How have Plant Protection Strategies Evolved Over Time?~~afeguarding Agriculture: A Comprehensive Review of Plant Protection Strategies~~

Abstract

The rapidly evolving landscape of agriculture faces myriad challenges, including pests, diseases, and environmental factors that ~~jeopardize~~jeopardise global food security. The urgency of these challenges necessitates innovative plant protection strategies that are both effective and environmentally sustainable. This review offers a comprehensive examination of the advancements and considerations in plant protection, from traditional methods to modern technological approaches. Traditional practices, although eco-friendly, often fall short in efficacy and scalability. The advent of chemical solutions such as pesticides ~~revolutionized~~revolutionised plant protection but brought about environmental and health concerns. Biological controls offer a middle-ground, leveraging natural predators and bio-pesticides to combat agricultural threats. Technology is playing an increasingly critical role in shaping the future of plant protection. Sensor technologies and drones are enabling precision agriculture, enhancing the monitoring and application of protection measures. Genetic engineering holds the promise of creating crops resistant to pests and diseases, albeit amid ethical and safety debates. Integrated Pest Management (IPM), a balanced, eco-friendly approach, is gaining traction, supported by case studies that validate its effectiveness and adaptability. Meanwhile, policy and regulation are evolving to better govern the use of chemicals, promote sustainability, and address the impacts of climate change on agriculture. This review ~~also~~ explores future trends, particularly the influence of emerging technologies such as nanotechnology and IoT, and potential shifts in global policies towards more sustainable practices. It argues for the imperative of integrating these multifaceted approaches, guided by robust policies and regulations, to achieve the dual objectives of high agricultural yield and environmental conservation. I~~By doing so, i~~t aims to provide a holistic understanding and guide future directions in plant protection strategies, ~~emphasizing~~emphasising the importance of adaptability, sustainability, and integration in facing the challenges of tomorrow.

Keywords: *Agriculture, Pesticides, Biopesticides, Technology, Regulation*

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Introduction

The significance of agriculture in global food security cannot be overstated. Agriculture plays a pivotal role in providing sustenance for the world's rapidly growing population. Beyond being a mere means for producing food, agriculture provides livelihoods for billions and is the foundation of many economies. According to the Food and Agriculture Organization (FAO), nearly 2.5 billion people are involved in full-time or part-time agricultural work, underlining the sector's importance in livelihood sustainability and economic development [1]. Agriculture is confronted by a range of challenges that ~~jeopardize~~jeopardise its productivity and, by extension, global food security. Among these challenges are the perennial problems of pests and diseases, which can devastate crops and result in substantial yield losses. Pest-related issues could~~an~~ cause the loss of up to 40% of the world's potential food production each year [2]. Likewise, diseases such as wheat rust and rice blast have the potential to wipe out entire fields, leading to food scarcity and even famine in vulnerable populations. These challenges are accentuated by environmental stressors such as extreme weather conditions, courtesy of climate change. Droughts,

floods, and temperature fluctuations could~~an~~ all have a deleterious impact on crop yield and quality. The environmental dimensions of these challenges could~~an~~not be ignored either. Modern agricultural practices often make excessive use of chemical pesticides and ~~fertilizers~~fertilisers, which may yield short-term benefits but can have long-term detrimental effects, including soil degradation, water pollution, and biodiversity loss. Over-reliance on monocultures also leaves agricultural systems more susceptible to disease outbreaks and reduces ecosystem resilience. The amalgamation of these challenges highlights the urgent need for comprehensive and sustainable plant protection strategies. The isolated approach, which concentrates only on chemical control or a single type of crop, is inadequate. Integrated plant protection strategies that include chemical, biological, and cultural methods offer a more robust approach to controlling pests and diseases. These integrated approaches are reliant on a nuanced understanding of the ecology of pests and diseases and the environmental factors affecting them. Application of big data in agriculture has the potential to ~~revolutionize~~revolutionise how decisions are made, offering more effective and environmentally sustainable solutions to crop protection [3]. The objectives of this review are ~~manifold~~several. It aims to offer an overview of the challenges impeding agricultural productivity, focusing on pests, diseases, and environmental factors. The review~~ will~~ also aims to explore the merits and limitations of existing plant protection strategies and highlight emerging methodologies and technologies. Finally, it aims to provide recommendations for the development of more effective and sustainable plant protection strategies.

Historical Context of Plant Protection

From the dawn of agriculture, approximately 10,000 years ago, human communities have been grappling with the issue of plant protection. The oldest traditional methods were inherently biological or physical in nature, employing practices that this review~~we would now categorize~~categorises as cultural or mechanical control. For instance, early farmers discovered that rotating crops could break the cycle of certain pests and diseases. In many ancient ~~civilizations~~civilisations, including those of~~ in~~ Egypt, China, and Mesoamerica, plant extracts were used to deter pests. For example, extracts of neem leaves have been used in India for centuries to control a wide range of agricultural pests [4]. Similarly, basic manual techniques such as hand-picking and trapping were widespread and are still used in various parts of the world. These methods were, understandably, labor-intensive and not particularly efficient on a large scale. However, they were ecologically sound and often contributed to the sustenance of complex, biodiverse agro-ecosystems. The 19th and early 20th centuries marked a watershed moment in the history of plant protection with the advent of chemical solutions. This period saw the increasing use of inorganic compounds like Bordeaux mixture and later, synthetic organic pesticides. In a post-war world that was already ~~industrializing~~industrialising rapidly, the development and proliferation of synthetic chemicals became emblematic of a new era of agriculture. DDT, hailed as a wonder chemical for its efficacy against a range of pests, became symbolic of this chemical revolution. The immediate impact was astonishing—crop yields soared, and for a while, it appeared that the challenges posed by pests and diseases had been surmounted. However, this triumph was short-lived. The environmental and health implications of widespread pesticide use started becoming increasingly evident. Pesticides were found to accumulate in the food chain, resulting in numerous ecological imbalances and health issues, including the endangerment of non-target species like birds and beneficial insects [5]. As the limitations of chemical control became apparent, attention shifted back to biological controls. The use of predators, parasites, and pathogens to manage pests is not new but gained prominence in the latter half of the 20th century as a viable alternative or complement to chemical methods. For instance, the classic case of the introduction of

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the vedalia beetle to control cottony cushion scale in California's citrus orchards in the late 19th century serves as one of the earliest and most successful examples of biological control [6]. In modern times, advances in molecular biology have led to the development of genetically engineered plants that could~~an~~ either resist pests or produce substances that act as natural pesticides. The adoption of Integrated Pest Management (IPM) approaches has also been critical in bringing biological controls to the forefront. IPM combines various methods chemical, biological, and cultural for more effective and sustainable plant protection.

Types of Threats to Agriculture

First, pests, usually insects and rodents, have been an enduring challenge in the realm of agriculture. Crop losses attributed to pest-related issues could~~an~~ be staggering. C~~For example, c~~aterpillars, aphids, and locusts are among the most notorious agricultural pests. In some years, the damage caused by pests like the Desert Locust was ~~has been~~ so extensive that it ~~has~~ led to famine and severe food insecurity in affected regions. Rodents are no less damaging; they dig up seeds, eat plant parts, and even spread diseases. However, it is not just the direct damage caused by pests that is of concern; it is also their ability to adapt. Overreliance on chemical pesticides has led to increased resistance among several species, making them even harder to manage. Nearly 40% of the world's potential food production is lost each year due to pests [7]. The second category, pathogens—comprising fungi, bacteria, and viruses complicates agricultural challenges. Fungi, such as those causing rusts and smuts, are particularly devastating for staple crops like wheat and corn. Moreover, bacterial infections like bacterial blight in rice could~~an~~ decimate yields. The challenge posed by pathogens is exacerbated by the fact that they can spread rapidly under ~~favorable~~favourable conditions. With global trade networks, the geographic reach of these pathogens has expanded, often affecting regions that were previously free of a specific disease. Pathogens are not static; they evolve. New strains emerge that may be resistant to existing treatments, thereby setting off a constant battle to develop effective countermeasures. These challenges require a deep understanding of pathogen ecology and biology~~, where significant strides have been made but a great deal remains to be understood~~. The final category comprises a myriad of environmental challenges, among which climate change and soil degradation are most critical. Climate change is altering the global landscape for agriculture in unpredictable ways. Extreme weather events such as droughts, floods, and storms are becoming increasingly frequent, causing direct damage to crops. Changes in temperature and precipitation patterns may make existing agricultural lands unsuitable for traditional crops, necessitating either a change in cropping patterns or interventions like irrigation. Another environmental challenge is soil degradation, resulting from the overuse of chemical ~~fertilizers~~fertilisers, poor crop rotation plans, and unsustainable farming practices. Soil degradation not only impacts yields but also threatens long-term food security. Nearly 30% of the global land area has been degraded due to various human activities, a worrying trend that could further exacerbate the challenges facing agriculture [8].

Chemical Approaches to Plant Protection

Chemical approaches have been the cornerstone in the realm of plant protection for the better part of the last century. From small-scale farmers to large agribusinesses, the use of chemical pesticides has become so widespread that it is difficult to imagine modern agriculture without them. Although the use of chemicals in agriculture has ~~revolutionized~~revolutionised our ability to control various threats to crop health and significantly boost yields, it is also accompanied by various drawbacks and limitations that

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need urgent attention. Starting with the positive impacts, chemical pesticides, fungicides, and herbicides have allowed for a level of pest control that was previously unattainable. In the battle against insects, weeds, and diseases, chemicals have given us the upper hand, leading to increased crop yields and thereby contributing to global food security. H~~For example, h~~erbicides like glyphosate allow farmers to control weeds effectively, which would otherwise compete with crops for nutrients and sunlight. Similarly, insecticides such as organophosphates and carbamates have been extremely effective in controlling a broad spectrum of insect pests. It was estimated that without pesticide use, crop losses due to pests could double from the current estimates, thus exacerbating the challenge of feeding an ever-growing global population [9]. Current advances in chemical solutions offer more than just enhanced efficacy. Today, the focus is not only on developing chemicals that are more potent but also those that are target-specific, reducing their impact on non-target species. Innovations like nano-pesticides aim to improve the delivery of active ingredients, thereby ~~minimizing~~minimising the amount needed for effective control. This is a critical advance, considering that one of the drawbacks of chemical pesticides is their impact on the broader environment, including soil and water quality.

Biological Approaches to Plant Protection

Biological approaches to plant protection serve as one of the most promising avenues for sustainable agriculture. The increasing concerns over the environmental, health, and ecological implications of chemical pesticides have led to a surge in interest in alternative methods that are less harmful yet effective. Among these, biological approaches such as the use of natural predators, beneficial insects, and biopesticides stand out for their innovative take on leveraging nature's inherent systems for crop protection [26]. Though these methods have shown promise, they are not without ~~their~~ challenges and limitations.

Table: 1 Biological Approaches to Plant Protection

Aspect	**Description**	**Examples**	**Limitations and Challenges**
Use of Natural Predators	Utilisation of natural enemies of pests to control their populations.	Ladybugs, spiders	Requires ecosystem balance
Beneficial Insects	Insects that actively contribute to pest control by preying on harmful insects.	Lacewings, parasitic wasps	Limited scope, specificity
Biopesticides	Pesticides derived from natural materials like plants, bacteria, or minerals.	Neem oil, Bacillus thuringiensis	Slower action, potential resistance
Microbial Controls	Use of bacteria, fungi, or viruses to control pests.	Nematodes	Environmental conditions affect efficacy

Plant-Based Solutions	Utilization of plant extracts or plant-incorporated substances that deter or kill pests.	Garlic spray	Varying effectiveness, decay rate
Environmental Considerations	The impact of biological approaches on non-target species and the environment.		Risk of disrupting natural balance
Cost and Scalability	Economic aspects of implementing biological approaches on a large scale.		Often costlier, labor-intensive

Natural Predators and Beneficial Insects

Using natural predators and beneficial insects for plant protection is not a new concept. T~~However, t~~he scientific understanding of these interactions has grown tremendously over the past few decades. Natural enemies of pests, such as ladybugs, spiders, and predatory beetles, have been used as biocontrol agents to reduce pest populations in various agricultural settings. L~~For instance, l~~adybugs are known to be effective in controlling aphids, a common pest that affects a range of crops. One of the key advantages of using natural predators is that they offer a form of control that is both self-sustaining and less damaging to the environment [27]. Unlike chemical methods, which can harm a wide range of organisms, natural predators are highly specific to their prey, thereby reducing the risk of unintended ecological consequences. It ~~P~~points to the significant economic value of~~ such~~ ecosystem services, which include natural pest control, and ~~emphasizes~~emphasises their importance in maintaining sustainable agricultural systems [10]. Using natural predators is not without challenges. One primary concern is the unpredictability and inconsistency of control. Factors such as weather conditions, availability of prey, and the presence of other predators can all affect the efficacy of natural predators. If not managed carefully, introducing new organisms into an ecosystem can sometimes lead to unintended consequences, such as the new species becoming invasive.

Table: 2 Natural Predators and Beneficial Insects

Category	Natural Predators	Beneficial Insects	Role in Ecosystem	Limitations and Challenges
Insects	Spiders, Dragonflies	Ladybugs, Lacewings	Pest Control	Limited scope, specificity
Birds	Owls, Hawks	N/A	Pest and rodent control	Possible disruption of ecosystem

Mammals	Bats, Foxes	N/A	Pest and rodent control	Risk to livestock, pets
Reptiles	Lizards, Snakes	N/A	Control of insect and rodent populations	Risk of predation on non-pest species
Role in Agriculture	Reducing the need for chemical pesticides	Enhancing natural pest control measures	Maintaining ecological balance	Requires balanced ecosystem
Environmental Impact	Generally low negative impact	Low to negligible impact	Preservation of biodiversity	Risk of imbalance
Economic Consideration	Low cost after initial setup	Low to medium cost	Cost-effectiveness in long term	Initial investment may be high

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Biopesticides

Biopesticides are another facet of biological approaches that have gained attention. These are generally derived from natural materials like animals, plants, bacteria, and certain minerals. T~~For example, t~~he bacterium Bacillus thuringiensis produces proteins that are toxic to certain insects but harmless to humans and other animals, making it a widely used biopesticide. Biopesticides are generally considered to be more environmentally friendly than synthetic pesticides. They are often target-specific and break down more quickly, reducing their environmental footprint. The risk of developing resistance to bio-pesticides is generally lower than for chemical pesticides, making them a more sustainable option in the long run [11]. Despite these advantages, there are limitations to the widespread adoption of bio-pesticides. Many bio-pesticides are less effective than their chemical counterparts and may require more frequent application, potentially increasing labor and costs. Additionally, the regulatory hurdles for bringing a new bio-pesticide to market could~~an~~ be significant, often making it a less attractive option for manufacturers.

Limitations and Challenges

Both natural predators and biopesticides have their challenges, including the potential for lower efficacy compared to chemical methods, logistical issues related to production and application, and regulatory hurdles. Additionally, while these methods could ~~an~~ reduce the need for chemical inputs, they often could ~~an~~not entirely replace them, particularly in large-scale, monoculture farming systems where pest pressure could ~~an~~ be high. Integrated pest management systems, which use a combination of chemical, biological, and physical methods, may offer the most effective and sustainable form of plant protection for the foreseeable future [12].

Technological Approaches to Plant Protection

Technological advancements have ushered in a new era of solutions for plant protection, providing tools that are increasingly effective, efficient, and sustainable. As traditional chemical and biological methods have their limitations, the integration of technological solutions has become an inevitable and promising trend in agriculture. Areas such as sensor technologies for early detection of disease, drone-based applications for treatment, and the often-controversial realm of genetic engineering and genetically modified organisms (GMOs) are contributing to what could be deemed a revolution in plant protection practices.

Sensor Technologies for Early Detection

The ~~utilization~~utilisation of sensor technology for detecting plant diseases and pests early has gained considerable attention in recent years. These sensors are designed to detect environmental conditions or plant responses that are indicative of disease or pest presence, even before visual symptoms appear. H~~For instance, h~~yperspectral imaging could~~an~~ identify nutrient deficiencies or diseases by measuring the light reflectance from plant leaves. By receiving early warnings, farmers could~~an~~ take preventive measures before the problem escalates, reducing both the severity of the disease and the amount of chemical treatment required. Yet, the efficacy of these technologies relies heavily on data analytics and machine learning algorithms, which parse through vast amounts of data to ~~recognize~~recognise patterns indicative of specific diseases or pest attacks. Here, scalability and data accuracy are of paramount importance. The integration of big data analytics with sensor technology opens up new avenues for more effective plant protection [13].

Drones for Efficient Application of Solutions

The advent of drone technology has also brought remarkable efficiency to plant protection strategies. Drones equipped with spray nozzles could~~an~~ cover large areas in a short period, applying pesticides or bio-pesticides more uniformly than traditional manual or tractor-based methods. The use of drones also facilitates the application of these substances in areas that are otherwise difficult to access. Additionally, drones equipped with sensors could ~~an~~ provide real-time data on crop health, moisture levels, and pest presence, offering a comprehensive approach to plant protection. By targeting only the areas that need treatment, drones could~~anminimize~~minimise the use of chemicals, reducing both costs and environmental impact [14].

Genetic Engineering and GMOs

The topic of genetic modification in agriculture is subject to much debate. However, the potential benefits of genetically modified organisms (GMOs) in plant protection could ~~an~~not be ignored. ~~For instance,~~ Bt cotton, which has been engineered to produce a toxin that kills specific insect pests, has successfully reduced the need for chemical pesticides, benefiting both farmers and the environment [15]. In the case of disease resistance, genetic engineering could~~an~~ introduce genes that provide resistance against specific viruses, fungi, or bacteria. This offers a more permanent solution compared to chemical treatments, which may need to be reapplied periodically and could contribute to resistance development in the pathogens. Yet, the ethical and environmental implications of GMOs, such as potential biodiversity loss and the long-term effects on non-target species, make them a subject of ongoing research and discussion [16]. Despite the promising prospects, each technological approach comes with its set of challenges and limitations. Sensor technologies require significant investment and expertise in data analytics, while the

efficiency of drones hinges on battery life, payload capacity, and regulatory restrictions. The application and acceptance of GMOs, meanwhile, are fraught with ethical and regulatory challenges.

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) stands as a quintessential approach to plant protection that converges the strengths of chemical, biological, and technological means. It is a strategy premised on a multifaceted approach, designed to be adaptable, sustainable, and, above all, effective. Rooted in a deep understanding of pest biology and ecosystem dynamics, IPM aims to manage pest populations in a way that ~~minimizes~~minimises both economic damage and negative environmental impact. Integrated Pest Management is a decision-making process that facilitates the timely use of multiple tactics for managing pest damage in an economically viable, environmentally sound, and socially acceptable manner. At its core, IPM involves continuous monitoring and assessment of pest and disease levels, in addition to a variety of control options. These options could range from the application of chemical pesticides to deploying natural predators, adjusting planting times, or using resistant crop varieties. The bedrock principles of IPM include but are not limited to pest identification, monitoring, economic thresholds, and control. One of the standout attributes of IPM is the notion of the Economic Threshold Level, a point at which the economic damage caused by a pest justifies the cost of artificial control measures. By understanding and applying this threshold, farmers can determine the most cost-effective time to manage pests. IPM also stresses the importance of "least-toxic methods." That is, when control is necessary, the method that is least damaging to all other components of the environment is preferred. This could mean using a natural predator to control a pest species, a bio-pesticide that degrades quickly, or targeted application of a more traditional pesticide [17].

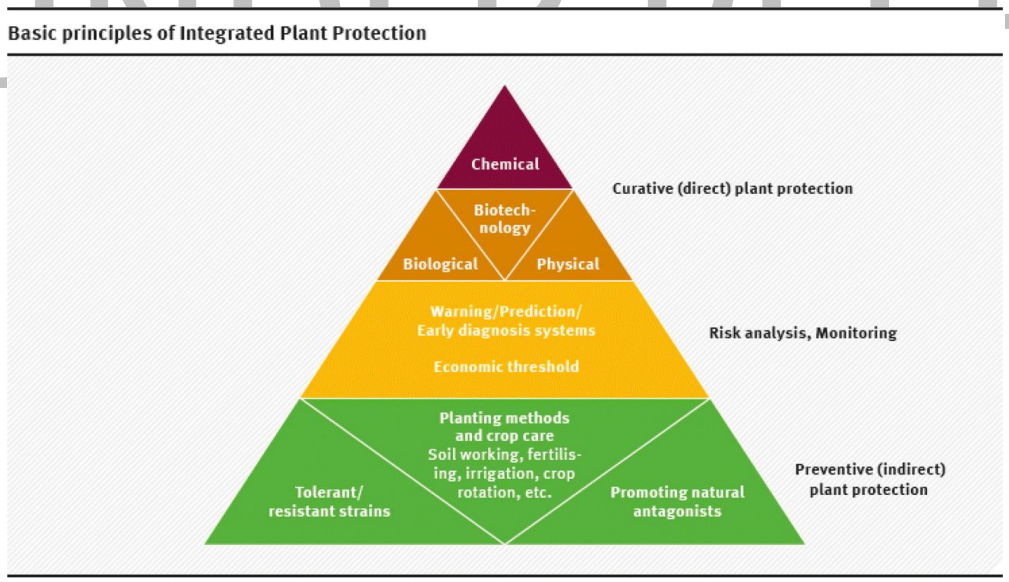

Image 1: Point programme for sustainable plant protection

Advantages and Limitations

The advantages of IPM are several~~manifold~~. Firstly, it's a versatile strategy that could~~an~~ be tailored to fit individual crop needs, local environmental conditions, and specific pests. It tends to ~~minimize~~minimise risks to human health and the environment by reducing, if not eliminating, the use of hazardous pesticides. The focus on long-term prevention of pests or their damage is both cost-effective and environmentally beneficial. IPM is not without its challenges and limitations. One of the main drawbacks is the need for extensive knowledge and expertise in multiple disciplines including entomology, plant pathology, climatology, and even socioeconomics for successful implementation. The upfront cost in terms of both money and time could ~~an~~ be significant, especially for small farmers. In some instances, the least toxic methods may not be the most efficient, or may not suffice to control the pest problem adequately [25]. While IPM seems to be the future of pest management, offering a more holistic, targeted, and sustainable approach, it demands a higher level of management skill, including decision-making based on comprehensive information gathering and assessment. As with any complex system, the efficiency of IPM is closely tied to the quality of the information upon which decisions are made and the appropriateness of the techniques used [18].

Policy and Regulation

Plant protection has gained precedence in global dialogues, manifesting in various international policy frameworks and ethical considerations that aim to secure both the future of agriculture and the environment. These policies are not isolated doctrines but rather interconnected pieces that shape a global vision for sustainable agriculture. Understanding these policies, the ethical implications of plant protection methods, and the existing regulatory frameworks can offer significant insights into the current landscape of agriculture and what may lie ahead. The first notable framework for plant protection is the International Plant Protection Convention (IPPC), which serves as a treaty among 184 contracting parties aiming to safeguard plants, whether cultivated or in the wild, from pests without impeding international trade. The IPPC sets the international standards for phytosanitary measures, facilitating science-based decision-making to protect plant health. The IPPC primarily focuses on pests that are detrimental to cultivated plants, giving lesser attention to wild flora. Another key global policy is the Codex Alimentarius, administered by the World Health Organization and the Food and Agriculture Organization, which sets international food standards and guidelines, including maximum residue levels for pesticides [19]. It aims to ensure safe, good food for everyone, everywhere. Regional bodies like the European Union have specific frameworks such as the European Pesticides Regulation, aiming to ensure a high level of protection for both humans and the environment [21]. In addition to international and regional policies, national regulations often dictate the use and registration of pesticides, biopesticides, and other plant protection products.T~~For instance, t~~he U.S. Environmental Protection Agency (EPA) is responsible for regulating pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Food Quality Protection Act (FQPA) [21].

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Future Trends and Developments

The agricultural landscape is rapidly evolving, influenced not just by advances in technologies but also by shifts in policies and increasing awareness of the need for sustainable practices. This dynamism heralds a promising yet challenging future for plant protection. O~~As we stand o~~n the cusp of these developments, it is imperative to understand what the future might entail, particularly in the realm of emerging

technologies, policy shifts, and sustainability. In the realm of technology~~Emerging Technologies~~ in Plant Protection~~In the realm of technology~~, the most noticeable trend is the rise of precision agriculture [22]. With the advent of the Internet of Things (IoT), sensor technology has come to the forefront, enabling farmers to measure variables like soil moisture levels, nutrient content, and pest presence with unprecedented accuracy. These sensors provide real-time data, facilitating timely interventions to protect crops. Advancements in drone technology have made it possible to apply pesticides or ~~fertilizers~~fertilisers more precisely, reducing the amount of chemicals used and thereby lessening their environmental impact [23]. Perhaps the most revolutionary advancement is in the field of genetic engineering, specifically the development of Genetically Modified Organisms (GMOs). Techniques like CRISPR are making it increasingly easy to engineer crops with built-in resistances to pests and diseases, reducing the need for external chemical applications [24]. Although GMOs have been met with considerable public skepticism, their potential for dramatically reducing the need for chemical pesticides could ~~an~~not be overlooked. Nanotechnology also offers potential. N~~For instance, n~~ano-encapsulated pesticides promise higher efficacy at lower doses, reducing the chemical footprint. The use of nano-sensors could help in the early detection of plant diseases and pests, allowing for timely control measures that are both effective and less harmful to the environment.

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Conclusion

The landscape of plant protection is complex and ever-changing, influenced by a variety of biological, chemical, and technological factors. Amidst rising concerns about global food security and environmental sustainability, this review has delved into the nuances of different plant protection strategies. From traditional methods that harness natural ecosystems, to chemical solutions that promise quick results but pose environmental challenges, to emerging technologies that offer precise and efficient solutions, the field is advancing rapidly. Integrated Pest Management stands out as a balanced, effective approach. Regulatory frameworks and ethical considerations further add layers of complexity. As the future beckons, the convergence of technology and sustainability is inevitable, requiring a ~~harmonized~~harmonised approach guided by sound policy and ethical principles to ensure both agricultural productivity and ecological balance.

Reference

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1. Aabø, E., & Kring, T. (2012). The political economy of large-scale agricultural land acquisitions: Implications for food security and livelihoods/employment creation in rural Mozambique. *United Nations Development Programme Working Paper*, 4, 1-61.

2. Heeb, L., Jenner, E., & Cock, M. J. (2019). Climate-smart pest management: building resilience of farms and landscapes to changing pest threats. *Journal of Pest Science*, *92*(3), 951-969.

3. Balaska, V., Adamidou, Z., Vryzas, Z., & Gasteratos, A. (2023). Sustainable Crop Protection via Robotics and Artificial Intelligence Solutions. Machines, 11(8), 774.

4. Mondal, E., & Chakraborty, K. (2016). Azadirachta indica-A tree with multifaceted applications: An overview. *Journal of Pharmaceutical Sciences and Research*, *8*(5), 299.

5. Kumar, A., Thakur, A., Sharma, V., & Koundal, S. (2019). Pesticide residues in animal feed: status, safety and scope. *J. Anim. Feed Sci. Technol*, *7*, 73-80.

6. Riley, C. V. (2019). Vedalia the "Wonder Beetle" and Biological Control. *Charles Valentine Riley: Founder of Modern Entomology*, 214.

7. Popp, J., Pető, K., & Nagy, J. (2013). Pesticide productivity and food security. A review. *Agronomy for sustainable development*, *33*, 243-255.

8. Arora, N. K., Fatima, T., Mishra, I., Verma, M., Mishra, J., & Mishra, V. (2018). Environmental sustainability: challenges and viable solutions. *Environmental Sustainability*, *1*, 309-340.

9. Gill, H. K., & Garg, H. (2014). Pesticide: environmental impacts and management strategies. *Pesticides-toxic aspects*, *8*(187), 10-5772.

10. Kunz, T. H., Braun de Torrez, E., Bauer, D., Lobova, T., & Fleming, T. H. (2011). Ecosystem services provided by bats. *Annals of the New York academy of sciences*, *1223*(1), 1-38.

11. Samada, L. H., & Tambunan, U. S. F. (2020). Biopesticides as promising alternatives to chemical pesticides: A review of their current and future status. *Online J. Biol. Sci*, *20*(2), 66-76.

12. Deguine, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., & Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, *41*(3), 38.

13. Jin, S., Sun, X., Wu, F., Su, Y., Li, Y., Song, S., ... & Guo, Q. (2021). Lidar sheds new light on plant phenomics for plant breeding and management: Recent advances and future prospects. *ISPRS Journal of Photogrammetry and Remote Sensing*, *171*, 202-223.

14. Mattivi, P., Pappalardo, S. E., Nikolić, N., Mandolesi, L., Persichetti, A., De Marchi, M., & Masin, R. (2021). Can commercial low-cost drones and open-source GIS technologies be suitable for semi-automatic weed mapping for smart farming? A case study in NE Italy. *Remote sensing*, *13*(10), 1869.

15. Sarwar, M. (2015). Biopesticides: an effective and environmental friendly insect-pests inhibitor line of action. *International Journal of Engineering and Advanced Research Technology*, *1*(2), 10-15.

16. Sanvido, O., Romeis, J., Gathmann, A., Gielkens, M., Raybould, A., & Bigler, F. (2012). Evaluating environmental risks of genetically modified crops: ecological harm criteria for regulatory decision-making. *Environmental Science & Policy*, *15*(1), 82-91.

17. Sharma, N. (2014). Biologicals. *Biological Controls for Preventing Food Deterioration*, 1-25.

18. Kock, A., & Georg Gemünden, H. (2016). Antecedents to decision-making quality and agility in innovation portfolio management. *Journal of product innovation management*, *33*(6), 670-686.

19. Ambrus, A., & Yang, Y. Z. (2016). Global harmonization of maximum residue limits for pesticides. *Journal of agricultural and food chemistry*, *64*(1), 30-35.

20. Brack, W., Dulio, V., Ågerstrand, M., Allan, I., Altenburger, R., Brinkmann, M., ... & Vrana, B. (2017). Towards the review of the European Union Water Framework Directive: recommendations for more efficient assessment and management of chemical contamination in European surface water resources. *Science of the Total Environment*, *576*, 720-737.

21. Schierow, L. (2001). Federal Insecticide, Fungicide, and Rodenticide Act. *Environmental Laws: Summaries of Statutes Administered by the Environmental Protection Agency*, 103.

22. Boursianis, A. D., Papadopoulou, M. S., Diamantoulakis, P., Liopa-Tsakalidi, A., Barouchas, P., Salahas, G., ... & Goudos, S. K. (2022). Internet of things (IoT) and agricultural unmanned aerial vehicles (UAVs) in smart farming: A comprehensive review. *Internet of Things*, *18*, 100187.

23. Hafeez, A., Husain, M. A., Singh, S. P., Chauhan, A., Khan, M. T., Kumar, N., ... & Soni, S. K. (2022). Implementation of drone technology for farm monitoring & pesticide spraying: A review. *Information processing in Agriculture*.

24. Vincelli, P. (2016). Genetic engineering and sustainable crop disease management: opportunities for case-by-case decision-making. *Sustainability*, *8*(5), 495.

25. Damalas, C. A., & Koutroubas, S. D. (2016). Farmers' exposure to pesticides: toxicity types and ways of prevention. *Toxics*, *4*(1), 1.

26. Koutouleas, A., Collinge, D. B., & Ræbild, A. (2023). Alternative plant protection strategies for tomorrow's coffee. *Plant Pathology*, *72*(3), 409-429.

27. Suckling, D. M., & Sforza, R. F. H. (2014). What magnitude are observed non-target impacts from weed biocontrol?. *PloS one*, *9*(1), e84847.