunting. Other significant soilborne necrotrophic fungi include *Rhizoctonia solani*, which produces sclerotia, affects crops like cereals, vegetables, and legumes, causing damping-off, root rot, and stem cankers. Additionally, some of the most substantial crop diseases globally include *Alternaria* spp., *Aspergillus* spp., *Penicillium* spp., *Sclerotinia sclerotiorum* (producing sclerotia). Also, *Cochiobolus* sativus impacts cereal crops like barley and wheat, causing common root rot. *Phoma* spp. affects cereals and oilseed crops, leading to root rot and seed decay. These examples demonstrate the diversity of soilborne pathogens (Panth *et al.* 2020; Richard *et al.* 2022; Bouri *et al.* 2023; Nji *et al.* 2023).

Varied cropping, supported by apps, creates diverse habitats that foster beneficial organisms with the capacity to control fungal pathogens (Ratnadass *et al.* 2012; Belmain *et al.* 2022; Lubdgren and Fausti 2015). Rotating diverse crop plant species by sequentially planting different crops over successive seasons in sustainable agriculture promotes biodiversity, enhances ecological resilience, and provides a range of benefits, including improved soil health, reduced pest and disease pressure, and increased overall sustainability (Deguine *et al.* 2023; Belmain *et al.* 2022). Practices associated with diverse crop plant species in agriculture include: polyculture, crop rotation, cover cropping, companion species, crop diversification, intercropping, and perennial agriculture. Different crops have different susceptibility to specific pathogens, and rotating them disrupts the pathogen's life cycle, thereby reducing its population and limiting the severity of diseases (Deguine *et al.* 2023; Erekalo *et al.* 2024). Understanding the dynamics of disease suppression in monoculture systems is an active area of research. Researchers are exploring the microbial and biochemical mechanisms involved in soil disease suppression with the goal of developing sustainable agricultural practices. Planting resistant crops for at least 3 years can reduce inoculum levels and infection risk. Certain crops like sorghum, sunflower, and some brassicas are known for their resistance to soilborne fungi (Ravelojaona *et al.* 2023). Internet apps play a vital role in facilitating these practices by providing farmers with valuable information and guidance. Common crop rotation systems, such as alternating between cereals, legumes, and oilseeds, are essential strategies for sustainable farming. Cover cropping, the planting of specific crops during periods when the main crop is not growing, can be effectively managed with the assistance of internet apps. These apps offer real-time data and recommendations, consider local conditions, climate, and specific farming objectives. Internet apps enhance farmers' ability to implement these practices, ensuring efficient weed control, soil erosion prevention, and improved soil health. Diversifying the types of crops grown on a farm is a risk mitigation strategy against market fluctuations, weather events, or pest outbreaks. Internet apps provide farmers with tools to create personalized crop rotation plans, by taking into account their soil category. In the context of fungal management, these applications aid in strategic crop rotation planning, disrupting the life cycles of fungal pathogens and reducing their population (Oteyo *et al.* 2021; Ali *et al.* 2023; Deguine *et al.* 2023; Erekalo *et al.* 2024; Escandon-Panchana *et al.* 2024; Morchid *et al.* 2024a).

Intercropping, involving the simultaneous planting of two or more crops in the same field, is another resource-efficient practice. Internet apps which consider different root structures and nutrient requirements of crops, play a pivotal role in optimizing resource use efficiency. The incorporation of perennial crops into agricultural systems, which contribute to biodiversity and reduce soil erosion, is also facilitated by internet apps, providing farmers with the necessary guidance and information (Deguine *et al.* 2023; Erekalo *et al.* 2024). Proper sanitation, such as removing and destroying infected plant material, helps control the spread of pathogens. This reduces the availability of the pathogen in the environment, disrupting its ability to infect susceptible hosts. Conservation tillage methods, such as reduced or no-tillage with residue retention or mulching, can enhance soil quality (Panth *et al.* 2020; Sadik *et al.* 2023). These practices improve soil properties, since they reduce primary infection-causing inoculum from previous planting seasons. These methods are key to creating a healthier soil environment that mitigates the risk of diseases. Cultural practices that create an unfavorable environment for pathogens such as optimizing planting density, proper spacing between plants, and adequate ventilation, collectively reduce the conditions conducive to disease development. The application of such cultural methods is instrumental in fostering plant health and minimizing the impact of pathogens. Proper irrigation practices are essential for disease management. Overly wet conditions can create a favorable environment for certain pathogens, while proper water management can help prevent disease development (Panth *et al.* 2020; Deguine *et al.* 2023; Erekalo *et al.* 2024).

One phenomenon related to monoculture and disease suppression is the concept of "monoculture disease suppressive soil" or "monoculture disease suppressiveness" (Deguine *et al.* 2023; Erekalo *et al.* 2024). This refers to the observed suppression of certain diseases in soils where a specific crop has been continuously grown for an extended period. Monoculture can lead to the buildup of specific soil-borne pathogens that target the cultivated crop. When the same crop is grown in the same location over multiple seasons, the population of pathogens that affects that particular crop may increase in the soil. Interestingly, in some cases, long-term monoculture has been associated with the development of disease-suppressive soils. These soils exhibit the ability to suppress the incidence or severity of diseases caused by specific pathogens. The mechanisms behind disease suppression in these soils are complex and not fully understood. It is believed that the soil microbial communities play a crucial role in disease suppression. Certain microorganisms, including bacteria, fungi, and other soil microbes, may become more abundant in monoculture systems and contribute to disease suppression. These microbes can compete with or antagonize pathogenic organisms, limiting their ability to cause disease. Long-term monoculture can lead to shifts in microbial diversity and the dominance of specific microbial groups. Some of these microbial communities may have beneficial effects on plant health, contributing to disease suppression. The disease-suppressive effect observed in monoculture systems is often specific to certain diseases and crops. The soil may suppress diseases that commonly affect the continuously grown crop but may not necessarily provide protection against diseases of other crops (Banerjee and van der Heijden 2023; Deguine *et al.* 2023; Erekalo *et al.* 2024).

One of the key strengths of internet apps is the adaptability to local conditions, climate variations, and specific farming objectives. By utilizing real-time data, these apps offer tailored recommendations, enabling farmers to dynamically adjust their practices in response to the ever-evolving environmental and agricultural landscape. This adaptability is particularly crucial in the context of fungal management, where staying abreast of changing conditions is vital for effective disease prevention. Apps also prove invaluable in assisting farmers with the formulation of personalized crop rotation plans based on their specific soil categories. This tailored approach is instrumental in fungal management as varied cropping and strategic rotation disrupt the life cycles of fungal pathogens. By doing so, these applications contribute to a reduction in pathogen populations and mitigate the severity of diseases, ultimately fostering healthier crops (Dong *et al.* 2021; Eichler Inwood and Dale 2019; Kasera *et al.* 2024; Morchid *et al.* 2024a, b; Papadopoulos *et al.* 2024).

Nutrient management

To ensure plant health, it is crucial to provide them with balanced and complete nutrition, incorporating all necessary mineral elements. Fertilizer recommendations should be tailored to the specific nutrient requirements at each crop growth stage, considering the soil's ability to provide such nutrients. Minerals impact plant health by regulating enzyme activity and influencing soil pH and nutrient content. This underscores the close relationship between sustainable management and plant breeding (Andres *et al.* 2021; Tripathi *et al.* 2022).

The pH value, both in the soil and plant tissues, is critical for determining fungal growth, development, and secondary metabolite synthesis. Stress related to pH can make plants more susceptible to fungal pathogens. Pathogens, in turn, are influenced by pH levels, affecting the production and secretion of virulence factors, including enzymes, toxins, and effectors. Levels of pH also impact nutrient availability, such as nitrogen-rich gamma-aminobutyric acid (GABA), to the pathogen. Most fungal pathogens thrive in oxidized and acidic conditions (Fang *et al.* 2021).

The role of major and minor nutrients in plant growth is well documented. Nitrogen (N) stands as an essential macronutrient crucial for fortifying plants against pathogens (Mur *et al.* 2017; Zetzsche *et al.* 2020), whereas potassium (K) and manganese (Mn) actively contribute to bolstering defense mechanisms. Phosphorus (P), on the other hand, does not play a significant role in plant disease resistance and, when present in high concentrations, may even contribute to increased vulnerability to invaders. Zinc (Zn) assumes a critical role in synthesizing essential plant compounds and influencing the growth of harmful microorganisms (Tripathi *et al.* 2022; Xu *et al.* 2021).

Despite its vital status as a plant nutrient, N's impact on plant susceptibility to diseases is multifaceted. The role of N in plant disease development is contingent on such factors as the type and quantity of available N, the pathogen type, and the plant's defense mechanisms. It is essential for plant development, since it is required to make both amino acids (for proteins) and nucleic acids (for DNA), and is used in the correct development and functioning of chlorophyll, thus being vital for photosynthesis. N can influence the infection strategy of pathogens, whether they are necrotrophic or biotrophic (Tripathi *et al.* 2022). Moreover, N, P, and magnesium (Mg) can impact the production and secretion of virulence factors, including enzymes, toxins, and effectors, as well as the availability of nutrients like gamma-aminobutyric acid (GABA) to the pathogen. Depending on the pathogen type (necrotrophic or biotrophic), N, P and Mg can exert diverse effects on the plant's defense mechanisms, which are manifested as physical, biochemical, or molecular defenses. Physical defenses, such as the cell wall, cuticle, and stomata, serve as barriers to pathogen entry. The N and Mg may adversely affect physical defenses by reducing cell wall and cuticle thickness and lignification. Biochemical defenses involve the production of antimicrobial compounds, such as phytoalexins, and defense-related proteins and enzymes. Nitrate can enhance the production of phytoalexins and PR proteins, whereas ammonium may inhibit them. Molecular defenses, influenced by N, P, and Mg operate through modulating amino acid metabolism and hormone production. This modulation, in turn, affects downstream defense-related gene expression via transcriptional regulation and nitric oxide (NO) production. NO, a crucial signaling molecule, mediates various aspects of plant immunity, including reactive oxygen species (ROS) generation, programmed cell death (PCD), and systemic acquired resistance (SAR) (Tripathi *et al.* 2022; Xu *et al.* 2021). Potassium is a vital nutrient and plays a multifaceted role in plant defense mechanisms (Wang *et al.* 2013). It regulates the opening and closing of stomata. Furthermore, it modulates the osmotic and turgor pressure of plant cells, essential for maintaining cell shape and function (Xu *et al.* 2021). Potassium activation extends to numerous enzymes involved in photosynthesis, respiration, protein synthesis, and carbohydrate metabolism. This activation aids plants in sustaining energy and growth, particularly under stressful conditions such as fungal infections. Additionally, K is integral to the production and signaling of hormones like abscisic acid (ABA), ethylene, and jasmonic acid (JA), which collectively influence plant responses to stress. Furthermore, K is actively engaged in the generation and scavenging of reactive oxygen species (ROS), molecules capable of causing oxidative damage to plant cells. By maintaining a balance in ROS levels, K assists plants in averting oxidative stress and activating defense responses (Andersen *et al.* 2018; Balint-Kurti 2019; Xu *et al.* 2021).

In contrast, the role of P and Mg in plant disease resistance is complicated and depends on various factors. Phosphorus can potentially impact physical defenses by diminishing cell wall thickness and lignification. Biochemical defenses, encompassing the production of antimicrobial compounds and defense-related proteins, are subject to positive or negative influences in the presence of P and Mg. Finally, molecular defenses involve the regulation of gene expression and signaling pathways pivotal to plant immunity. Arbuscular mycorrhizal fungi (AMF) contribute significantly to P acquisition from soil. Understanding the factors influencing AMF-supported nutrient uptake is crucial for the development of sustainable agroecosystems. Fungicide application best explains hyphal P transfer in cropland soils. Notably, AMF communities in grassland soils demonstrate superior efficiency in acquiring P, transferring 64% more to plants than those in cropland soils. Furthermore, the use of fungicides, resulting in a decline in AMF richness in croplands, is associated with a 43% reduction in P uptake (Panth *et al.* 2020; Pontigo *et al.* 2022; Salim *et al.* 2023).

In summary, effective nutrient management and fertilization play major roles in ensuring optimal plant health, crop productivity, and biodiversity. Apps aim to provide balanced and complete nutrition, incorporating essential mineral elements based on crop growth stages and soil nutrient levels. The goal is to enhance plant resilience, regulate enzyme activity, and maintain suitable soil pH levels. Additionally, these apps take into consideration the interplay between nutrient availability, plant health, and susceptibility to fungal pathogens. By tailoring fertilization practices to specific crop and soil requirements, these apps contribute to sustainable and environmentally friendly agricultural practices, promoting long-term soil health and overall ecosystem balance (Dong *et al.* 2021; Tripathi *et al.* 2022; Omia *et al.* 2023).

Alternative control in sustainable fungal plant pathogen management

When pests reach a critical level threatening plant health, employing natural biological processes and materials becomes a compelling strategy for effective pest control, minimizing environmental impact, and often achieving cost savings (Llorens and Agusti-Brisach 2022; van Lenteren *et al.* 2018). These methods harness the power of beneficial biological agents, providing a sustainable alternative that relies on nature's own mechanisms to maintain a balance in agricultural ecosystems. The primary aim is to encourage the proliferation of beneficial biological agents for plant health organisms (Bouri *et al.* 2023). Various studies outline 'biology-based' and 'environmentally friendly' techniques applicable on a large scale within IPM strategies (Richard *et al.* 2022; Galli *et al.* 2024; Ikhwani *et al.* 2024).

One of the most widely used non-chemical plant protection methods is biological. It relies on beneficial biological agents (BCAs) that are safe for both humans and the environment. These agents are divided into two main groups: those naturally occurring in a specific environment and those originating from other areas and/or industrially produced and subsequently introduced or released into a given environment (Fenibo 2021; Llorens and Agusti-Brisach 2022; van Lenteren *et al.* 2018; Galli *et al.* 2024; Ikhwani *et al.* 2024).

BCAs employ a variety of mechanisms to protect plants from pathogenic invasion. These agents can interact with pathogens directly or indirectly, using one or a combination of processes to mitigate plant diseases. In the rhizosphere, BCAs compete with pathogens for space and resources and disrupt their pathogenicity through the production of various antimicrobial substances such as lipopeptides, biosurfactants, bacteriocins, volatiles, and enzymes. These substances slow down the development or metabolic activity of pathogens. Therefore, understanding the mechanisms behind a BCA's protective effects is crucial for optimizing biological control. This includes establishing ideal conditions for the interactions between the BCA, the pathogen, and the host, and developing effective formulations and application techniques to enhance plant health and promote sustainable agriculture.

Numerous studies have explored the role of beneficial bacteria in promoting plant growth and enhancing disease resistance in crops. Bacteria from genera such as *Bacillus*, *Paenibacillus*, *Agrobacterium*, *Bradyrhizobium*, *Acinetobacter*, *Azospirillum*, *Azotobacter*, *Pseudomonas*, *Rhizobium*, and *Streptomyces* have been identified as biocontrol agents against various crop diseases (Massawe *et al.* 2018; Ayaz *et al.* 2021, 2023). These beneficial bacteria produce secondary metabolites such as surfactin, iturin, bacillomycin, and fengycin, which reduce pathogen populations by establishing plant-microbial interactions in the rhizosphere (Farzand *et al.* 2019; Ayaz *et al.* 2023). Bacillus spp. can attach to mycelial cell walls and deform hyphae through extracellular enzymes such as chitosanase, protease, glucanase, and cellulase (Gao *et al.* 2016). Lipopeptides, including fengycin, iturin, pumilacidin, mixirin, and surfactin act as antifungal peptides against pathogenic fungi in rhizospheres (Farzand *et al.* 2019; Ayaz *et al.* 2023). *Bacillus*, *Pseudomonas*, and *Burkholderia* spp. are known to suppress nematodes in various plants by affecting nematode feeding and reproduction behaviors (Farzand *et al.* 2019; Gao *et al.* 2016). Biological treatments with *Bacillus* isolates have effectively controlled root-knot nematode infestations and reduced nematode populations in infested roots and soil (Ayaz *et al.* 2021). Additionally, *Bacillus* spp. have been reported to stimulate induced systemic resistance in plants against various pathogens by increasing defense-related enzyme activity, such as polyphenol oxidase, peroxidase, and phenylalanine ammonia-lyase (PAL), as well as modifying root exudates with amino acids and polysaccharides (Farzand *et al.* 2019).

Fungal genera such as *Trichoderma*, *Aspergillus*, and *Penicillium* are widely used as biocontrol agents against both bacterial and fungal plant diseases. Fungi like *Gliocladium* and *Saccharomyces* also exhibit antagonistic activity against various pathogens (Farzand *et al.* 2019; Ayaz *et al.* 2023). Many fungal endophytes live asymptomatically within plant tissues, interacting closely with their hosts through mutualism and occasionally parasitism. Endophytic fungi are valuable for discovering novel secondary metabolites with potential agricultural applications. *Trichoderma*, in particular, is renowned for its broad-spectrum antagonistic activities against various phytopathogens. This genus, which includes filamentous fungi, is found in soil as residents, saprotrophs, plant symbionts, and mycoparasites, and has been extensively investigated and employed as a biocontrol agent in agriculture (Thambugala *et al.* 2020; Ayaz *et al.* 2023).

However, these methods are not without shortcomings. For example, there can be inconsistencies caused by variations in BCA quality and quantity, environmental stress, biotic interactions, incompatibility with other pest control methods, and regulatory barriers due to their target pests or narrow pest spectrum. Specificity can be advantageous in reducing non-target effects but disadvantageous in limiting the scope of BCA applicability against multiple and complex pest infestations. Cost-effectiveness can be influenced by BCA production, formulation, storage, transportation, application, registration, adoption, evaluation, and marketability (van Lenteren *et al.* 2018; Galli *et al.* 2024; Ikhwani *et al.* 2024).

To overcome these challenges and improve the sustainability of BCA use, several "best practices" are available to farmers. One such practice is Biological Control Integration (BCI), which combines BCAs with other methods of pest control in a coordinated and complementary manner (Ali *et al.* 2022). BCI aims to enhance the performance and persistence of BCAs while reducing reliance on pesticides and maximizing the use of ecological and cultural methods. The application of only BCAs when necessary, at the right time, rate, place, and by the right method is essential. Reasonable BCA application can reduce BCA waste and exposure and increase BCA efficiency. Equally vital is the adoption of BCA stewardship, which includes reading and following label instructions, wearing appropriate personal protective equipment (PPE), properly storing and disposing of BCAs, preventing BCA drift and runoff, monitoring pest populations and BCA effects, and reporting any incidents or problems. In the realm of plant protection, three main biological strategies, classical, augmentative, and maintenance, can be distinguished. Each of these strategies relies on different biological agents for given applications (Fenibo 2021; Llorens and Agusti-Brisach 2022; van Lenteren *et al.* 2018; Galli *et al.* 2024; Ikhwani *et al.* 2024).

In addition to biological control methods, another effective approach to plant protection involves the use of plant biostimulants. These preparations enhance plant growth and development by improving their natural metabolism (Ali *et al.* 2022; Giordano *et al.* 2022). They boost plant processes by increasing their efficiency. Biostimulants offer several benefits, including increased crop yields and quality, and enhanced plant resistance to disease. In agricultural production, there is a constant need for new technologies to boost plant resistance to diseases and improve yield quality, making biostimulants increasingly popular. Their positive impact on plant growth, development, and yield, and, most importantly, their safety for humans and the environment, are the main reasons for their popularity. To improve plant health, soil microbes enhance the soil microbiome, which is the community of microorganisms that live in the soil and interact with plants. Some soil microbes improve plant growth, nutrient uptake, stress tolerance, and disease resistance. They provide nitrogen fixation, phosphate solubilization, siderophore production, and induced systemic resistance (Hatt and Osawa 2019; Fenibo *et al.* 2021; Zehra *et al.* 2021; Galli *et al.* 2024; Ikhwani *et al.* 2024)

In addressing post-harvest concerns, various disease management technologies come into play. These techniques involve applying a range of methods to prevent or reduce disease-induced reductions in the quality and quantity of agricultural products after harvest (Sadik *et al.* 2023). Some of these techniques include cold storage, modified atmosphere packaging, irradiation, heat treatment, biological control agents, and edible coatings. Lastly, if pest populations reach damaging levels, targeted and judicious use of pesticides may be advisable. IPM integrates these approaches to efficiently manage pests, while also minimizing environmental consequences and safeguarding crop well-being (Dong *et al.* 2021).

Further studies are essential to develop biological control measures that demonstrate consistent effectiveness across a range of crops and environments. This is crucial not only for assessing the benefits in agriculture but also for practical applications by farmers in sustainable agriculture (Fenibo *et al.* 2021). Bridging the gap between research findings and on-farm implementation is imperative to ensure the successful integration of these biological control strategies into agricultural practices. Fungicide use in agriculture can be slightly reduced with improved spray application methods. However, a drastic decrease in the number of applications is essential to achieve more substantial reductions. Numerous experimental field studies have been carried out to assess the performance of fungicides on multiple crops and diseases across diverse regions. However, the data derived from these experiments are yet to be fully compiled and subjected to rigorous statistical analysis to assess the benefits of applying them in apps developed for farmers to use them in sustainable agriculture (Lázaro *et al.* 2021; Zhai *et al.* 2020).

Climate change impact on fungal pathogen management: challenges and strategies

Climate change is identified as a key contributor to increased disease outbreak risks. The alteration of pathogen evolution and interactions leads to the emergence of new pathogenic strains (Richard *et al.* 2022; Bouri *et al.* 2023; Singh *et al.* 2023; Juroszek and von Tiedemann 2013, 2015; Semenov *et al.* 2014; Miedaner and Juroszek 2021). The pathogen range can shift, spreading plant diseases into new areas (Miller *et al.* 2022; Caminade *et al.* 2019; Hjelkrem *et al.* 2021). It is very important to examine how plant disease pressures are likely to evolve in specific future climate change scenarios and how these changes will impact plant productivity in natural and agricultural ecosystems. Furthermore, more studies are needed to explore the current and future impacts of climate change on pathogen biogeography, disease incidence, and severity, and their effects on natural ecosystems, agriculture, and food production (Juroszek and von Tiedemann 2013, 2015; Caminade 2019; Miller *et al.* 2022).

Various risk assessments have been conducted to account for the dynamic nature of potential climate change effects on crop diseases. These assessments cover a time range, including the baseline, 2020, 2050, and 2080, and can help identify potential peaks of impact to facilitate the development of adaptation and mitigation strategies. Resource allocation can be appropriately managed based on such information (Juroszek and von Tiedemann 2013, 2015; Caminade 2019).

Overall, the northern latitudes are expected to experience the most extreme temperature conditions due to climate change. Summers and winters in Europe will become warmer, with average increases expected to range from 3.5°C to 4.7°C. Meanwhile, tropical regions are set to face less pronounced changes in average temperatures, even though both the minimum and maximum temperatures and the diurnal temperature range will likely increase. In summary, because weather conditions and climate change influence the development of pathogens, they should be taken into account when developing strategies for pathogen management (Juroszek and von Tiedemann 2013, 2015; Caminade 2019; Miedaner and Juroszek 2021; Miller *et al.* 2022; Singh *et al.* 2023).

Plant monitoring technologies for improving agricultural fungi management strategies

Precision management of fungal plant pathogens utilizes technologies and strategies of avoidance, monitoring, and suppression (Khanal *et al.* 2017; Bonke *et al.* 2018; Dong *et al.* 2021). Employing an integrated approach that combines multiple methods and strategies in a coordinated and complementary manner is crucial for nondestructive pathogenic fungal management. The IPM process starts with monitoring, which includes inspection and identification, followed by assessing economic injury levels (Mahlein 2016; Ceballos *et al.* 2019; Richard *et al.* 2022). Visual inspections are used to monitor pest levels, while record-keeping is essential to support control decisions based on known target pest behaviors and reproductive cycles. The degree days of an environment determine the optimal time for specific fungal pathogen outbreaks (Lazaro *et al.* 2020, 2021). Systematic monitoring of pests and pathogens is critical for identifying potential biological threats based on the records of diseases that have occurred in specific fields and surrounding areas (Ansaldi *et al.* 2018).

What makes this vital is the variability of the observed biotic interaction responses, ranging from beneficial to negative to neutral. Such inconsistency may prevent the detection of trends in given biotic interactions across different agroecosystems and agroclimatic conditions over large areas, making it difficult to attain a complete understanding of the responses of biotic interactions to management measures. For this purpose, the processes involved and the relevant cropping operations need to be identified as a function of both the organisms at play and the interactions considered. It is essential to review pest management practices at all cropping levels, since crop growth conditions can be improved with measures taken by farmers at the field scale (Belmain *et al.* 2022; Banerjee and van der Heijden 2023; Deguine *et al.* 2023).

Spectral imaging, driven by cutting-edge data processing, has played a vital role in facilitating crop monitoring to aid decision-making in the implementation of spatially variable agronomic practices and/or inputs (Khanal *et al.* 2017; Mahlein 2016; Bahrani *et al.* 2022; Stolarski 2022; Terentev *et al.* 2022; Omia *et al.* 2023). Furthermore, recent data fusion approaches have eliminated the need to compromise between spatial and spectral resolutions. Due to recent technical advances, the remote sensing community now has access to both dense time-series data and high-spatial spectral-resolution images, without the need to approximate the compromised components using fusion methods (Vishnoi *et al.* 2021; Omia *et al.* 2023). Moreover, machine-learning, and deep-learning approaches have substantially enhanced the processing and analysis of spectral information. In these approaches, it is assumed that there are sufficient computational resources, and that no data transmission cost is incurred for their optimal application; however, this is not always the case (Traversari *et al.* 2021; Vishnoi *et al.* 2021).

Remote sensing technologies such as satellites can provide valuable information about crop health and potential disease outbreaks based on changes in vegetation patterns. Drones (Unmanned Aerial Vehicles - UAVs) equipped with cameras or sensors can capture high-resolution images of crops, enabling detailed monitoring of plant health (Bourisianis *et al.* 2022; Stolarski *et al.* 2022; Neupane and Baysal-Gurel 2021; Li *et al.* 2022a; Muruganantham *et al.* 2022; Vélez *et al.* 2023). The European *Sentinel-2* is a valuable data source for periodic satellite Remote Sensing, significantly increasing temporal resolution, e.g., to approximately 6 days for most of Central Europe. Key information lies in the vegetation indices derived from the R (red), and NIR (near infra-red) light. The Normalized Difference Vegetation Index (NDVI) coefficient calculated with satellite imagery at the time of plant growth is a common method used for assessing vegetation health, including monitoring crops and detecting potential disease outbreaks. NDVI is calculated based on the difference between the reflectance of NIR and R light. Vegetation strongly reflects NIR light and absorbs R light. Unhealthy or stressed vegetation, such as plants affected by diseases, may have different reflectance patterns. Regular monitoring of NDVI over time allows for the assessment of changes in vegetation health. Deviations from the normal NDVI values for a particular area may indicate potential issues, including disease outbreaks or stress. Satellite imagery, equipped with NDVI calculations, is useful for large-scale monitoring of agricultural fields, providing insights into spatial and temporal variations in vegetation health, thereby helping farmers and agricultural experts make informed decisions. Changes in NDVI patterns can be indicative of disease outbreaks affecting crops. Early detection through NDVI analysis enables timely intervention and management practices to mitigate the impact of diseases. Overall, NDVI analysis with satellite imagery is a valuable tool in precision agriculture, offering a non-invasive and efficient means of monitoring crop health and identifying potential disease issues across large agricultural areas (Pluto-Kossakowska 2021; Vishnoi *et al.* 2021; Shafi *et al.* 2022; Vidican *et al.* 2023; Morchid *et al.* 2024a; 2024b; Papadopoulos *et al.* 2024; Raihan 2024).

Monitoring diseases using cameras involves capturing images of plants and employing various image analysis techniques to identify visual symptoms associated with diseases. Higher resolution allows for more accurate analysis. Computer vision can be utilized to process and analyze the captured images. Machine learning models, such as convolutional neural networks (CNNs), can be trained to recognize patterns associated with different diseases. By extracting relevant features from the images, such as color, texture, and shape characteristics, specific diseases can be indicated. The most important problem is that disease symptoms may include discoloration, lesions, patterns, or other visual cues. Models that correlate visual features with specific diseases need to be developed. These models can be trained on a dataset of images labeled with disease information. For example, a model might learn to associate certain patterns or discolorations with a particular plant disease (Lazaro *et al.* 2020, 2021). It is very important to implement the disease detection system in a real-world scenario to ensure proper lighting conditions and image quality for accurate analysis. This is much easier under greenhouse conditions than under field conditions, especially if drones are used. Therefore, it is important to regularly validate and calibrate the system using ground truth data. Ground truth data involves on-site verification the presence or absence of disease to refine and improve the accuracy of the detection system (Bahrami *et al.* 2022; Boursianis *et al.* 2022).

Fluorescence imaging is a technique involving the capture and analysis of natural fluorescence emitted by plants. This technique has been employed to assess leaf diseases, including leaf rust and powdery mildew of wheat, cercospora leaf spot of sugar beet, common bacterial blight for beans, and downy mildew of lettuce (Mahlein 2016; Traversari *et al.* 2023).

Specialized cameras equipped with filters and detectors capture specific wavelengths of light emitted by chlorophyll during fluorescence. Image analysis interprets fluorescence images, with abnormal patterns indicating various physiological conditions such as stress, disease, or nutrient deficiencies. Changes in fluorescence patterns can detect stresses like pathogen infections or nutrient imbalances before visible symptoms appear, enabling early disease detection and assessment of photosynthetic efficiency for insights into overall plant health (Omia *et al.* 2023). For fungal monitoring and management, Internet of Things (IoT) devices like soil and plant sensors collect real-time data on environmental conditions, moisture levels, and nutrient content. Weather stations are crucial for predicting and understanding the spread of diseases, and providing data on temperature, humidity, and precipitation (Lazaro *et al.* 2020, 2021).

Despite UAV-based hyperspectral imaging system benefits, challenges and limitations exist, including sensor validation, calibration, image registration, orthorectification, atmospheric correction, radiometric normalization, data storage, transmission, processing, analysis, fusion with other data sources (e.g., soil sensors), and interpretation (Bahrami *et al.* 2022). In summary, all technologies should develop systems for generating alerts or notifications upon detecting potential diseases. Decision support tools for farmers or agronomists should be provided, suggesting appropriate management actions (Dong *et al.* 2021; Alibabaei *et al.* 2022; Ali *et al.* 2023).

Many websites and apps rely on web servers to provide information, services, and solutions to the agricultural sector (Carmona *et al.* 2018) e.g.: SmartfLAIr (Yield management Crop yield), SnapCard (Weed and pest control Crop spraying) (Ferguson *et al.* 2016), vitisBerry (Crop health Berry assessment), vitisFlower (Crop health Flower assessment) (Aquino *et al.* 2018), WheatCam (Risk management Crop insurance) (Ceballos *et al.* 2019), AgriMaps (Land management Crop and land management recommendations) (Jordan *et al.* 2016), FarmManager (Farm management Capturing farm data) (Lantzos *et al.* 2013), BioLeaf (Crop health Leaf health monitoring) (Machado *et al.* 2016), Canopeo (Crop health Estimating canopy development) (Patrignani and Ochsner. 2015), Plant Disease (Crop health Plant disease diagnosis) (Petrellis 2019), FruitSize (Crop health Fruit size assessment) (Sinha and Dhanalakshmi 2022), and MISSR (A Mentoring Interactive System for Stripe Rust) (Omara *et al.* 2022). They are designed for Decision Support Systems (DSS). Apps like Sustainable AgroVariety developed for Polish farmers, exemplify online services based on IPM principles for sustainable agriculture, integrating preventive methods for fungal management. The Pest Warning System provides information about post-infection fungal management. Both are online services available to every user for fungi management in sustainable agriculture free of charge.

Case Study: AgroVariety application of plant pathogen management

The AgroVariety app, designed for sustainable agriculture, offers a range of functionalities (https://agrobank.pcss.pl/variety/). The AgroVariety app is being developed to incorporate pre-infection (preventive) IPM components and may cooperate with the Pest Warning System, which caters to post-infection scenarios. The AgroVariety app, aligned with the principles of sustainable agriculture, agroecology, and agronomics, aims to positively impact farmers' incomes while optimizing yields for cereals, legumes, potatoes, and beets – the primary focus for farmers. In the cereals group, wheat (spring and winter), and barley (winter and spring) were included. Soybeans and peas were in the legumes group, while potatoes and beets were in the root group. The goal is to supply people with healthy food devoid of pesticides, in compliance with EU recommendations. With AgroVariety farmers or farmer advisors, can identify the presence of a disease at different plant growth stages and receive information indicating how its severity will impact the final yield. The Pest Warning System provides guidance on preventing disease development on a plantation to minimize losses.

The goal of developing the AgroVariety app is to inform users about the final yield as they make decisions per hectare (dt/ha) at different stages of plant growth, ranging from plantation establishment to harvest (Planting Yield Potential during plantation establishment and Forecasting Yield and Predicting Yield during vegetation time). The models integrated into the app are built on user-accessible data concerning the resistance of various varieties to pathogens and other agronomically important traits. Furthermore, this dataset encompasses information about soil and climate conditions, which are critical factors influencing pathogen development. Sentinel-2 satellite remote sensing data have been utilized for several purposes: (1) assessing climate change in Poland from 1970 to 2000 and forecasting it through the year 2100, (2) estimating the risk of drought, freezing, and flooding for a specific field and crop, (3) providing an accurate depiction of field homogeneity in order to divide a field into homogeneous parcels, and (4) monitoring crops throughout the growing season, offering users advice on the condition of the plants and whether any action is required. The key components of AgroVariety are presented in Figure 2.

AgroVariety app: Components and functionality of "Field Definition"

After registration in the AgroVariety app system, the user's first step is to specify the prospective field location (geographic location). As the selected models rely on the locations of future crops, high accuracy of the location is paramount. The app user can indicate the location of their field using their plot registration number or manually draw the plot using map drawing tools (Step 1 of the app). For a specified location, users provide information on soil nutrient contaminants, including P, K, Mg, as well as soil pH. Additionally, users report any prior use of organic fertilizers, detailing quantities, types, and years of app (Step 2 of the app). Subsequently, users furnish the history of crops grown in the field over the past 3 years, specifying the crop type in the most recent year and the intensity of its cultivation. This information is then used to generate nutrient and crop rotation recommendations (Step 3 of the app).

The app creates homogeneous field parcels with soil class information suitable for the species of the

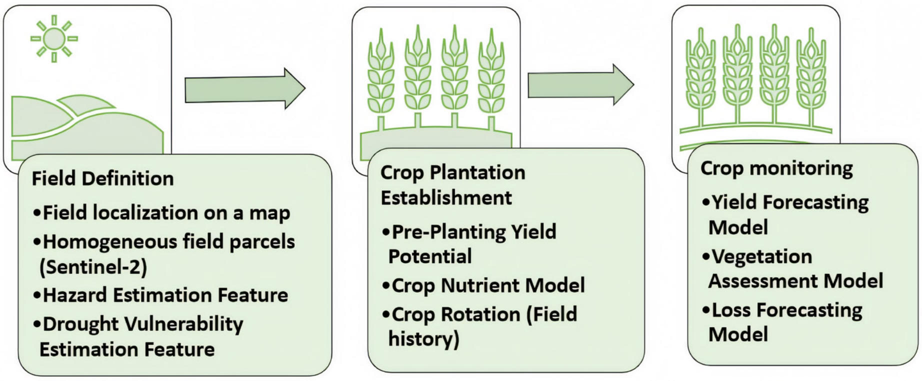

Fig. 2. Components and functionality of the AgroVariety app

cultivation group. Employing previously collected data, the app marks homogeneous parcels in the user's field. Parcel identification is based on Sentinel-2 satellite images. For a given location, an NDVI coefficient is calculated at the time of the most intense plant growth. Subsequently, cluster analysis is conducted to identify areas with homogeneous vegetation. The outcome is presented to the user as the number of parcels and their approximate locations in the field. Users can then use geometry editing tools to modify parcel shapes according to their needs and expectations. The soil category class and the soil appropriateness complex for a specific group of cultivation species are crucial for modeling yield potential in the next app step (Step 5 of the app).

The Risk Estimation Feature is based on the climate change data collected by Sentinel-2. The app user receives information on the drought, freezing, and flooding risks for particular parcels. All such risks are specific to the crop species selected by the app user and, of course, site-specific as well. Differences in average annual air temperatures (°C) in Poland between 2011–2020, 2041–2050, and 2091–2100 relative to 1971–2000 under the RCP4.5 scenario and in the RACMO22E were used for model simulation. Precipitation was assessed by comparing the three 10-year periods of 2011–2020, 2041–2050, and 2091–2100 with the base period of 1971–2000 (Subsection 5.2).

Moreover, users have access to the Agricultural Drought Monitoring System offered by the Polish Institute of Soil Science and Plant Cultivation State Research Institute (IUNG-PIB: https://susza.iung.pulawy.pl/en/index/) [Accessed: 27.11.2023].

AgroVariety app: Components and functionality of "Crop Plantation Establishment"

Potential yield model: plantation establishment

Step 5 is an important component of the AgroVariety app. Taking into consideration the environment and crop rotation it assists in defining the species and cultivar most suitable for cultivation on the user's field. The Planting Yield Potential Model is a cutting-edge tool designed to predict the potential crop yield before establishing a plantation. This model involves advanced algorithms and incorporates various agricultural factors to provide farmers with valuable insights for strategic planning. Soil category and the soil appropriateness complex for a specific group of cultivation species are crucial for modeling yield potential (Step 5 of the app.). Based on the collected data regarding the field, users obtain information about the yield potential calculated by the implemented Planting Yield Potential model (Components of Planting Yield Potential model: regional coefficients, soil coefficients, and agronomic coefficients). The app user receives preliminary information on the crop species which is expected to yield the most benefits when grown on the soil type identified in Step 4 of the app (the most recommended for their field).

The app presents a list of recommended species and varieties for the farm field. A list of recommended species/varieties is based on Polish post-registration variety testing trials (PRVT) conducted by the Research Center for Cultivar Testing (COBORU) (https://coboru.gov.pl/index_en). In the PRVT, disease resistance is deemed to be a key trait as it influences the final yield. Trials conducted in all regions of Poland are made available, broken down by region and presented in the form of all-region averages. In the PRVT, disease resistance is a key trait that significantly affects the final yield's quality and quantity (Niedbała *et al.* 2022). Moreover, the information provided by the app encourages farmers to increase biodiversity in their fields by growing older varieties. Farmers can access information on their field characteristics and instructions on how to order seeds through the Polish Gene Bank (EGISET) database (https://bankgenow.edu.pl/en/baza-danych/bazy-kcrzg/; https://nasionaregionalne.edu.pl/).

Models: crop nutrients and crop rotation

The app user receives information on appropriate fertilization to ensure high agronomic and economic efficiency, as well as sustainable soil fertility. This is based on the potential yield (as Step 6 of the app) and crop rotation (as Step 7 of the app). The starting point for this assessment is always based on the plant species used in the previous year. Next, individual crops which are suitable for cultivation in subsequent years are recommended.

AgroVariety app: Components and functionality of "Crop monitoring"

Yield Forecasting Model

Monitoring the crop during the growing season is the second functionality of the AgroVariety app. The previous section of the AgroVariety app is the 'Variety Choice' functionality. During the growing season, users obtain information about forecasting yield (Forecasting Yield) for crops such as spring and winter wheat, spring barley, maize, and rapeseed, enabling them to determine whether additional crop protection measures and other actions are necessary and advantageous. This functionality is based on NDVI calculated using *Sentinel-2* images, the sum of effective temperatures for crop growth, and MAXagro, MEANagro, MINagro (as Step 8 of the app).

The user does not obtain detailed information about the disease that impacts the yield. However, the user receives information about whether biotic stresses (diseases) or abiotic stresses (e.g., drought) affect the yield and if additional crop protection measures or other actions are necessary and advantageous. The user receives detailed information using the Pest Warming System (www.agrofagi.com.pl) application which is described in the next Section.

Predicting Yield Model

The second option during the vegetation time is predicting yield (based on the implemented PREDICTING YIELD Model). It is based on statistical models of empirical data collected from experimental fields around Poland, including air and ground temperature, precipitation levels, fertilization volumes, and infection levels for the selected disease (as an example, for spring barley a model was developed by Czembor *et al.* 2022. Yield models for spring and winter wheat, soybean, pea, and rape were developed by Czembor *et al.* 2020.

Yield Loss Forecast Model

During the growing season, yield loss is forecast for users by the Agricultural Drought Monitoring System offered by the Polish Institute of Soil Science and Cultivation State Research Institute (IUNG-PIB: https://susza.iung.pulawy.pl/en/index/, accessed: 27.11.2023). This system, which is integrated with the app, provides estimations on potential yield losses caused by drought.

AgroVariety app: models to estimate climate-related risks

For the sustainable AgroVariety app (https://agrobank.pcss.pl/variety/), climate change data about Poland are collected by *Sentinel-2*. Based on such data, the user receives information on drought, freezing, and flooding risks for parcels on which the recommended variety is to be grown. Such risks are always specific to the species selected by the app user and change from one site to the next. The risks are assessed on the basis of data from Poland collected by *Sentinel-2*. Climate change simulations for Poland from the EURO-CORDEX project which relies on the regional dynamic model RACMO22E, are used. Climate change analyses for Poland have been carried out and made available online at https://esgf-data.dkrz.de/search/cordex-dkrz/. Notably, the climate scenarios are not predictions of future climate, but rather descriptions of the probable future conditions. The climate model data used in the analysis have been adjusted for local conditions as part of the CORDEX-Adjust project, and include daily data for minimum, maximum, and average air temperatures, and precipitation. Further information on the bias adjustment method is available online at http://is-enes-data.github.io/CORDEX_adjust_add.html. The models used in the AgroVariety app have been adopted from the AGROBANK project (Czembor *et al.* 2020, 2022). Table 1, as well as Figures 2 and 3, compare the specific average annual and monthly air temperatures for Poland during the periods 1971–2000, 2011–2020, 2041–2050, and 2091–2100, each spanning a decade. Table 1 presents variations in the average monthly and average annual air temperature (°C) in Poland for the analyzed periods (Czembor *et al.* 2020).

Data presented in Table 1 were used to generate maps illustrating the average annual air temperature (Fig. 3) and variations in thermal conditions for the periods 2011–2020, 2041–2050, and 2091–2100 in comparison to the baseline period of 1971–2000 (Fig. 4).

The average annual air temperature in Poland under the RCP4.5 scenario for the RACMO22E model in 1971–2000 was 7.8°C. However, by 2020, 2050, and 2100, the average annual temperature is expected to be 8.3°C, 9.3°C, and 10.0°C, respectively. This indicates a temperature increase of 0.5°C, 1.5°C, and 2.2°C compared to the baseline period by 2020, 2050, and 2100, respectively (Fig. 4). Regarding the average daily temperatures under the RCP4.5 scenario for the RACMO22E model, it needs to be noted that especially in winter there are greater temperature fluctuations.

Table 1. Average monthly and annual air temperatures (°C) in Poland for the periods 1971–2000, 2011–2020, 2041–2050, and 2091–2100 under the RCP4.5 scenario and in the RACMO22E model simulation

Period	Air temperature [°C]												
	January	February	March	April	May	June	July	August	September	October	November	December	Average
1971–2000	−2.8	−1.3	2.4	7.6	13.1	15.6	17.7	17.4	13.1	8.6	2.6	−0.9	7.8
2011–2020	−1.5	−0.4	2.0	7.5	13.3	15.8	18.4	18.0	14.3	8.2	4.1	−0.1	8.3
2041–2050	−0.9	−1.1	4.0	10.0	15.6	18.0	18.9	18.1	14.5	9.2	5.1	−0.1	9.3
2091–2100	−1.2	1.7	5.8	9.8	15.5	17.9	19.8	18.6	15.2	10.5	5.6	0.5	10.0

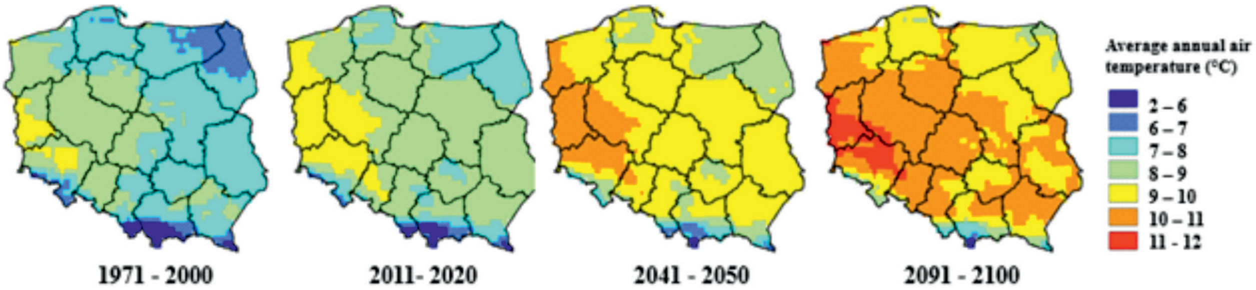

Fig. 3. Average annual air temperatures [°C] in Poland for the periods 1971–2000, 2011–2020, 2041–2050, and 2091–2100 under the RCP4.5 scenario and in the RACMO22E model simulation

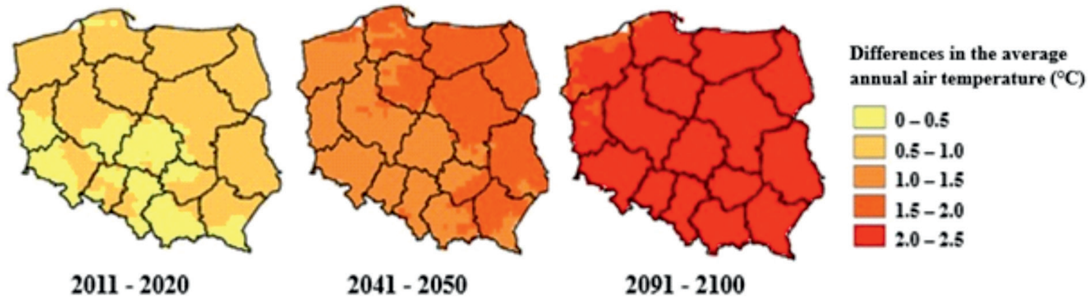

Fig. 4. Differences in average annual air temperatures [°C] in Poland for the periods 2011–2020, 2041–2050, and 2091–2100 relative to 1971–2000 under the RCP4.5 scenario and in the RACMO22E model simulation

Precipitation [mm · m^{-2}] is evaluated by comparing the three 10-year periods of 2011–2020, 2041–2050, and 2091–2100 against the base period of 1971–2000. Table 2 presents the average monthly and annual precipitation (mm) in Poland for the study periods. The average annual precipitation for Poland under the RCP4.5 scenario in the RACMO22E model for the period 1971–2000 was 686.9 mm.

Based on data presented in Table 2, maps have been created depicting the total average annual precipitation and the differences in precipitation for 2011–2020, 2041–2050, and 2091–2100 relative to 1971–2000. By 2020, 2050, and 2100, the average annual precipitation is expected to increase to 756, 734, and 782 mm, respectively. This represents a 70 mm, 47 mm, and 95 mm increase from the base period by 2020, 2050, and 2100, respectively.

Case Study: Pest Warning System of fungal plant pathogen management

The online Pest Warning System (www.agrofagi.com.pl) portal offers a sizeable database of materials and publications from Poland's most renowned

Table 2. Average monthly and annual precipitation (mm · m^{-2}) in Poland in 1971–2000, 2011–2020, 2041–2050, and 2091–2100 under the RCP4.5 scenario and in the RACMO22E model simulation

Period	Precipitation [mm · m^{-2}]												
	January	February	March	April	May	June	July	August	September	October	November	December	Average
1971–2000	47.6	41.5	48.8	42.8	60.2	75.6	93.6	73.6	54.4	47.1	45.4	56.4	686.9
2011–2020	43.1	47.5	65.0	57.6	69.7	73.5	88.3	98.3	54.2	48.3	47.0	64.0	756.4
2041–2050	42.5	33.9	56.0	50.5	62.2	72.0	108.6	79.2	62.8	53.6	47.9	64.8	733.8
2091–2100	47.3	42.1	48.6	59.9	69.1	69.3	100.4	101.6	70.9	48.1	53.1	71.8	782.2

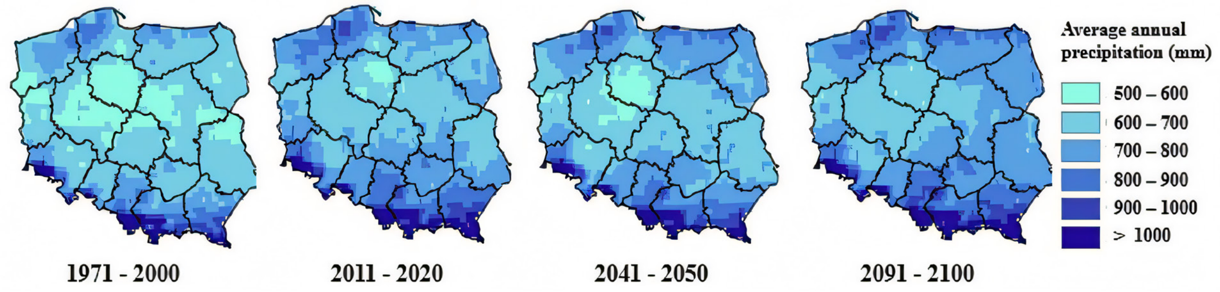

Fig. 5. Average annual precipitation [mm · m^{-2}] in Poland for the periods 1971–2000, 2011–2020, 2041–2050, and 2091–2100 under the RCP4.5 scenario and in the RACMO22E model simulation

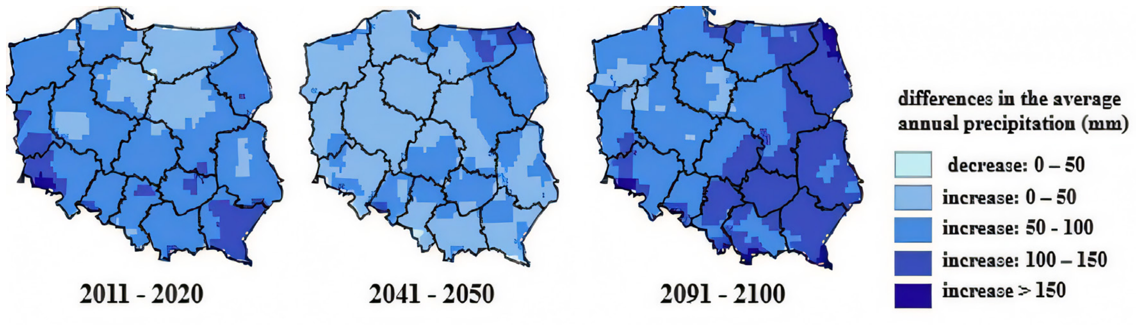

Fig. 6. Differences in the average annual precipitation [mm · m^{-2}] in Poland for the periods 2011–2020, 2041–2050, and 2091–2100 relative to 1971–2000 under the RCP4.5 scenario and simulation of the RACMO22E model

agricultural institutions. Its main objective is to disseminate general IPM principles and prevent plant protection product-related risks. The tool enables interested organizations to collaborate in plant protection within the scope of disease control warnings, disease monitoring, and warning methodologies, integrated plant production, online programs, plant protection recommendations, including those for organic farming, plant protection product search engines, and PPP labeling.

A definite advantage of the platform is having pest warnings issued during the growing season. The database offers growing-season advice on disease and pest-related threats (Fig. 7).

Together with agricultural advice, this unique information accurately provides farmers with high-risk site locations and prevention options. Field observation findings help mitigate damage risk and eliminate excessive and superfluous use of plant protection products in conformity with IPM guidelines.

The Online Pest Warning System (www.agrofagi.com.pl) plays a key role in supporting the pursuit of objectives and activities seeking to ensure compliance with integrated production and control guidelines. Launched on September 1, 2016, the Online Pest Warning System tool enables all concerned parties to engage in broad-based consistent collaboration to ensure crop protection.

Species: maize

Pathogen: wykaz szkodników

Fig. 7. Online Pest Warning System (www.agrofagi.com.pl) portal - the result of field observations regarding the risk of pathogenic fungi and other pests. Green dot color: pests were not found, yellow dot color: pests found, red dot color: recommended protection using pesticides or other methods

Internet applications for fungal plant pathogen management: future outlook

To meet future global needs, it will be crucial that the attempts to improve the sustainability of crop production and crop resilience are complemented by technological advances to increase plant yield. Effective fungal disease management plays an important role in ensuring food security and safety. The integration of data analytics and artificial intelligence (AI) in agricultural apps will enhance decision-making processes. By analyzing data from various sources such as crop health, weather patterns, and soil conditions, these apps can provide valuable insights for farmers, enabling them to make informed choices. The availability of a wide range of sensors for monitoring the environment, soil/growing media, and eco-physiological parameters allows the implementation of predictive and real-time IPM (Rani *et al*. 2023; Belmain *et al*. 2022). Methods of managing fungal pathogens may vary depending on crop type, local environmental conditions, and the severity of fungal diseases in specific regions. This is very important as modern agriculture increasingly emphasizes sustainable and environmentally friendly practices to ensure the long-term health and productivity of farms while minimizing the ecological impact of fungal pathogen management strategies. Effective management strategies using the latest knowledge and developments provided by apps can help farmers produce more food with fewer resources while mitigating adverse impacts on the ecosystem and human health (Richard *et al*. 2022). Through mobile apps or online platforms, farmers can readily access updated information about IPM tools, facilitating informed and data-driven decision-making. Agricultural apps will continue to contribute to the advancement of precision sustainable agriculture. During the implementation of IPM strategies for the effective management of plant diseases, it is crucial to consider the interaction between the plant and pathogen in specific environments (Rani *et al.* 2023; Gojon *et al.* 2022).

The effect of a plant's response to proper agronomic practices is genetically or physiologically determined. Crop breeding that relies on new genetics is key to sustainable increases in production. Climate-smart varieties are one element of the paradigm shift that is needed to ensure sustainability on a greener and more food-secure planet (Delabre *et al.* 2021; Richard *et al.* 2022; Singh *et al.* 2023). However, many existing apps are structured around functions that primarily focus on variables concerning the influence of weather conditions on pathogen development, often neglecting the critical role of the pathogen host plant. Recognizing that weather conditions represent just a single facet within the complex ecosystem supporting crop growth, it is crucial to note that farmers have limited influence over these conditions. However, the key role is played by the soil, which farmers can effectively influence by implementing strategic farming techniques such as target fertilization and cutting-edge agrotechnical practices. These practices significantly influence plant growth and development, which are ultimately transmitted through key mechanisms like pathogen detection, signal transduction, and defensive responses (Dong *et al.* 2021; Richard *et al.* 2022; Gojon *et al.* 2022; Rani *et al.* 2023; Erekalo *et al.* 2024; Escandon-Panchana *et al.* 2024).

In summary, it should be noted that many studies have been conducted on model species or on a limited number of crops and/or under specific and controlled conditions. It will be crucial to extend this knowledge to a wider range of crops that are grown under field conditions. Only data collected under field conditions can be used to develop apps for sustainable agriculture. This applies to both the impact of crop management on plant resistance and the genetic resistance of plants (Deguine *et al.* 2023; Erekalo *et al.* 2024; Escandon--Panchana *et al.* 2024; Morchid *et al.* 2024a).

The AgroVariety app is an example of integrating models of the most important preventive components of IPM, such as creating homogenous field parcels with soil class information, variety recommendations, appropriate fertilization, and crop rotation recommendations. Next, it includes models for near-real-time assessment of crop health during the plant growing time based on Sentinel-2 images. The app user receives information about potential yield losses and assesses whether additional plant protection measures and other actions should be taken, as well as determining their potential advantages. Additionally, second yield prediction models were developed based on data collected from many experimental fields in Poland, with a differential sets of varieties for each crop over 3 years (Czembor *et al.* 2022). Traits such as air and ground temperature, precipitation levels, fertilization levels, and the infection levels by the most important fungi and genetic yield potential were described and used to develop such models. Using these models, the app user receives information about predicted yield losses and decides if some additional actions are necessary (Erekalo *et al.* 2024; Escandon-Panchana *et al.* 2024).

The success of Information Technology (IT) apps like AgroVariety is heavily reliant on a comprehensive understanding of the local context and the establishment of robust partnerships with experts and agricultural organizations to ensure the precision and efficacy of the information and services provided (Rani *et al.* 2023; Salman *et al.* 2023; Erekalo *et al.* 2024). The regular incorporation of updates, rigorous testing, and user feedback are pivotal and are integral components of the ongoing development and maintenance processes, contributing to the continual refinement and enhancement of the app over time.

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