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Integrated pest management in beetroot cultivation: A systematic review

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Abstract

This systematic review delves into the realm of Integrated Pest Management (IPM) within the context of beetroot cultivation, scrutinizing both the application and efficacy of diverse strategies. Through a meticulous synthesis of existing literature, the study evaluates key IPM approaches—ranging from biological control and cultural practices to chemical interventions—specifically tailored to address pest management challenges in beetroot farming. The review systematically identifies and examines prevailing trends, challenges, and successes in the implementation of these IPM strategies, providing a comprehensive overview intended for a diverse audience including researchers, practitioners, and policymakers engaged in beetroot agriculture. By comprehensively analysing a spectrum of studies, this review significantly contributes to the broader comprehension of sustainable pest management practices, furnishing valuable insights that can be harnessed for optimizing IPM strategies in beetroot cultivation, thereby fostering more effective and environmentally conscious pest control measures.

Keywords: Thrips; Integrated Pest Management; Biological Control; Sustainable Agriculture; Technology

1. Introduction

Beetroot, scientifically known as *Beta vulgaris* ssp. *vulgaris* L. and belonging to the Chenopodiaceae family, stands as a paramount root vegetable with global culinary significance. Exhibiting a spectrum of colours, shapes, and sizes, cultivated forms of *Beta vulgaris* encompass beetroot (also known as table beet or garden beet), leaf beets such as spinach beet and chard, as well as sugar beet and fodder beet (Lange *et al*., 1999). Its cultivation is diverse, serving human consumption, commercial sugar production, fodder for livestock, and extraction of natural dyes. This versatile vegetable is a nutritional powerhouse, boasting significant quantities of carbohydrates, lipids, fats, micronutrients, and bioactive compounds like betain, betalins, carotenoids, flavonoids, and polyphenols (Chhikara *et al*., 2019; Lim, 2016). The nutrient profile of beetroot is impressive, with 87.5 g of water, 9.56 g of carbohydrates, 6.76 g of total sugar, 2.8 g of fiber, 1.61 g of protein, and 1.25 g of ash per 100 g, providing 43 kcal energy (USDA-ARS, 2014). Furthermore, the extracted juice from beetroot contains essential vitamins (B3, B6, B7, and B12) and minerals (phosphorus, iron, calcium, magnesium, sodium) (Wootton-Beard *et al*., 2011). In essence, beetroot emerges as not only a culinary delight but also a nutritional treasure trove, embodying a fusion of taste and health benefits.

Cultivating Beetroot (Beta vulgaris) occupies a pivotal position in the global agricultural sphere, making significant contributions to both economic and nutritional realms. Renowned for its vivid colour and distinctive earthy taste, beetroot stands out not just as a versatile culinary element but also as a valuable reservoir of essential nutrients and bioactive compounds. With the escalating demand for a varied and nutrient-rich food supply, a comprehensive understanding of the intricacies associated with beetroot cultivation becomes indispensable for farmers, researchers, and policymakers. As a member of the Amaranthaceae family, beetroot has experienced resurgence in popularity attributable to its nutritional advantages. Abundant in vitamins, minerals, and antioxidants, beetroot boasts a diverse

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range of health-promoting properties, spanning from cardiovascular support to anti-inflammatory effects. Consequently, beetroot cultivation assumes a crucial role in addressing concerns related to food security and public health priorities.

Beyond its nutritional significance, beetroot cultivation is deeply interwoven into the agricultural landscape as a lucrative cash crop. Its versatile applications in the food and beverage industry, encompassing the production of natural food colorants and additives, render beetroot a profitable commodity for farmers and agribusinesses alike. Functioning as a root vegetable, beetroot exhibits adaptability to various climates and soil conditions, establishing itself as a resilient choice for cultivation across diverse regions.

Nevertheless, akin to any other crop, beetroot encounters challenges from an array of pests that can detrimentally impact both yield and quality. Effectively addressing these challenges necessitates a holistic approach, and integrated pest management (IPM) emerges as a strategic and comprehensive solution. This systematic review endeavours to delve into the present state of knowledge concerning IPM in beetroot cultivation, scrutinizing the varied methods employed to safeguard crops sustainably and ensure the enduring viability of beetroot farming systems. Through this exploration, our aim is to illuminate the manifold importance of beetroot cultivation and underscore the pivotal role that IPM plays in sustaining its production in an environmentally conscious manner.

The cultivation of beetroot, a robust root crop, confronts a spectrum of challenges encompassing both biotic and abiotic stresses throughout its growth cycle. Within the realm of biotic stress, insects emerge as pivotal factors that significantly influence the ultimate yield of beetroot. Over 150 pest species exert their impact on beet crops, featuring notorious actors such as leaf miners, tobacco caterpillars, cutworms, leafhoppers, thrips, aphids, mites, and flea beetles, as identified by Lange *et al.* (1999). Notably, the literature addressing the specific pests afflicting beetroot crops in the Indian context remains scarce, highlighting a critical gap in our understanding of these challenges and underscoring the need for more comprehensive research in this domain. This review endeavours to systematically scrutinize and distil the existing body of knowledge surrounding IPM, focusing specifically on its application in beetroot cultivation. Beetroot, a crop of multifaceted importance, confronts its own array of pest challenges. Through an exhaustive analysis of the literature, we aspire to unravel the intricacies of IPM strategies deployed in beetroot farming. The goal is to unravel the effectiveness of these strategies, identify knowledge gaps, and contribute insights that can shape sustainable and progressive practices in beetroot cultivation. By doing so, this exploration not only aims to inform farmers, researchers, and policymakers but also seeks to usher in a paradigm shift towards a more enlightened and sustainable approach to beetroot cultivation within the broader agricultural landscape.

2. Beetroot Cultivation Practices

Beetroot cultivation unfolds as a meticulously choreographed symphony of agricultural practices, wielding profound influence over the vegetable's exquisite quality. Every facet, from the initial soil preparation to the delicate post-harvest nuances, orchestrates a ballet of elements that shape the beetroot's size, shape, colour, flavor, and nutritional essence. The artistry lies in implementing not just cultivation techniques but an intricate tapestry of efficient management practices, a pivotal pursuit in delivering a harvest that caters to the discerning preferences of consumers craving fresh, nutritious, and aesthetically captivating produce. Below encapsulates the key agricultural practices entwined in beetroot cultivation, each resonating with a transformative impact on the vegetable's unparalleled quality:

Climate and Soil Preparation: Beetroot, resilient to low temperatures, thrives in cool climates, with optimal colour and texture development. Strategic soil preparation in well-drained, loose soil rich in organic matter is the canvas for fostering healthy root growth, shaping the beetroot's size and form.

Seed Selection and Planting: The alchemy begins with high-quality seeds, boasting excellent germination rates and disease resistance. Timing is crucial, raising beetroot in winter plains and as a spring-summer crop in hills, ensuring a bounty of 6 kg seeds per hectare.

Irrigation and Water Management: The lifeblood of consistent and ample water supply during beetroot growth, particularly root formation, ensures an artistic dance of even moisture distribution. Precise irrigation, choreography of 5-6 sessions in summer and three in winter, prevents root compromise, cracking, or excessive drying.

Nutrient Management: The symphony of beetroot's optimal growth requires a harmonious balance of nitrogen, phosphorus, and potassium. Apply FYM at 20 t/ha and 60:160:100 kg of NPK/ha as basal and 60 kg N/ha after 30 days. Fertilization, a carefully measured composition of FYM and NPK, weaves the nutritional tapestry necessary for nutrient-rich beetroots.

Weed Control: An exquisite ballet unfolds in weed control, minimizing competition for nutrients and water, preventing misshapen or smaller beetroots. The field is a canvas, kept weed-free through the artistry of light hoeing and tender care in earthing up swollen roots.

Pest and Disease Management: The vigilant gaze of regular monitoring and precision in pest and disease management safeguards beetroot from potential damage. A symphony of defence against insect pests, fungal diseases, and viral threats ensures the preservation of beetroot's visual allure and nutritional essence.

Thinning and Harvesting: Thinning, a delicate act of nurturing beetroot seedlings to optimal spacing sets the stage for uniform root development. Harvesting, a crescendo 8-10 weeks post-sowing, is a performance art in pulling with hand, grading, and presenting medium-sized tubers to a world that cherishes their tender allure.

Post-harvest Handling and Storage: The curtain call demands meticulous post-harvest handling, unveiling a master class in washing and cleaning, preserving the freshness and preventing the spoilage of each precious tuber. The grand finale, where tubers take their bow, unfurls at a crisp 0°C and 90% RH, orchestrating a storied epilogue.

Processing Techniques: Beetroot's narrative extends beyond the harvest, embracing processing methods like canning, pickling, and drying, where each method is a brushstroke preserving nutritional value, flavour, and visual allure.

Crop Rotation and Rotation Period: The closing act embraces the wisdom of crop rotation, a choreography that manages pests, diseases, and soil nutrient depletion. The rotation period, an interlude that safeguards against nitrates' over-accumulation, ensures the enduring quality of the beetroot's narrative.

In the grand tapestry of beetroot cultivation, each practice is not merely a step but a brushstroke contributing to a masterpiece of agricultural artistry, where quality transcends the ordinary and emerges as a symphony for the senses.

3. Significance of Beetroot

Beetroot (*Beta vulgaris*) stands as a multifaceted marvel, weaving significance across culinary, nutritional, medicinal, and industrial realms. Behold the profound aspects that underscore the extraordinary significance of beetroot:

Nutritional Powerhouse: Beetroot emerges as a treasure trove of nutrients, boasting vital vitamins (including C and B-complex), essential minerals (such as potassium, magnesium, and iron), and dietary fiber. Its vivid hue is a testament to the presence of phytonutrients like betalains and antioxidants. Beet roots serve as a rich reservoir of essential minerals, including manganese, which promotes bone health, as well as magnesium, potassium, sodium, phosphorus, iron, zinc, copper, boron, silica, and selenium (Babarykin *et al*., 2019).

Heart Health: Nitrates within beetroot unveil a symphony of potential cardiovascular benefits, orchestrating the dilation of blood vessels, enhanced blood flow, and regulated blood pressure, thereby contributing to optimal heart health.

Exercise Performance: A portion of beetroot juice, rich in nitrates, weaves tales of heightened exercise performance, enhancing oxygen utilization, and bolstering endurance. Athletes, captivated by its potential performance benefits, incorporate beetroot into their dietary repertoire.

Anti-Inflammatory Properties: Betalains, the vibrant pigments adorning beetroot's red tapestry, command attention for their studied anti-inflammatory and antioxidant prowess. These properties become harmonious contributors to overall health and well-being. The chemical composition and distribution of nutritional compounds in red beetroot vary based on the anatomical part of the plant, such as the leaf, stem, root, or peel (Sawicki *et al*., 2016). Notably, beetroot leaves exhibit a higher concentration of carotenoids compared to the tubers. This phenomenon is attributed to the accumulation of carotenoids in the chloroplasts of the green plant parts, comprising a mix of α- and β-carotene, β-cryptoxanthin, lutein, zeaxanthin, violaxanthin, and neoxanthin (Paliwal *et al*., 2016).

Liver Health: Beetroot unfolds its support for liver health through compounds like betaine, facilitating detoxification processes. Studies align with this narrative, showcasing improved liver function with beetroot consumption.

Digestive Health: A beacon of dietary fibre, beetroot champions digestive well-being by fostering regular bowel movements and nurturing a wholesome gut environment.

Culinary Versatility: In the culinary arena, beetroot takes centre stage as a versatile virtuoso. Whether roasted, boiled, pickled, juiced, or grated, it adds a unique flavor and a kaleidoscope of vibrant colour to an array of sweet and savoury creations.

Natural Food Colouring: The natural pigments within beetroot, notably betalains, transcend mere vegetable status to become sought-after natural food colorants. In the food industry, beetroot extracts paint a red masterpiece without the need for synthetic dyes.

Sugar Production: The illustrious sugar beet, akin of beetroot, commands the stage as a major player in the commercial sugar industry. Extracting sugar from these beets constitutes a pivotal chapter in the global sugar saga.

Industrial Uses: Beyond the culinary canvas, beetroot leaves an indelible mark in industrial landscapes. Its natural dyes grace textiles, and its high sugar content positions it as a promising contender in the quest for biofuel sources.

Agricultural Crop Rotation: In the agricultural tapestry, beetroot assumes the role of a transformative rotational crop, enriching soil structure and nutrient content. A beacon of sustainability, it mitigates risks associated with pests and diseases, offering a harmonious alternative to continuous monoculture.

In summation, the brilliance of beetroot radiates across diverse domains, rendering it not merely a vegetable but a symphony of versatility and value in nutrition, health, industry, and agriculture.

4. Common Pests of Beetroot

Beetroot crops stand as a tantalizing target for an array of pests, capable of disrupting their growth and compromising yields. Among these adversaries:

4.1. Beet leaf miner: *Pegomyia hyocyami*

The adult female deposits eggs on the lower surface of the leaves. Upon hatching, the larvae target tender leaves, creating serpentine mines in the epidermal layers. These mines, characterized by trapped air, manifest a silvery appearance. Affected leaves undergo a transformation, adopting a pallid yellow colour, distortion, and crumpling, ultimately leading to gradual desiccation and death.

Control: To mitigate the impact of this infestation, it is recommended to implement control measures, including the thorough removal of all fallen leaves and plant debris post-root harvest. Additionally, the application of Methyl Demeton (0.03%) and Phosphamidon (0.035%) on the underside of leaves upon the emergence of new leaves proves to be highly effective.

4.2. Web Worms: *Hymenia* sp. or *Loxostege* sp.

Clusters of eggs are affixed to the lower side of leaves and bound together by a gelatinous adhesive. Green caterpillars intricately weave the leaves into a tangled mass, residing within this entwined structure. The detrimental impact extends to hinder flowering and pod formation. To curb the progression of the disease, it is advised to eliminate and eradicate the webbed clusters of leaves.

Control: An effective control method involves spraying with Rogor at a concentration of 1 ml per liter of water.

4.3. Semiloopers (*Plusia* spp.)

The green caterpillars consume foliage voraciously, causing significant damage to the green leaves.

Control: To manage this pest, manual removal of the larvae and the application of Endosulfan (0.05%) or Carbaryl (0.1%) through crop spraying prove effective control measures.

4.4. Root Aphids (Aphidoidea)(Rhopalosiphum rufiabdominalis)

Root aphids primarily target the secondary roots, though in significant numbers, they may also be present on the tap root. While mild infestations may escape notice without root inspection, severe cases can manifest aboveground symptoms such as leaf wilting and yellowing. Drought stress further amplifies the impact on sugar beets, exacerbating aboveground symptoms and damage. The infestation's spread occurs through the movement of wingless aphids from one plant to neighbouring ones, resulting in distinct elliptical damage patterns in fields, a consequence of the closer proximity of beets within rows compared to the spaces between rows.

Control: The management of sugar beet root aphids poses a challenge due to limited registered insecticides and the absence of rescue treatments. Consequently, addressing this pest in sugar beets relies heavily on the utilization of resistant varieties and the implementation of cultural control practices. This strategic approach aims to mitigate the impact of root aphids by incorporating plant varieties with inherent resistance and adopting specific agricultural practices that disrupt the pest's life cycle or limit its proliferation.

4.5. Flea Beetles (Chrysomelidae)

Beet flea beetles, characterized by their small black to bronze shiny bodies measuring up to 2 mm in length, possess well-developed hind legs that allow them to jump when disturbed. Apart from beets, they also find other host plants such as *Polygonum* spp. and mangolds suitable for their feeding.

Symptoms: The feeding activity of beet flea beetles leaves small pits in the cotyledons and young leaves, evolving into distinct holes often described as 'shot-holing' as the foliage expands. In cases of severe infestation, the green leaf area of the plants may be significantly reduced, rendering them more susceptible to herbicide damage. The distinctive shot-holding pattern serves as a visible indicator of the beetle's feeding impact on the plants.

Control: Maintain fields free of weeds, especially targeting the elimination of field bindweed and mustard. These weeds are preferred hosts for flea beetles. Implementing integrated pest management practices can contribute to the effective control of flea beetles in beet fields, promoting healthier crops and minimizing economic losses.

4.6. Cutworms (Noctuidae) *Agrotis* spp.

Cutworms are particularly notorious for their method of feeding. They often cut through the stems of young plants near the soil surface, causing the plants to topple over. This cutting behavior is where they get their name. As they feed, they may move along a row of plants, leaving a trail of devastation in their wake. The damage caused by cutworms to sugar beet plants is noted to be similar to that caused by leatherjackets. Leatherjackets are the larvae of crane flies, and like cutworms, they can also feed on the roots and lower stems of plants.

4.7. Wireworms (Elateridae)

Wireworms are the larval stage of click beetles, and they are notorious for their subterranean feeding habits that can cause significant damage to crops, including beets. These larvae have a hard, slender, and cylindrical body, resembling a wire, which is how they got their common name. Their feeding activity can lead to various issues, including stunted growth, reduced vigor, and potential yield losses. The tunnels they create in the soil can interfere with the plant's ability to take up water and nutrients, further contributing to growth problems. Managing wireworm infestations can be challenging due to their subterranean lifestyle.

4.8. Thrips (Thripidae)

Thrips are tiny, slender insects that can indeed become problematic for beetroot plants and other crops. These diminutive intruders use their mouthparts to pierce plant tissues and feed on the cell contents, resulting in characteristic stippling and distortion of leaves. Thrips feeding can cause a silvering or bronzing of the affected plant parts.

4.9. Whiteflies (Aleyrodidae)

Whiteflies are small, winged insects that can indeed cause significant issues for beetroot plants and various other crops. Whiteflies feed on plant sap by piercing the plant tissue with their needle-like mouthparts. This feeding can lead to yellowing, distortion, and wilting of beetroot leaves. The damage is often more pronounced on the undersides of leaves where whiteflies tend to feed.

4.10. Spider Mites (Tetranychidae)

Spider mites feed on plant sap by puncturing the cells with their needle-like mouthparts. This feeding causes stippling, a characteristic pattern of tiny, light-colored dots on the leaves, as well as discoloration and overall diminished vigor in beetroot plants. Monitoring beetroot plants regularly for signs of spider mite infestations and implementing appropriate control measures promptly are crucial for managing these pests effectively.

4.11. Slugs and Snails (Gastropoda)

Under the cloak of cool and moist conditions, slugs and snails emerge as leaf-chomping marauders, leaving irregular holes in their wake and contributing to the challenges faced by beetroot crops.

To fortify the beetroot stronghold against these adversaries, the strategic arsenal of Integrated Pest Management (IPM) beckons. Through the deployment of natural predators, thoughtful crop rotation, and targeted pesticides, the resilience of beetroot crops can be safeguarded. Vigilant monitoring and timely intervention emerge as the vanguards in the relentless battle against these formidable foes.

5. Integrated Pest Management

5.1. Definition

Integrated Pest Management (IPM) is an innovative and eco-conscious strategy that artfully weaves together a tapestry of practices to masterfully control pests while treading lightly on the environment. This holistic approach delves deep into the intricate dance of pest biology, unravelling their life cycles and interactions with the environment. IPM is a symphony of control methods, seamlessly blending cultural, biological, and mechanical interventions, and resorting to chemical measures only when absolutely essential. The overarching objective of IPM is an economic mastery of pest management, executed with a delicate touch to safeguard people, property, and the environment from unnecessary hazards.

Integrated Pest Management (IPM) unfolds as a strategic symphony in the realm of pest control, orchestrating a masterful dance between nature and human ingenuity. The ballet of control encompasses a series of intricately choreographed steps:

Set Action Thresholds: Integrated Pest Management (IPM) adopts a strategic approach by establishing an action threshold, a specific point determined by pest populations or environmental conditions, signalling the necessity for pest control. Contrary to reacting impulsively to individual pests, IPM acknowledges that a single sighting may not warrant immediate action. The decisive factor is the economic threat level, representing the point at which pests can cause significant damage, guiding the timing and necessity of future pest control measures. This ensures a balanced and economically informed approach to pest management, minimizing unnecessary interventions while addressing potential threats effectively.

Monitor and Identify Pests: Integrated Pest Management (IPM) recognizes that not every insect, weed, or living organism necessitates control; many are harmless or even beneficial. To ensure judicious decision-making, IPM programs focus on thorough monitoring and accurate identification of pests. This proactive approach, aligned with predetermined action thresholds, prevents the unnecessary use of pesticides. By avoiding interventions when not required and ensuring the right pesticides are chosen when needed, IPM promotes environmentally conscious and targeted pest management strategies.

Prevention: Integrated Pest Management (IPM) prioritizes proactive measures as the initial defence against pests, focusing on the management of crops, lawns, or indoor spaces to prevent pest threats. In agriculture, this involves employing cultural methods like crop rotation, selecting pest-resistant plant varieties, and using pest-free rootstock. These methods are not only highly effective and cost-efficient but also pose minimal risk to both people and the environment. By emphasizing preventive strategies, IPM aims to create resilient and sustainable systems that mitigate the need for more intrusive pest control measures.

Control: In the Integrated Pest Management (IPM) approach, once monitoring and identification reveal the need for pest control, and preventive measures prove inadequate, a careful evaluation is conducted. IPM prioritizes effective and low-risk control methods, opting for highly targeted options like pheromones to disrupt pest mating or mechanical controls such as trapping or weeding. If on-going monitoring indicates that these less risky strategies are ineffective, more intensive methods, like targeted pesticide spraying, may be employed. However, IPM underscores the importance of minimizing environmental impact, with broad-spectrum pesticide broadcast spraying reserved as a last resort measure. This systematic decision-making process ensures a balanced and environmentally responsible approach to pest control.

5.2. The role of IPM in sustainable agriculture

Applies sustainable pest control: Integrated Pest Management (IPM) is rooted in harnessing ecosystem services, leveraging natural processes like pest predation while safeguarding vital functions such as pollination. By promoting a harmonious balance in the ecosystem, IPM contributes significantly to enhanced farm productivity and increased food availability. This is achieved through the systematic reduction of pre- and post-harvest crop losses, emphasizing a sustainable and holistic approach to pest management that benefits both agricultural production and the broader environment.

Reduces pesticide residues: Integrated Pest Management (IPM) plays a crucial role in ensuring food and water safety by actively minimizing the reliance on pesticides. Through its strategic approach, IPM reduces the overall use of pesticides, consequently lowering the residues in food, feed, fiber, and the environment. This not only mitigates potential health risks associated with pesticide residues in consumables but also contributes to the broader goal of environmental protection. By emphasizing sustainable and targeted pest management practices, IPM underscores its commitment to enhancing both food safety and the health of ecosystems.

Enhances ecosystem services: Integrated Pest Management (IPM) operates with the overarching goal of preserving the balance within the national crop ecosystem. In doing so, it not only aims to safeguard the essential natural resource base, including soil, water, and biodiversity but also actively enhances ecosystem services. By promoting practices that support pollination, maintain healthy soils, and preserve the diversity of species, IPM contributes to the overall sustainability and resilience of the agricultural landscape. This approach reflects a commitment to long-term environmental health and the harmonious coexistence of agricultural activities with the surrounding ecosystems.

Increases income levels: Integrated Pest Management (IPM) provides a dual benefit for farmers by lowering production costs through a reduction in pesticide use and enhancing crop quality. By employing targeted and efficient pest management strategies, IPM minimizes the need for excessive pesticide applications. This not only decreases the financial burden on farmers but also results in higher quality crops with fewer pesticide residues. Such high-quality produce often commands better prices in markets, ultimately contributing to increased farmer profitability. IPM, therefore, serves as a financially prudent and sustainable approach, aligning economic gains with environmental responsibility.

Strengthens farmer knowledge: Integrated Pest Management (IPM) fosters farmer stewardship by empowering them with knowledge tailored to their local context and the functioning of the ecosystem. By providing farmers with a deeper understanding of the intricacies of their specific environment, including the relationships between pests, crops, and beneficial organisms, IPM encourages a more informed and sustainable approach to agriculture. This knowledge equips farmers to make sound decisions, adapt their practices to local conditions, and actively participate in the stewardship of their agricultural ecosystems. Ultimately, IPM promotes a collaborative and ecologically sensitive partnership between farmers and their environment.

5.3. Benefits of IPM in Beetroot Cultivation

Environmental Sustainability: IPM promotes environmentally friendly pest control methods, minimizing the use of harmful chemicals. This approach reduces the impact on non-target organisms, soil, water, and air quality, contributing to overall environmental health.

Preservation of Beneficial Organisms: By emphasizing biological control methods, IPM helps conserve natural enemies of pests, such as predators and parasites. This preservation of beneficial organisms contributes to the overall balance of the ecosystem and reduces the likelihood of pest resurgence.

Reduced Pesticide Residues: IPM strategies aim to limit the use of pesticides, leading to lower residues in harvested beetroot. This benefits consumers by ensuring food safety and reduces the risk of pesticide-related health issues.

Cost-Effectiveness: While the initial implementation of IPM may require investment, it often proves cost-effective in the long run. By reducing the reliance on chemical inputs, farmers can cut down on pesticide costs, leading to economic benefits.

Resistance Management: The judicious use of pesticides in IPM helps mitigate the development of pesticide-resistant pest populations. Rotating pesticides and incorporating diverse control methods hinder the adaptation of pests to specific chemicals.

Integrated Approach: IPM integrates various control strategies, including biological, cultural, and mechanical methods, providing a comprehensive and flexible framework. This adaptability allows farmers to tailor pest management strategies to the specific needs and conditions of their beetroot crops.

Community and Stakeholder Support: Sustainable and environmentally friendly farming practices, such as IPM, often garner support from communities, consumers, and stakeholders. This positive perception can contribute to the marketability of beetroot products.

5.4. Challenges of IPM in Beetroot Cultivation

Educational Barriers: Farmers may face challenges in adopting IPM practices due to a lack of awareness or understanding of these integrated approaches. Educational programs and outreach efforts are essential to facilitate the adoption of IPM.

Initial Implementation Costs: Implementing IPM practices may involve upfront costs for training, monitoring equipment, and initial adjustments to farming practices. Some farmers may perceive these costs as a barrier to adopting IPM.

Knowledge and Skill Gaps: Successful IPM implementation requires knowledge of pest biology, monitoring techniques, and the integration of various control methods. Farmers may face challenges in acquiring the necessary skills and expertise.

Resistance to Change: Traditional farming practices, especially reliance on chemical inputs, may be deeply ingrained. Resistance to change, whether due to cultural factors or scepticism about the effectiveness of alternative methods, can impede the adoption of IPM.

Complex Decision-Making: Implementing IPM involves making complex decisions based on pest monitoring data, ecological considerations, and economic factors. Some farmers may find it challenging to navigate this complexity without adequate support and information.

Weather and Environmental Variability: External factors such as unpredictable weather patterns and environmental variations can impact the success of IPM strategies. Adapting to these changes requires flexibility and continuous monitoring.

Limited Research and Extension Services: In some regions, the availability of research and extension services focusing on IPM for beetroot cultivation may be limited. Strengthening these services can provide crucial support to farmers in adopting and optimizing IPM practices.

Addressing these challenges and promoting the benefits of IPM in beetroot cultivation requires a collaborative effort involving farmers, researchers, policymakers, and extension services. Overcoming these obstacles can contribute to the long-term sustainability and resilience of beetroot farming systems.

5.5. Sustainable Pest Management Strategies

Biological Control: The escalating resistance of insects, weeds, and pests to traditional pesticides has triggered a concerning cycle of escalating application rates, heightened crop losses, and substantial financial burdens on farmers trapped in a relentless pesticide treadmill (Pimentel, 2005; Oerke, 2006; Heap, 2014). This relentless surge in pesticide usage not only poses a severe threat to crop yields but also poses an alarming risk to the health of farmers, farmworkers, rural communities, and consumers alike (Bell *et al*., 2006; Colborn and Carroll, 2007; Calvert *et al*., 2008; Mills *et al*., 2009; Bergman *et al*., 2013; IARC, 2014; Mesnage *et al*., 2014; Myers *et al*., 2016; Kim *et al*., 2017).

Furthermore, the adverse effects of pesticides extend beyond human health, encompassing detrimental impacts on soil health, water quality, and wildlife habitats (Gilliom *et al*., 2007; Wightwick *et al*., 2010; Pisa *et al*., 2014; Stone *et al*., 2014; Stehle and Schulz, 2015). The existing system of subsidizing specific commodity crops inadvertently encourages monocultures, fostering an inefficient use of resources in their production (Fausti, 2015). The non-market costs associated with these detrimental impacts, although challenging to quantify precisely, cast a substantial global burden (Muller *et al*., 2017).

In response to this escalating crisis, Integrated Pest Management (IPM) and organic agriculture emerge as transformative approaches, offering viable alternatives that reduce dependence on conventional pesticides. Emphasizing ecological balance, biological control stands out as a scientifically grounded and environmentally responsible strategy applicable in both organic and conventional farming systems. IPM, as a comprehensive decision-making process, incorporates a suite of science-based tactics, underscoring its relevance and efficacy in addressing the pressing challenges faced by both agricultural paradigms.

Precision Agriculture and Technology: Precision agriculture, often referred to as smart farming, involves the use of advanced technology to optimize various aspects of farming, including pest management. Modern technologies such as drones, sensors, and data analytics play a crucial role in improving the efficiency, sustainability, and productivity of agricultural practices. Here's a discussion on their role in optimizing pest management and showcasing precision agriculture techniques that minimize input usage and reduce environmental impact:

5.6. Drones in Pest Management

Aerial Surveillance: Drones, armed with advanced cameras and sensors, play a pivotal role in modern agriculture by offering real-time aerial surveillance of fields. This technology empowers farmers to closely monitor the health of their crops, enabling the early detection of potential issues such as pest infestations or disease outbreaks. By providing timely and detailed insights, drones contribute to more efficient and proactive agricultural management, allowing farmers to implement targeted interventions and ultimately enhance crop yields.

Precision Spraying: Drones equipped with precision spraying systems represent a transformative advancement in agriculture, enabling the targeted application of pesticides exclusively to affected areas. This precision technology not only optimizes resource utilization but also significantly reduces the overall use of chemicals, mitigating potential environmental impact. By precisely delivering treatments where they are needed, these drones contribute to more sustainable farming practices, promoting both environmental conservation and cost-effectiveness for farmers.

Data Collection: Drones, equipped with high-resolution cameras and sensors, capture detailed images and data from agricultural fields, forming a valuable dataset that can be analyzed through machine learning algorithms. This sophisticated analysis enables the mapping of the extent of pest damage with precision, providing farmers with crucial insights into the specific areas affected. By leveraging machine learning, the collected data assists in making informed decisions on pest control strategies, allowing for targeted interventions and more effective management practices. This integration of drone technology and artificial intelligence enhances the efficiency of pest control measures, contributing to improved crop protection and overall agricultural productivity.

5.7. Sensors and IoT in Pest Monitoring

Soil Sensors: The sensors on drones play a crucial role in monitoring soil conditions and supplying valuable information regarding the presence of pests or diseases in the soil. By conducting real-time assessments, these sensors empower farmers with timely data to detect potential threats early on. Armed with this information, farmers can implement preventive measures or apply targeted treatments, minimizing the risk of crop damage and optimizing resource utilization. This proactive approach facilitated by drone technology contributes to more sustainable and efficient agricultural practices, supporting farmers in making informed decisions to enhance crop health and overall yield.

Weather Stations: Drones equipped with sensors that collect data on temperature, humidity, and other weather parameters play a critical role in monitoring weather conditions for agricultural purposes. This information is invaluable for farmers as it aids in predicting and responding to potential pest threats. By continuously gathering data from the air, these sensors enable a comprehensive understanding of the environmental conditions that influence pest behavior. This proactive monitoring allows farmers to anticipate pest outbreaks and take timely measures, such as adjusting planting schedules or implementing targeted pest control strategies. The integration of weather-monitoring drones enhances the resilience of agriculture by providing farmers with the tools to respond effectively to dynamic environmental conditions and safeguard their crops.

5.8. Data Analytics for Decision-Making

Predictive Modeling: Utilizing advanced analytics and machine learning models, drones can analyze historical data to predict potential pest outbreaks in agricultural fields. This proactive approach enables farmers to receive early warnings about the likelihood of pest infestations, allowing them to plan and implement interventions strategically. By leveraging predictive capabilities, farmers can reduce their reliance on reactive pest control measures, fostering a more efficient and sustainable approach to crop management. The integration of technology-driven predictive analytics not only enhances the precision of pest management but also empowers farmers to make informed decisions and optimize resource allocation, ultimately contributing to improved crop yields and agricultural sustainability.

Integration of Data Sources: An integrated approach to pest management involves combining data from diverse sources such as satellite imagery, weather data, and on-farm sensors to create a comprehensive view of the farm's ecosystem. By assimilating information from these various channels, farmers gain a holistic understanding of the factors influencing pest dynamics. This integrated data approach facilitates more informed decision-making for pest management. Farmers can analyze trends, anticipate potential risks, and deploy targeted interventions effectively. The synergy of satellite imagery, real-time weather data, and on-farm sensor information provides a powerful toolset, empowering farmers to optimize their pest control strategies, reduce environmental impact, and enhance overall agricultural productivity.

5.9. Precision Agriculture Techniques to Minimize Inputs

Variable Rate Technology (VRT): Variable Rate Technology (VRT) is a significant advancement in agriculture that enables farmers to adjust the rate of inputs, such as fertilizers and pesticides, based on the specific needs of different areas within a field. This precision application is achieved through the use of technology, including GPS and sensor systems, allowing farmers to tailor the application of inputs according to the varying soil conditions, crop requirements, and pest pressures across their fields. By implementing VRT, farmers can minimize overuse and reduce wastage of inputs, leading to more efficient resource utilization and cost-effectiveness. This targeted approach not only promotes sustainable farming practices but also contributes to environmental conservation by mitigating the potential negative impacts associated with excessive chemical use in agriculture.

Smart Irrigation Systems: IoT-enabled irrigation systems represent a cutting-edge technology in agriculture, offering the ability to optimize water usage and enhance crop health. These systems utilize sensors and real-time data to monitor soil moisture levels, weather conditions, and crop water requirements. By dynamically adjusting irrigation schedules based on these factors, farmers can prevent waterlogging and minimize the risk of waterborne diseases in crops. This precision in water management not only conserves a valuable resource but also contributes to sustainable farming practices. The integration of IoT in irrigation systems allows for more efficient and targeted water delivery, promoting healthier crops and overall improved agricultural productivity.

Crop Rotation and Cover Crops: The integration of traditional agricultural practices with modern data analytics represents a holistic approach that can break pest cycles and enhance soil health, consequently reducing the reliance on chemical inputs. By combining time-tested methods with advanced analytics, farmers can leverage historical knowledge and real-time data to make informed decisions about crop rotation, cover cropping, and other sustainable practices. This integrated approach allows for a more comprehensive understanding of the ecosystem, helping to break the cycles of pests and diseases. Moreover, it promotes soil health through natural processes, such as nutrient cycling and microbial activity, which in turn reduces the necessity for synthetic chemical inputs. The synergy of traditional wisdom and modern analytics contributes to a more sustainable and environmentally friendly approach to agriculture.

5.10. Environmental Impact Reduction

Ecosystem Preservation: Precision agriculture plays a crucial role in minimizing the impact on non-target organisms and ecosystems by precisely targeting areas in need of treatment. Through the use of advanced technologies such as GPS, sensors, and data analytics, farmers can apply inputs such as pesticides and fertilizers with high accuracy, focusing only on the specific areas that require attention. This targeted approach reduces the overall amount of chemicals used, minimizing the potential harm to non-target organisms and the broader ecosystem. By optimizing resource utilization and minimizing environmental impact, precision agriculture promotes a more sustainable and eco-friendly farming paradigm, balancing the need for efficient crop management with environmental conservation.

Reduced Chemical Footprint: The adoption of technology in agriculture, specifically for precision application of pesticides and fertilizers, allows farmers to significantly reduce the overall chemical footprint on their fields. Through the use of advanced equipment, sensors, and data analytics, farmers can target specific areas with precision, applying the necessary inputs only where needed. This targeted approach minimizes the amount of chemicals used, reducing the environmental impact associated with overuse. By optimizing the application of pesticides and fertilizers, farmers contribute to more sustainable and eco-friendly agricultural practices, promoting environmental stewardship and preserving the health of ecosystems surrounding their fields.

In summary, the integration of modern technology in precision agriculture offers sustainable and efficient solutions for pest management. By leveraging drones, sensors, and data analytics, farmers can make informed decisions, optimize input usage, and contribute to a more environmentally friendly and economically viable agricultural sector.

6. Conclusion

In conclusion, this systematic review provides a thorough examination of Integrated Pest Management (IPM) strategies in the context of beetroot cultivation. The synthesis of diverse studies highlights the multifaceted nature of IPM approaches, encompassing biological control, cultural practices, and chemical interventions. Through the exploration of trends, challenges, and successes in implementing these strategies, this review offers a holistic understanding of the current landscape of pest management in beetroot agriculture. The findings underscore the importance of adopting a diversified approach, integrating various methods for optimal results. Furthermore, the review serves as a valuable resource for researchers, practitioners, and policymakers, offering a comprehensive overview that can inform decision-making in sustainable pest management. Moving forward, continued research and practical applications guided by the insights presented here will be instrumental in refining and enhancing IPM strategies for the benefit of beetroot cultivation and broader agricultural sustainability.

Compliance with ethical standard

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No conflict of interest to be disclosed.

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