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Sustainable Pest and Disease Management in Agriculture Crop Production System

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Global agriculture faces significant challenges from dependence on synthetic pesticides, increasing pesticide resistance and antimicrobial resistance, pest expansion due to climate change, and rapid biodiversity loss. Despite heavy chemical use, 20–40% of global crop production is lost each year to pests and diseases, showing the diminishing effectiveness of chemical-based plant protection strategies. Sustainable Pest and Disease Management (SPDM) as an improved version of Integrated Pest Management (IPM 2.0), combining biological, cultural, technological, and policy-based methods. Evidence from long-term field studies suggests that SPDM can cut chemical pesticide use by 30–70% while keeping yields stable within ±5–10% of traditional systems. New technologies like AI-based disease diagnostics, RNA interference (RNAi), and IoT-enabled monitoring further improve precision and environmental safety. And effective pest and disease management requires a systems-based "silver buckshot" approach, moving away from single-solution strategies to ensure food security amidst climate change.

Keywords: Disease; Integrated; Pest; Management and Sustainable.

Introduction: The Global Imperative

Modern agricultural systems face serious challenges due to the unintended effects of heavy chemical pest control. This includes a heavy reliance on synthetic pesticides, increasing pesticide resistance, antimicrobial resistance (AMR), pollution of soil and water, and loss of biodiversity. All these factors threaten long-term food security and the stability of agro-ecosystems **(Pimentel, 2005; Heeb *et al.*, 2019).**

Even though global pesticide use exceeds 4 million tonnes each year, around 20 to 40% of crops still suffer losses from pests and diseases. This points to diminishing returns from chemical-based plant protection strategies and highlights the well-known pesticide paradox. Here, excessive pesticide use disrupts natural pest enemies and leads to new pest outbreaks **(FAO, 2019; Kogan, 1998).** Climate change makes these problems worse. Higher temperatures, changed rainfall patterns, and shifting climate zones speed up pest development, increase survival rates over winter due to slightly high temperature, and allow invasive species to spread. This results in significant yield losses, especially in tropical and subtropical areas **(Deutsch *et al.*, 2018; FAO, 2021).**

In this situation, Sustainable Pest and Disease Management (SPDM) has emerged as a new approach. It builds on Integrated Pest Management by promoting a mix of biological control, host-plant resistance, cultural practices, and new digital and molecular technologies. The goal is to achieve crop protection that is resilient, economically viable, and environmentally friendly in an uncertain climate **(Pretty & Bharucha, 2015; Gurr *et al.*, 2017).**

The Props of Integrated Pest Management (IPM) 2.0

Sustainable Pest and Disease Management (SPDM) is a new form of Integrated Pest Management, often called IPM 2.0. It moves from reacting to problems with pesticides to managing pest populations based on the ecosystem **(Kogan, 1998; Pretty & Bharucha, 2015)**. Unlike traditional IPM, which often uses chemicals once economic thresholds are passed, IPM 2.0 focuses on preventive design, ecological diversity, and the combination of biological, genetic, cultural, and technological tools to improve agro-ecosystem resilience as climate changes **(Heeb *et al.*, 2019).**

Biological Control and Ecological Engineering

Biological control is the ecological basis of IPM 2.0. It helps to manage pest populations using predators, parasitoids, and entomopathogens **(Van-Lenteren *et al.*, 2018).** Conservation biological control, achieved by diversifying habitats with flowering strips, banker plants, and reducing pesticide use, boosts natural enemy numbers by 40–60% and lowers pest populations by 30–50% in major crops **(Gurr *et al.*, 2017).** Meta-analyses show that using conservation biocontrol can reduce insecticide sprays by 1.5–2.5 per season without affecting yield **(Pretty & Bharucha, 2015).**

Augmentative biological control involves releasing mass-reared natural enemies like *Trichogramma spp*. and *Chrysoperla spp*. to quickly suppress important insect pests in intensive systems. Field studies show 50–85% parasitism, 8–15% yield improvement, and cost-benefit ratios between 1:1.8 and 1:3.2 in crops like maize, sugarcane, and vegetables **(Van-Lenteren *et al.*, 2018).**

Host-Plant Resistance and Molecular Breeding

Host-plant resistance is one of the most cost-effective and environmentally friendly pest and disease management strategies. It offers protection throughout the season without needing extra inputs **(Kogan, 1998).** Advances in marker-assisted selection (MAS) have cut breeding time by 30–40% and allowed for the stacking of resistance genes, extending resistance from 3–5 years to over a decade **(Collard & Mackill, 2008).**

Recent advancements in CRISPR/Cas9 genome editing have also improved host resistance. This approach allows targeted changes to plant susceptibility genes instead of introducing foreign DNA. Crops modified with genome editing have shown reductions of 60–80% in disease severity without affecting yield of crop **(Zaidi *et al.*, 2020).**

Cultural and Physical Control Strategies

Cultural and physical control practices serve as the preventive mainstay of IPM 2.0. They disrupt pest life cycles and lower pathogen levels before economic harm occurs. Crop rotation and diversification can reduce soil-borne diseases by 20–50% and improve soil microbial diversity and stability **(Larkin, 2015).** Intercropping increases functional diversity and interferes with pest-host interactions, minimizing establishment and spread **(Gurr *et al.*, 2017).** A notable example of ecological engineering is Push-Pull technology.

This method combines repellent intercrops and attractive trap crops to influence pest behaviour **(Khan *et al.*, 2014).** Long-term studies in East Africa show 80–90% reductions in stem borer damage, more than 85% suppression of Striga, and maize yield increases of 2–3 tons per hectare under low-input conditions **(Khan *et al.*, 2014).** Soil solarization, especially effective in warm areas, cuts soil-borne pathogens and nematode populations by 60–90%. This offers a solid non-chemical option for managing diseases **(Katan, 2017).**

Host-Plant Resistance

Host-plant resistance (HPR) is one of the most cost-effective and environmentally friendly methods as it offers natural protection against pests and diseases without needing ongoing external inputs **(Kogan, 1998)**. By decreasing pest survival, feeding efficiency, and reproduction, resistant cultivars help control pest population growth and reduce the need for chemical pesticides. This improves long-term agro-ecosystem stability **(Painter, 1951; Stout, 2013).** Studies show that using resistant varieties can cut pesticide use by 20–40% in major crops **(Sharma *et al.*, 2017).**

Mechanisms of Host-Plant Resistance

Host-plant resistance works through three main mechanisms: antibiosis, antixenosis (non-preference), and tolerance. Each mechanism affects pest behaviour and performance in different ways **(Painter, 1951).** Antibiosis negatively impacts pest survival and reproduction through specific traits in plants, leading to reduced pest fitness **(Stout, 2013).** Antixenosis discourages pests from settling, feeding, or laying eggs, which helps lower initial infestation levels and slows the development of pest outbreaks **(Smith, 2005).** Tolerance allows plants to handle or recover from pest damage without significant yield loss. This is especially important in conditions with high pest pressure and varying climate **(Sharma *et al.*, 2017).** Environmental factors greatly influence how these mechanisms work, highlighting the need to combine host resistance with other SPDM elements **(Stout, 2013).**

Role of Host-Plant Resistance in Climate-Resilient Agriculture

Climate change is expected to increase pest pressure and alter pest-host interactions. This makes host-plant resistance more crucial in climate-resilient agriculture **(Deutsch *et al.*, 2018)**. Resistant cultivars create a stable level of protection under changing climate conditions and lessen the need for reactive pesticide use during outbreaks **(Sharma *et al.*, 2017)**. When combined with biological control, cultural practices, and digital decision-support tools, host-plant resistance helps build strong, low-risk, and economically sustainable pest and disease management systems **(Stout, 2013; Pretty & Bharucha, 2015).**

Socio-Economic and One Health Dimensions

While SPDM requires a higher initial investment in training and monitoring, long-term studies show net profits 15–35% higher over 5–8 years due to lower input costs and better yield stability **(Pretty & Bharucha, 2015).** Reduced pesticide use supports the One Health approach by decreasing risks of occupational exposure, groundwater contamination, and cross-resistance that contributes to AMR in human pathogens **(Fisher *et al.*, 2018).**

Global Case Studies

1. The "Push-Pull" Strategy (East Africa): Farmers planted Desmodium between rows to repel stem borers and used Napier grass borders to trap them. This method successfully protected maize crops **(Hassanali et al., 2007).** It increased yields by over 100% and improved soil health without synthetic pesticides **(Kebede et al., 2018).**
2. Mating Disruption in Orchards (USA & Europe): Orchard growers filled the air with synthetic sex pheromones to confuse male Codling Moths. This prevented them from locating females and mating **(Whitfield & Fountain, 2024).** This technique significantly reduced insecticide use and addressed the problem of chemical resistance in pome fruits **(Ferracini et al., 2021).**
3. Biological Control of Diamondback Moth (Australia): Brassica growers stopped using broad-spectrum sprays to protect the *Diadegma semiclausum* wasp. This allowed it to parasitize and control resistant Diamondback Moths **(Furlong & Zalucki, 2017).** This shift to enhanced integrated pest management reduced pest control costs and restored the natural predator-prey balance **(Nam et al., 2022).**
4. Large-Scale Biocontrol in Greenhouses (Spain): To meet export demands for residue-free produce, greenhouse growers in Almería released large numbers of predatory mites like *Amblyseius swirskii* to consume thrips and whiteflies **(Pérez-Hedo et al., 2017).** The strategy was so effective that most pepper growers adopted it to secure premium market prices **(Calvo et al., 2015).**
5. China (Rice): Genetic diversity through mixed planting cut blast disease by 94% without using fungicides **(Zhu *et al.*, 2000).**
6. California (Vineyards): Drone-released sterile insects reduced pesticide residues in groundwater **(Vreysen *et al.*, 2021).**

Conclusion

Sustainable Pest and Disease Management signifies a move from reactive chemical control to proactive, ecosystem-based regulation. Moving away from single "silver bullet" solutions in favour of a "silver buckshot" strategy that integrates biological, genetic, cultural, digital, and policy tools is vital for long-term agricultural resilience in the face of climate change.

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