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Behavioural Manipulation of Insect Pests in Integrated Pest Management

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ABSTRACT: The threat posed by the usage of insecticides in reducing the damage caused by insect pests has led to an expansion in the potential scope of managing these insect pests by manipulating their behaviour via external and internal cues. Here in this review, we explore techniques for manipulating behaviour through the utilization of natural and/or artificial signals, such as pheromones, kairomones, vibrations, and sounds. It fits seamlessly within IPM's multi-disciplinary framework, as it combines biological, ecological, and chemical approaches to pest management. We place particular emphasis on three types of behavioural manipulation methods using stimuli to reduce pest damage: (a) chemical stimuli (e.g., sex pheromones for monitoring, mass trapping, mating disruption, attract and kill), (b) visual stimuli, and (c) host plant volatiles (including attractants, repellents, stimulants, and deterrents). It is crucial to comprehend the fundamental behavioural patterns in insects to effectively manipulate their behaviour, and we delve into the potential of these techniques for environmentally sustainable insect pest management strategies.

Keywords: Behavioural manipulation, IPM, chemical stimuli, visual stimuli, host plant volatiles, sustainability.

INTRODUCTION

Crop losses represent an impending danger to the welfare of individuals, to the economies of trade and government on a comprehensive scale, and to worldwide food security. On national and regional scales across various continents, the impact of pests and diseases on crop yields has been approximated to fall within the bracket of 20% to 40% for essential food and cash crops (Oerke, 2006). The insect pests alone are thought to be responsible for the loss of over 18–20% of global food production (Sharma *et al*., 2017; Rakesh *et al*., 2023). According to the Food and Agriculture Organization of the United Nations, invasive insects cost the global economy over $70 billion annually (https://www.nifa.usda.gov/). In Indian economy, agriculture industry plays a significant role by accounting around 20 per cent GDP (Gross Domestic Product) (Balkrishna *et al*., 2021). Additionally, crop losses can have repercussions extending far beyond agricultural fields since a decline in production can influence complete rural communities and areas, markets and overseas sales, and, at the most comprehensive level, the provision of sustenance for the global populace (Cerda, 2017). The use of chemical pesticides continues to play a dominant role in the management of these insect pests owing to their quick effectiveness, ease of use, and broad range of action (Deguine *et al*., 2021). However, the indiscriminate use of insecticides has harmful negative consequences for the environment, human health, and beneficial organisms (Mishra, 2020). The excessive use of these xenobiotics/insecticides promotes the emergence of resistance insect pest populations, resurgence, and pesticidal residual accumulation (De Franca, 2013). In recent times, pest control methods that depend on pesticides are progressively being substituted with greener alternatives that promote ecological farming intensification and diminish human interventions, especially insecticides (Garibaldi *et al*., 2019). In this context, scientists are currently engaged in crafting ecologically and environmentally sustainable integrated pest control methods. One of these methods revolves around modifying a pest's behaviour by utilizing communication disruption techniques. These techniques aim to disrupt the pest's usual behaviours with the goal of mitigating their adverse impact on crop yields.

The idea of controlling a pest's behaviour to protect a resource is not a novel concept. Nevertheless, the interest in managing insect pest populations through behavioural methods has increased in recent decades, in part due to advancements in analytical technology and a growing commitment to reduce dependence on broad-spectrum insecticides (Oerke, 2006). Insect behaviour can be categorized into two types: innate or stereotyped behaviour (which is genetically inherited and can be influenced by experience or learning) and learned behaviour (which is not inherited but acquired through interactions with the environment) (Awasthi, 2001; Agarwal and Sunil 2020). Inputs to behaviour, and more specifically, the stimuli that provide these inputs, are commonly employed to modify the behaviour of insects (Haynes, 1988). Insect behaviour is influenced not only by external stimuli but also by a multitude of both external and internal stimuli (Carde *et al.*, 1995). Consequently, insect behaviour arises from the integration by its central nervous system (CNS) of various inputs originating from stimuli acting on proprioceptors (which perceive the relative positions of body parts), enteroceptors (which perceive the internal physiological condition of the insect), and exteroceptors (which perceive external events affecting the insect) (Carde *et al*., 1995). Alterations to the inputs or the way the central nervous system processes these inputs are necessary to manipulate behaviour (Rodriguez-saona and Stelinski, 2009). Behavioural manipulation techniques for managing insect pests entail disrupting core behaviours, particularly feeding and mating, through the utilization of natural and/or artificial signals, such as pheromones, kairomones, vibrations, and sounds (Agarwal and Sunil 2020). This technology aligns effectively with interdisciplinary approaches. Behavioural manipulation fits seamlessly within IPM's multi-disciplinary framework, as it combines biological, ecological, and chemical approaches to pest management. By harnessing the natural behaviours of insect pests, IPM offers a sustainable and effective way to control their populations while promoting long-term agricultural and environmental health.

Integrated Pest Management (IPM) is an essential approach in modern agriculture aimed at effectively managing pest populations while minimizing environmental harm and reducing reliance on chemical pesticides. IPM is based on usage of multiple methods to maintain insect pests below economic threshold level (ETL) in the fields. Recent advancements in IPM *viz.*, biopesticides, microbial products, semiochemicals and beneficial insects which are implemented successfully in developing countries like India (Geedi and Reddy 2023). A key facet of IPM involves the behavioural manipulation of insect pests, which is an innovative and environmentally sustainable strategy. This approach seeks to disrupt or modify the normal behaviours of insect pests to reduce their negative impact on crop production. Behavioural manipulation in IPM includes various techniques, such as the use of pheromones, which are chemical signals insects use to communicate, and altering the physical environment to deter or confuse pests. These approaches are ecologically sound, as they target specific pests without harming beneficial insects or contaminating the environment with chemicals. The present review underscores the significance of comprehending and altering the behaviour of insect pests to mitigate their detrimental influence on crops and ecosystems.

CONCEPT OF BEHAVIOURAL MANIPULATION

The definition of manipulation as per Foster and Harris (1997) is, "the use of stimuli that either stimulate or inhibit behaviour and thereby alter its expression." There are three essential components of behavioural manipulation methods: the behaviour of the pest, the means by which behaviour is appropriately modified, and the method employing behavioural manipulation to protect resources from pests. It is more likely that modifying a pest's problematic behaviour, such as resource consumption, or a closely related behaviour, such as locating the resource, will be effective for pest management compared to manipulating a behaviour unrelated to the resource, like mating. Stimuli are utilized to manipulate a pest's behaviour with the goal of safeguarding valued resources. Methods are categorized into two groups: those that influence behaviour from a longer distance (e.g., volatile chemicals, visual and auditory cues) and those that affect behaviour at shorter distances (<1 cm), including volatile chemicals. Resource protection from pests is typically achieved by insecticide poisoning, but it can also involve altering pest behaviour. The concept of controlling pest activity to safeguard resources is not new; trap cropping, a practice in which a valuable resource is used as bait to divert pest attacks, has been known for centuries (Foster and Harris 1997). There are three types of behavioural manipulation methods: (a) chemical stimuli (e.g., sex pheromones for monitoring, mass trapping, mating disruption, attract and kill), (b) visual stimuli, and (c) host plant volatiles (including attractants, repellents, stimulants, and deterrents). As per Rodriguez-Saona and Stelinski (2009), the choice of a stimulus for behavioural manipulation typically relies on several features (attributes of stimuli), akin to those illustrated in Fig. 1.

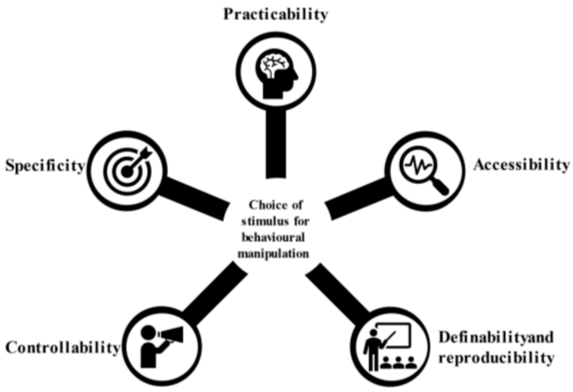

Fig. 1. Attributes of a stimulus for behavioural manipulation.

BEHAVIOURAL MANIPULATION APPROACHES FOR SUSTAINABLE INSECT PEST MANAGEMENT

Behavioural manipulation approaches represent innovative and sustainable solutions for insect pest management in agriculture and ecosystem protection. These strategies leverage the intricate behaviours of insects, harnessing their natural instincts for the benefit of pest control. The fundamental principle underlying these methods is to disrupt critical aspects of the insect's life cycle, such as mating, feeding, or orientation, by employing various stimuli. One of the distinguishing features of behavioural manipulation is its eco-friendly nature. These approaches minimize the need for chemical pesticides, reducing the environmental footprint and protecting non-target organisms. Moreover, they align with the principles of integrated pest management (IPM), emphasizing sustainable, holistic, and multifaceted strategies to mitigate pest damage. In this exploration of behavioural manipulation approaches, we delve into various methods and their applications, highlighting their role in fostering sustainable pest management practices.

A. Chemical stimuli

In contrast to vertebrates, insects employ chemical communication to a greater extent, particularly when interacting with conspecifics (members of their own species). Insects emit chemicals for various purposes and rely on specific chemoreceptors to sense their environment. Chemical communication is an essential element of an insect's survival strategy, allowing them to adapt their behaviour in response to their surroundings. In this context, the sex pheromone stands out as the most widely recognized species-specific pheromone, exerting a powerful attraction on individuals of opposite sexes for mating (Abd El-Ghany, 2020).

The initial identification and synthesis of moth sex-attractant pheromones were first documented more than four decades ago (Arn, 1992). Subsequently, sex pheromones have been discovered for various pests, particularly lepidopterans (Rodriguez-saona and Stelinski, 2009). These compounds offer distinct advantages for the attract-and-annihilate approach due to their specificity, long-distance effectiveness in eliciting responses, and durability in the field. However, instead of being primarily utilized in the attract-and-annihilate strategy, the majority of sex pheromones have been deployed in monitoring or mating disruption methods, often due to their production by females and their ability to elicit responses from males. For instance, the citrus flower moth in Israel and stored product pests in warehouses are cases in point. The limitation of sex pheromones attracting only males can be surmounted by combining them with female attractants. Such a combination is expected to be more effective in the attract-and-annihilate approach than using either attractant alone. For instance, a combination of pheromones with food lures like phenethyl propionate, eugenol, and geraniol, which predominantly attract females, has been successfully employed against the Japanese beetle, *Popillia japonica* Newman. Aggregation pheromones, which attract both sexes and, in some cases, immature individuals (e.g., nymphs of the German cockroach, *Blatella germanica* (Linnaeus)), are well-suited for the attract-and-annihilate method. Aggregation pheromones have proven effective in controlling various coleopterans, including the cotton boll weevil and bark beetle (Foster and Harris 1997). The specificity of pheromones and their remarkable ability to detect minute levels have been key factors in utilizing these chemicals as a potential management tool (Agarwal and Sunil 2020). Sex pheromones are primarily employed in three ways: monitoring, mating disruption, and attract-and-annihilate.

Monitoring. Sex pheromones serve various purposes in pest management and monitoring, including (a) assessment of the density of natural enemies: evaluating the abundance of beneficial organisms that prey on or parasitize pest insects (b) assessment of pest phenology: studying the life cycle and seasonal patterns of pest insects (c) assessment of the effectiveness of mating disruption: gauging the success of methods designed to interfere with the mating behaviour of pests (d) monitoring of insecticide resistance: keeping track of the development of resistance in pest populations to insecticides (e) decision support: providing data and information to aid in making informed pest management decisions.

These applications help establish crucial information such as adult emergence timing, pest population size, temporal distribution, and early detection of pest outbreaks. Accurate pest population estimates can be obtained by strategically placing traps in fields or orchards containing appropriate sex pheromones (Agarwal and Sunil, 2020). Various types of pheromone dispensers are used, including hollow fibres, plastic laminates, impregnated ropes, twist ties, wax formulations, polyethene vials, sol-gel polymers, and rubber septa (Vacas *et al*., 2009). For example, sex pheromones are employed in the monitoring of pests like the gypsy moth (*Lymantria dispar* L.), *Heliothis* spp., and codling moth. Aggregation pheromones are utilized to monitor pests like the boll weevil and plum curculio etc. (Tewari *et al*., 2014).

Mass trapping. The fundamental idea behind this strategy is that by placing traps in the field, a substantial number of pests can be captured, significantly impeding their ability to reproduce and generate a new generation of pests. Pheromones can be utilized for mass trapping of sexually active individuals, often males, with the aim of reducing pest population density and curtailing their reproductive potential. It is also employed for the direct suppression of insect pest populations (Agarwal and Sunil, 2020). Mass trapping involves the use of pheromone-baited traps to capture a significant portion of the pest population before they mate, lay eggs, or cause damage to crops (Rodriguez-saona and Stelinski 2009). This method yields effective results when a lure is combined with a trap. It is particularly effective for geographically isolated pests and when pest densities are low (El-Sayed *et al*., 2009). Regular trap replacement is essential. The mass-trapping strategy has been applied to pests belonging to the orders Lepidoptera, Coleoptera, and Diptera (Tewari *et al*., 2014). It tends to be more effective for coleopterans and dipterans compared to lepidopterans (Cork *et al*., 2005). However, because this approach is dependent on pest density, the practical application of mass trapping in IPM programs has been somewhat limited (Rodriguez-saona and Stelinski 2009).

Mating disruption. Mating Disruption, also known as the confusion or decoy method, is an extremely effective approach for managing pest population dynamics. It involves the interference with mating communication by dispersing sex pheromones into the environment (Greenblatt and Lewis, 1983). This process permeates the air with synthetic sex pheromones, making it challenging for insects to locate mates emitting natural pheromones in the treated area (Agarwal and Sunil, 2020). As a result, reproductive rates decrease, and crop protection is achieved, reducing the need for insecticides. This method is widely employed worldwide to control moth pests in various crops, including fruits, vegetables, and forestry (Peshin and Dhawan 2009). Mating disruption is considered environmentally friendly, approved for use in organic and biorational production systems, and has no adverse effects on non-target organisms (Vacas *et al*., 2012). It is effectively implemented against numerous lepidopteran pests, including the pink bollworm, oriental fruit moth, grape berry moth, rice striped stem borer, gypsy moth, and codling moth (Tewari *et al*., 2014). Both mass trapping and mating disruption are viable control strategies for many lepidopteran pests (Teixeira *et al*., 2010).

The attract-and-kill Method, also referred to as "attract-annihilate" (Foster and Harris 1997) or "lure-and-kill" (Rodriguez-saona and Stelinski 2009), is a straightforward strategy for pest management. The goal of this method is to draw pests to a specific location where they can be removed from the environment as efficiently as possible. There are two main variations of the "attract and kill" approach: (a) target device-based: this variant employs a "target device" such as a trap to attract and capture pests (b) natural surface-based: In this approach, pests are attracted to a natural surface, such as host tree foliage, where they are dealt with (Agarwal and Sunil 2020). This method is one of the most commonly used behavioural manipulation techniques for pest management. It not only reduces environmental pollution but also enhances the effectiveness of chemical pest control. Although it bears similarities to mass trapping, it does not require the physical trapping of the target pests. Numerous case studies demonstrate the long-term pest management success of the lure-and-kill method. It has been effectively applied to control pests like the pink bollworm, Egyptian cotton leafworm, apple maggot, biting flies, bark beetles, *Cydia pomonella* Linnaeus (Ioriatti and Angeli 2002), Glossina spp. (Esterhuien *et al*., 2006) and *Bactrocera oleae* (Gmelin)) (Broumas *et al*., 2002) etc. It has also been used to eradicate invasive species like tephritid fruit flies and boll weevils (El-Sayed *et al*., 2009). Additionally, the male annihilation technique (MAT), which involves lacing methyl eugenol with insecticides to suppress Oriental fruit flies, has been successful in managing pests like the *Dacus dorsalis* (Hendel) on Rota Island (Mandanayake *et al*., 2023). PB ropes (Pheromone-Baited Ropes) for pink bollworm management in cotton, specifically in California, where insecticide (permethrin) is incorporated into a sticky substance used to affix the pheromone formulation to the plant's leaves. The application rate is 200 per hectare, as detailed by Patil (2007). PB ropes represent an alternative approach for controlling pink bollworms without causing harm to the ecosystem or its natural enemies, as supported by research studies conducted by Ghauri *et al*. (2019); Mangan and Bouyer (2021). Screwworm flies, specifically *Cochliomyia hominivorax* (Coquerel) and *C. macellaria* (Fabricius), are significant livestock pests in tropical America. These flies lay their eggs in wounds and are drawn to carrion. To control or monitor them, traps are baited with raw meat, often a blend of liver and sodium sulphide. Several of the chemicals in decomposing meat that attract screwworm flies have been identified and employed as an attractant, originally referred to as swormlure. The most effective formulation, now known as swormlure-4, comprises ten components, including butanol, various organic acids, phenols, cresol, indole, and dimethyl disulphide (Hickner *et al*., 2020). The screwworm adult suppression system (SWASS) is composed of a pelletized formulation that incorporates a chemical lure, dried blood as a food source, a feeding stimulant (sugar), and an insecticide. This system is designed for the suppression of adult screwworm flies (Hickner *et al*., 2023).

B. Visual stimuli

Visual stimuli methods in the behavioural manipulation of insect pests are designed to exploit insects' visual perception to alter their behaviour. One common approach involves using visual cues to disrupt mating or guide pests away from crops. Visual stimuli, when used alone, are less commonly employed in insect pest management compared to chemical stimuli. Many insects, including hemipterans and species from various other orders, are attracted to light in the green-yellow region of the spectrum. Extensive research in this area has led to the development of sticky traps designed for monitoring a variety of pests. For example, yellow sticky traps are used for monitoring whiteflies, blue sticky traps are effective for capturing thrips, and white sticky traps are designed for beetles. However, visual stimuli are most frequently utilized in combination with chemical stimuli. This combination enhances the overall effectiveness of pest management methods when compared to the use of either stimulus type in isolation (De Franca, 2013). One effective application of visual stimuli in the behavioural manipulation of insect pests is demonstrated in the management of fruit flies. In particular, the Mediterranean fruit fly (*Ceratitis capitata* (Wiedemann)) is a significant pest of fruit crops worldwide. Researchers have developed and tested a mating disruption technique using visual cues in the form of colour-attracting spheres. These spheres, coated with a specific colour that attracts male fruit flies, are placed in orchards. When male flies are lured to the coloured spheres, they become disoriented and fail to locate female mates, thus disrupting their mating patterns (Baldwin *et al*., 2018). In the management of the codling moth a major pest of apple orchards, researchers have employed the use of visual stimuli in the form of mating disruption ribbons. These ribbons feature a pattern of red and white stripes, mimicking the appearance of female codling moths. When males encounter these ribbons, they are attracted to them, disrupting their ability to locate real females for mating (Knight *et al*., 2017). In cotton farming, the cotton bollworm (*Helicoverpa armigera* (Hubner)) is a significant pest. Visual stimuli in the form of light traps have been effectively used for monitoring their populations. Light traps emit a specific spectrum of light that attracts adult moths. This method helps farmers track pest populations and make informed pest management decisions (Khan *et al*., 2019). For the management of aphid pests in greenhouse crops, blue sticky traps have been used as visual stimuli. Aphids are attracted to the colour blue, and these traps are coated with a sticky substance. When aphids approach the traps, they become stuck, helping to reduce their population (Adam *et al*., 2016).

C. Host plant volatiles

Host plant volatiles (HPVs) are chemical compounds emitted by plants that play a pivotal role in the behavioural manipulation of insect pests. These volatile organic compounds serve as powerful communication tools between plants and insects, influencing the behaviour, feeding patterns, and reproductive activities of herbivorous insects. HPVs can act as attractants, repellents, or disruptors, shaping the dynamics of insect-plant interactions (De Franca, 2013). One of the most well-documented functions of HPVs is their role in attracting insect pests to host plants. Plants release specific volatile blends that serve as olfactory beacons, guiding herbivores to their preferred feeding and breeding sites. However, these same volatile cues can be harnessed to manipulate insect behaviour in pest management strategies. For instance, synthetic blends of host plant volatiles can be used to lure insect pests into traps or disrupt their mating patterns, ultimately reducing their populations (Bruce *et al*., 2011). Research in this field has led to innovative approaches for sustainable pest control, such as the use of HPVs in integrated pest management (IPM) programs. By understanding the chemical language of plants and insects, scientists and farmers can develop targeted and environmentally friendly strategies to mitigate pest damage while minimizing the use of chemical insecticides. In apple orchards infested with codling moths, researchers have employed HPVs to develop a monitoring and management strategy. They used a blend of apple volatiles to attract male moths to traps. This approach allows for the early detection of pest populations, enabling timely intervention (Judd *et al*., 1993). Mating disruption using HPVs has been employed in the management of the peach twig borer (*Anarsia lineatella* Zeller). Researchers used synthetic HPVs to disrupt the communication between male and female moths, reducing mating success and subsequent pest populations (Knight *et al*., 2017).

The Stimulo-Deterrent or Push-Pull strategy is an IPM approach that combines the use of attractants (stimulo) to lure pests away from crops and repellents (deterrent) to deter them from settling on the crops. This strategy aims to manipulate pest behaviour and reduce crop damage (Mazzoni, 2021; Choudhary and Mansion 2023). In maize farming systems in Africa, the African maize stem borer (*Busseola fusca* (Fuller)) is a significant pest. Researchers have implemented the Push-Pull strategy to manage this pest effectively. In this approach, attractive plants, like Napier grass (stimulo), are intercropped with maize to lure the stemborers away from the main crop. Additionally, repellent plants, such as *Desmodium*, are planted as a border crop (deterrent) to deter stemborer movement into the maize fields (Khan *et al*., 2000). In East Africa, the tsetse fly is a vector of African trypanosomiasis, a deadly disease affecting both humans and livestock. The Push-Pull strategy has been adapted for livestock pest control. By using attractive odours (push) to lure tsetse flies away from cattle and combining it with the planting of repellent crops (pull) like Napier grass, farmers can protect their livestock from tsetse fly bites and disease transmission (Khan *et al*., 2007). In wheat cultivation, aphids pose a significant threat as common and destructive pests. To address this issue, Cook *et al.* (2020) in the United Kingdom employed a Push-Pull strategy for efficient aphid management. Their approach involved cultivating wheat as the primary crop and interspersing it with beans (push). Beans naturally release volatile compounds that discourage aphid infestations. Furthermore, the researchers strategically placed pheromone traps in the fields to draw aphids towards them (pull), effectively diverting the pests away from the wheat plants. This innovative strategy resulted in a notable reduction in aphid populations within the wheat fields, consequently decreasing the reliance on insecticides for pest control. In sub-Saharan Africa, maize stands as a crucial staple crop, facing persistent threats from stemborer pests. Midega *et al*. (2021) have successfully implemented the Push-Pull strategy to safeguard maize crops in this region. Their strategy involved the intercropping of maize with *Desmodium* (push), a plant known for its ability to repel stemborer moths effectively. Simultaneously, they introduced Napier grass (pull) to the cropping system to allure and ensnare stemborer pests. This innovative approach yielded remarkable results by substantially diminishing stemborer-related damage to maize plants, ultimately leading to increased yields for smallholder farmers.

FACTORS INFLUENCING THE EFFECTIVENESS OF BEHAVIOURAL MANIPULATION APPROACHES IN PEST MANAGEMENT

Behavioural manipulation approaches being a subset of integrated pest management (IPM) strategies aim to control insect pests by altering their behaviour rather than directly killing them. These approaches have both benefits and risk factors (Fig. 2) associated with their use. The effectiveness of behavioural manipulation approaches can vary depending on the target pest species. Some methods, such as pheromone-based traps or mating disruption, are highly species-specific, while others may have a broader range of effectiveness. Environmental factors, including temperature, humidity, wind speed, and light conditions, can influence the success of behavioural manipulation methods. Inconsistent environmental conditions may reduce the efficacy of pheromone-based traps or disrupt mating patterns (Agarwal and Sunil 2020). Regular monitoring and detection of pest populations are essential to assess the effectiveness of behavioural manipulation methods. Inadequate monitoring can lead to delayed responses and reduced control. The population density of the target pest can influence the effectiveness of behavioural manipulation. High pest densities may overwhelm the disruption or trapping methods. The timing of behavioural manipulation applications is critical. For instance, releasing pheromones or deploying traps at the right developmental stage of the pest or during the appropriate part of the season is crucial for success (Potting *et al*., 2005; Wallingford *et al*., 2017). Like chemical pesticides, pests can develop resistance to behavioural manipulation methods over time. Proper management and rotation of control strategies are important to mitigate resistance (Polajnar *et al*., 2015; Eigenbrode *et al*., 2016). Behavioural manipulation approaches are often most effective when integrated with other IPM strategies, such as biological control, cultural practices, and selective pesticide use.

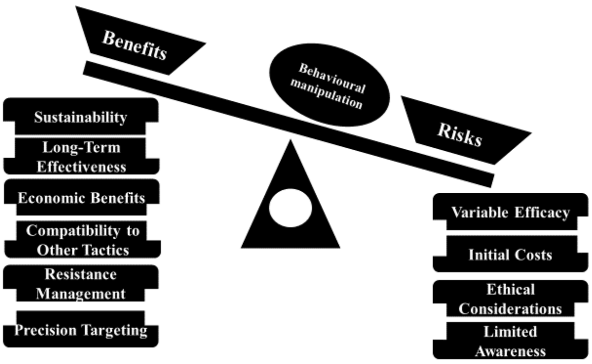

Fig. 2. Benefits and risk factors associated with behavioural manipulation approaches of insect pest management.

PROSPECTIVE FUTURE OUTLOOKS

The behavioural manipulation of insect pests within the framework of Integrated Pest Management (IPM) holds promising future prospects as agriculture continues to evolve and adapt to new challenges. With the advancement of technology, the integration of behavioural manipulation techniques with precision agriculture is on the horizon. Smart sensors, drones, and automated systems can monitor pest populations in real time and deliver behavioural manipulation cues precisely when and where they are needed, minimizing environmental impact and optimizing pest control. The use of genetically modified crops that emit specific host plant volatiles to deter pests or produce pheromones to disrupt mating is a burgeoning area of research. These "smart crops" have the potential to reduce the need for external attractants and repellents, providing sustainable pest control within the plant itself. As climate change alters pest distribution and behaviour, the use of behavioural manipulation can help adapt pest management strategies. Research may focus on developing pest-specific responses to changing environmental conditions, ensuring IPM remains effective under evolving climatic scenarios. As concerns about pesticide residues and environmental impact grow, behavioural manipulation offers an eco-friendly alternative. The future may see a significant reduction in pesticide reliance as IPM programs increasingly prioritize behavioural methods. The future will likely see increased adoption of these methods to meet consumer expectations for environmentally friendly farming practices. Continued research, technological advancements, and global collaboration will be key drivers of progress in this field.

CONCLUSIONS

The use of broad-spectrum pesticides currently dominates insect pest management. But pest control through the manipulation of pest behaviour by utilizing chemical stimuli, visual stimuli and host plant volatiles is gaining momentum over broad-spectrum insecticides because of the stringent restrictions placed on the use of insecticides around the world. Behavioural manipulation is a highly specific, non-toxic and environmentally sustainable replacement tool in IPM and which are expected to play a pivotal role in high-tech crop protection. A meticulous understanding of the behaviour of the pest and its ecology is a must to develop a successful behavioural manipulation tactic. Ultimately the adoption of a behavioural manipulation strategy for the control of insect pests will depend on farmers' view of these strategies (e.g., cost when compared to other current management practices). Therefore, during the development of technologies to alter insect behaviour, there is a wider scope for effective collaboration between firms, academics, extension specialists, members of agribusiness, and farmers.

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