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Integrated Management of White Grubs in Groundnut: Sustainable and Climate-smart Approaches

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ABSTRACT

Groundnut (Arachis hypogaea L.) is an important oilseed and food legume in India, supporting nutritional security, rural livelihoods, and the national oilseed economy, especially in semi-arid regions such as Gujarat. However, its productivity is seriously threatened by white grubs (Coleoptera: Scarabaeidae). The larvae feed on roots and pegs, causing heavy plant mortality and yield losses that can exceed 40% during outbreak years. Damage is particularly severe under rainfed conditions, in light-textured soils, and under increasing climatic variability that influences pest emergence, survival, and spread. This review brings together available research on Integrated White Grub Management (IWGM) in groundnut, with a focus on Indian conditions and Gujarat agro-ecosystems. The evidence clearly indicates that exclusive dependence on chemical insecticides is neither reliable nor sustainable, owing to inconsistent field performance, environmental risks, and regulatory constraints. In contrast, IWGM, by integrating cultural practices such as crop rotation, deep summer ploughing, and timely sowing with biological control agents, mechanical methods, seed treatments, and need-based chemical interventions, provides more effective and environmentally responsible suppression of white grub populations. The coordinated use of these components improves early crop establishment, stabilizes yields under drought and erratic rainfall, and reduces overall pesticide use through judicious, threshold-based applications. Biological control agents, particularly Metarhizium anisopliae and Beauveria bassiana applied at 2.5-5.0 kg ha^{-1} (FYM-based formulations), along with entomopathogenic nematodes (Heterorhabditis spp.) at $2.5\text{-}5.0 \times 10^9$ infective juveniles ha^{-1}, offer sustained soil-level regulation of white grub populations when supported by appropriate agronomic practices. During outbreak situations, targeted application of relatively safer insecticides at economic threshold levels, such as imidacloprid, thiamethoxam, chlorantraniliprole, fipronil, and clothianidin, provides effective corrective control. Overall, IWGM emerges as a climate-resilient, economically viable, and sustainable strategy for managing white grubs in groundnut-based production systems, particularly well-suited to smallholder farmers in semi-arid regions.

INTRODUCTION

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed and food legume crops grown across tropical and subtropical regions of the world. It serves multiple purposes, providing edible oil, human food, livestock fodder, and raw material for several industrial products. Globally, groundnut is cultivated on about 31-32 million ha, with annual production exceeding 50 million tonnes, largely concentrated in Asia and Africa (FAO, 2023). India ranks second in global groundnut production; however, national productivity remains below the global average. This yield gap is mainly attributed to the predominance of rainfed cultivation and the crop's exposure to multiple biotic and abiotic stresses (Reddy, 2017; FAO, 2023). Within India, Gujarat occupies a leading position in groundnut production, particularly in the semi-arid Saurashtra region, where light-textured soils and a heavy dependence on monsoon rainfall strongly influence crop performance (ICAR-DGR, 2020).

Among the various insect pests affecting groundnut, white grubs (Coleoptera: Scarabaeidae) are considered one of the most destructive. Important species such as *Holotrichia serrata*, *H. consanguinea*, and *Anomala dimidiata* damage the crop by feeding on roots and pegs, leading to wilting, plant mortality, and substantial yield losses. Reported losses range from 10% to more than 50% during severe outbreak years (Veeresh, 1988; Anitha *et al*., 2006; Gautam *et al*., 2023). The incidence and severity of white grub infestation are closely linked to soil type, cropping history, rainfall patterns, and the presence of preferred host trees, conditions that are widely prevalent in major groundnut-growing areas of Gujarat.

Management of white grubs has traditionally depended on chemical insecticides. However, this approach has become increasingly problematic due to inconsistent field efficacy, escalating input costs, environmental and non-target effects, and tightening regulatory restrictions (FAO, 2017; Sharma and Reddy, 2020). These challenges are further intensified by climate change, which influences beetle emergence, larval survival, and the frequency and intensity of outbreaks. As a result, white grub management has become more complex and less predictable in semi-arid, rainfed production systems, highlighting the need for more sustainable and climate-resilient management strategies.

MATERIALS AND METHODS

A systematic literature review was conducted following established evidence-synthesis guidelines (Tranfield *et al*., 2003; Moher *et al*., 2009) to evaluate white grub management in groundnut, with particular emphasis on sustainable and climate-resilient Integrated White Grub Management (IWGM) approaches. Relevant peer-reviewed literature was retrieved from Web of Science, Scopus, CAB Abstracts, institutional library journals, and Google Scholar, supplemented by targeted Google searches. AI-assisted tools were used to support literature screening, organization, and synthesis.

The review included peer-reviewed articles, field and laboratory studies, reviews, and meta-analyses relevant to groundnut-based production systems, with a primary focus on India and agro-ecologically comparable regions, especially Gujarat. Information on pest incidence, yield losses, management efficacy, recommended doses, and ecological impacts was synthesized using a thematic and comparative approach to assess the effectiveness and integration of different components within an IWGM framework.

RESULTS AND DISCUSSION

White grub species complex, biology, and damage in groundnut

White grubs, the larval stages of scarab beetles (*Coleoptera*: *Scarabaeidae*), form one of the most damaging soil-dwelling pest complexes of groundnut in India, particularly in rainfed and semi-arid agro-ecosystems. Surveys and long-term studies consistently report a diverse assemblage of economically important species associated with groundnut, primarily belonging to the genera *Holotrichia*, *Anomala*, *Apogonia*, *Schizonycha*, *Adoretus*, *Maladera*, and *Leucopholis* (Veeresh, 1988; Anitha *et al*., 2006; Sharma and Reddy, 2020; Chandel *et al*., 2023).

In western India, especially in Gujarat, *Holotrichia consanguinea* and *H. serrata* are the most prevalent and destructive species. These grubs cause extensive root injury, leading to wilting, plant collapse, and severe yield losses in groundnut fields (Pal, 1977; Veeresh, 1988; Gangwar *et al*., 2015; Kumar and Sagar, 2018). Recent surveys in the Saurashtra region have also documented the presence of *Apogonia rauca*, *Schizonycha ruficollis*, and several *Adoretus* species (*A. bicolor*, *A. deccanus*, and *A. versutus*), underscoring the region-specific and multi-species nature of white grub infestations (Chudasama *et al*., 2019).

The biology of dominant species, particularly *H. consanguinea*, is closely synchronized with monsoonal rainfall. Adult beetles emerge following pre-monsoon or early monsoon showers during May-June and remain active for about 14-28 days. During this period, they feed and mate on host trees such as neem (*Azadirachta indica*), ber (*Ziziphus mauritiana*), and babul (*Acacia* spp.), before laying eggs in moist sandy loam to loamy soils at shallow depths (Veeresh, 1988; Gangwar *et al*., 2015). The egg stage lasts 7-14 days, after which newly hatched larvae move deeper into the soil.

The larval stage, consisting of three instars, is the most destructive and extends from July to September-October, with a total duration of about 60-90 days. Early instars primarily feed on organic matter and fine roots, while later instars progressively inflict greater damage. The third instar, lasting 30-50 days, feeds aggressively on tap roots, pegs, and developing pods, often causing rapid wilting and plant mortality. Damage is most severe when infestation coincides with early crop growth and pegging stages (Anitha *et al*., 2006; Kumar and Sagar, 2018).

With the onset of declining soil moisture, mature larvae migrate to deeper soil layers and enter a quiescent phase, followed by pupation in earthen cells at depths of 20-45 cm during October-November. The pupal stage lasts 14-28 days, after which newly formed adults remain dormant in the soil throughout winter (December-April). Emergence resumes with the onset of the following monsoon, completing a univoltine life cycle typical of *Holotrichia* species (Veeresh, 1988; Gangwar *et al*., 2015). (fig 1)

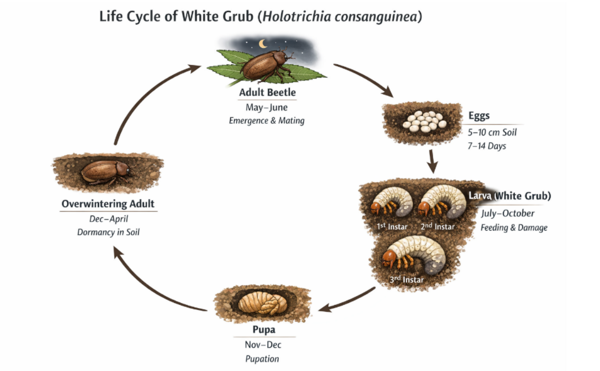

Figure 1. Life cycle of white grub (Holotrichia consanguinea Blanch.) showing seasonal occurrence and duration (days) of different developmental stages. (Source: Compiled and adapted from published reviews and life-history studies on H. consanguinea)

In the Saurashtra region, the combination of light-textured soils, rainfed groundnut monocropping, and the widespread presence of adult host trees creates highly favourable conditions for repeated infestations and sustained white grub pressure (Anitha *et al*., 2006; Gangwar *et al*., 2015; Chudasama *et al*., 2019). Yield losses typically range from 15-30% under moderate infestation levels but may escalate to 40-50% during severe outbreaks, particularly when attacks occur at early crop stages (Bakhetia, 1983; Gangwar *et al*., 2015; Sharma and Reddy, 2020). The coexistence of multiple white grub species with overlapping life cycles further complicates management and highlights the need for integrated, area-wide approaches rather than species-specific control strategies.

Integrated white grub management (IWGM): Conceptual basis

IWGM is a holistic pest management framework that brings together cultural, agronomic, biological, mechanical, and carefully targeted chemical interventions to sustainably suppress white grub populations in groundnut-based cropping systems. White grubs, particularly *Holotrichia* spp., are soil-dwelling and highly polyphagous scarab larvae that damage roots and entire plants. Their subterranean habitat and cryptic life cycle make them difficult to manage using any single control method, highlighting the need for integrated strategies that act across multiple stages of the pest's biology rather than relying on sporadic, short-term control measures (Chandel *et al*., 2018; Patil *et al*., 2025).

In semi-arid agro-ecological regions such as Gujarat, groundnut is predominantly grown under rainfed conditions on light-textured soils, where climatic variability strongly influences pest dynamics. These conditions often favour white grub survival and infestation while simultaneously reducing the consistency and effectiveness of chemical control measures (Bhut *et al*., 2021b). IWGM therefore represents a shift away from reactive, high-dose insecticide use towards prevention, early intervention, and system-level resilience, with particular emphasis on improving soil health and ecological stability.

The IWGM approach integrates a range of complementary tactics, including cultural practices such as deep summer ploughing and soil amendments, the use of biological control agents like entomopathogenic fungi and nematodes, mechanical methods such as grub collection, and need-based application of low-impact insecticides within an overall Integrated Pest Management (IPM) framework (Chandel *et al*., 2018; Patil *et al*., 2025). When applied in a coordinated manner, these components reinforce one another and enhance the durability of control.

By combining compatible management practices, IWGM reduces dependence on chemical inputs, strengthens natural biological regulation, and maintains white grub populations below economic threshold levels. As a result, it supports sustainable and climate-resilient groundnut production by promoting ecological balance and soil-centred pest suppression in vulnerable semi-arid production systems.

Cultural and agronomic management practices under IWGM

Cultural and agronomic practices form the backbone of IWGM in groundnut, offering environmentally sound and cost-effective options for reducing grub populations while simultaneously improving soil health and crop resilience. These practices are particularly critical in semi-arid regions such as Gujarat, where rainfall variability, predominantly rainfed cultivation, and limited input use often reduce the reliability of chemical control when used alone (Pal, 1977; Veeresh, 1988; Gangwar *et al*., 2015).

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Crop rotation plays a key role in disrupting the white grub life cycle by breaking host continuity and creating less favourable soil conditions for larval survival. Rotations involving non-host cereal crops such as sorghum, pearl millet, and maize have consistently been shown to lower grub incidence, whereas continuous groundnut monocropping favours population build-up of *Holotrichia* spp. (Pal, 1977; Anitha *et al.*, 2006; Reddy, 2017). Intercropping groundnut with cereals or castor further modifies the crop microclimate and adult oviposition behaviour, resulting in reduced plant mortality and greater yield stability (Veeresh, 1988; Sharma and Reddy, 2020).

Soil and sowing management practices also contribute significantly to white grub suppression. Repeated deep summer ploughing helps reduce carry-over populations by exposing larvae and pupae to desiccation, predation, and other natural mortality factors (Veeresh, 1988; Parasharya *et al.*, 1994). Sowing time is equally important, as adjusting planting to avoid synchronization with peak adult emergence can minimize early crop damage. In contrast, very early pre-monsoon sowing under irrigated conditions may increase infestation risk by coinciding with adult beetle activity (Bakhetia, 1983; Gangwar *et al.*, 2015).

The effectiveness of cultural and agronomic practices is further enhanced when they are integrated with complementary interventions such as seed treatment, soil-applied insecticides, and balanced nutrient management. Evidence from field studies and reviews indicates that such integrated packages substantially reduce early plant mortality and improve pod yields compared to standalone practices, underscoring their central role within IWGM frameworks (Gangwar *et al.*, 2015; Patel *et al.*, 2020b).

Mechanical and Indigenous Practices within IWGM

Mechanical and behaviour-based practices that target adult scarab beetles are important supportive components of IWGM. Suppression of the adult stage directly reduces egg laying and, consequently, subsequent larval pressure in the soil. Since white grub larvae are difficult to control once established below ground, many reviews emphasize adult-stage management as a critical preventive strategy within IWGM programmes (Gangwar *et al.*, 2015).

Light traps are commonly used to monitor the seasonal emergence and population dynamics of adult scarab beetles. Adult emergence is closely linked to the onset of monsoon rains, and light trap catches serve as an effective early warning system for initiating timely IWGM interventions (Gangwar *et al.*, 2015; Danu *et al.*, 2025). Although light traps alone contribute only limited population suppression, their strategic placement near field boundaries and host trees can reduce local adult densities. More importantly, light traps support accurate decision-making by guiding the timing of complementary measures such as deep summer ploughing, seed treatment, biological control, or targeted soil application of insecticides. Within IWGM, therefore, light traps function primarily as monitoring and decision-support tools rather than standalone control measures (Sushil *et al.*, 2022; Danu *et al.*, 2025).

Pheromone traps provide a more species-specific option for monitoring and suppressing adult *Holotrichia* spp. populations in groundnut ecosystems. Review studies highlight their usefulness in detecting adult emergence, identifying peak flight periods, and facilitating timely implementation of integrated management practices. Strategic deployment of pheromone traps during the early monsoon has been reported to reduce local adult populations and subsequent larval pressure when used as part of a broader IWGM programme (Bhut *et al.*, 2021b).

Mating disruption represents another behaviour-based approach, in which synthetic sex pheromones are used to interfere with mate-finding by saturating the field environment. The identification of female-produced sex pheromone components in *Holotrichia* spp. provided the mechanistic basis for this strategy by clarifying male attraction and mating behaviour (Yasui *et al.*, 2012). Field evaluations in western India have shown that pheromone-based mating disruption applied during peak adult emergence can significantly reduce successful mating and oviposition. When integrated with other IWGM components, this approach resulted in lower larval densities and improved crop establishment in groundnut (Mevada *et al.*, 2023).

Indigenous practices also contribute meaningfully to adult beetle management. Mud pot traps baited with fermented castor seed extract offer a simple, low-cost option for trapping adult beetles. Studies report that such traps can attract 40-55% of emerging *Holotrichia consanguinea* adults during the early monsoon period, thereby lowering beetle pressure in groundnut fields (TNAU, 2015).

Overall, the combined use of light traps for monitoring, along with pheromone and indigenous traps for population suppression, enables early-season reduction of adult beetle populations and limits oviposition. These practices complement cultural, biological, and chemical interventions within IWGM and are particularly valuable in semi-arid, rainfed groundnut production systems (Gangwar *et al.*, 2015; Sushil *et al.*, 2022).

Organic, traditional, and mineral strategies

Traditional, organic, and cow-based amendments offer eco-friendly ways to manage white grubs (*Holotrichia* spp.) in groundnut, especially as part of an integrated approach. These methods work by improving soil health, deterring pests, and enhancing natural biological control.

Plant-based organic amendments: Organic materials like neem cake (*Azadirachta indica*), castor cake (*Ricinus communis*), and vermicompost have been shown to reduce white grub damage when combined with biological agents. Patel *et al.* (2022) reported that applying *Metarhizium anisopliae* with neem or castor cake significantly lowered grub populations and plant mortality while improving groundnut yield. These organic substrates not only suppress pests but also enhance soil fertility and microbial activity.

Cow-based and vedic formulations: Traditional cow-based preparations, such as cow urine-based extracts, Panchagavya, Beejamrut, and Jeevamrut, have been widely used in Indian farming. Rani *et al.* (2013) found that neem and jatropha extracts prepared in cow urine significantly reduced white grub populations and potato tuber damage. These formulations can be applied to soil or used for seed treatment, helping young seedlings establish well while limiting early grub feeding. Although direct studies in groundnut are limited, these methods show promise for integrating with modern IWGM practices.

Mineral-based inputs: Natural minerals like diatomaceous earth (DE) and kaolin clay act as physical barriers to pests. DE abrades insect cuticles, causing dehydration, while kaolin changes soil and root surface properties, making it less favourable for larvae. Though most studies focus on other pests, these minerals can potentially reduce white grub activity when incorporated into the soil (Zeni *et al.*, 2021; Oliveira *et al.*, 2022).

Integration within IWGM: No single organic or cow-based amendment alone can fully control white grubs. However, combining plant-based amendments, cow-based formulations, and mineral inputs with cultural practices (deep ploughing, crop rotation) and biological agents (*Metarhizium anisopliae*, *Beauveria bassiana*) creates a healthier, pest-unfriendly soil environment. This integrated approach reduces dependency on chemical insecticides, promotes ecological balance, and supports sustainable, climate-resilient groundnut production.

Biological control of white grubs under IWGM

Biological control is a central, eco-friendly component of IWGM, particularly well-suited to rainfed and semi-arid groundnut ecosystems where repeated chemical interventions are neither economically feasible nor environmentally sustainable. White grub populations are naturally regulated by a wide range of biological agents, including entomopathogenic fungi, bacteria, entomopathogenic nematodes (EPNs), and vertebrate predators. When appropriately integrated, these natural enemies can be effectively harnessed to provide sustained suppression of grub populations within IWGM frameworks (Veeresh, 1988; Georgis *et al.*, 2006; Chandel *et al.*, 2018).

Among the available biological agents, entomopathogenic fungi (EPF) have shown the greatest and most consistent promise against *Holotrichia* spp. Soil application of *Metarhizium anisopliae* (Bhut *et al.*, 2021b; Chavan *et al.*, 2023; Joshi *et al.*, 2025) and *Beauveria bassiana* (Patel *et al.*, 2022; Yadav *et al.*, 2024) has repeatedly resulted in significant reductions in grub populations and associated plant mortality in groundnut. Their effectiveness is further enhanced when applied along with organic amendments such as neem cake, castor cake, vermicompost, or farmyard manure, which improve soil moisture retention, promote fungal persistence, and increase contact between the pathogen and the host (Chandel *et al.*, 2018; Patel *et al.*, 2022; Joshi *et al.*, 2025). Area-wide field evaluations in Gujarat have demonstrated that integrating *M. anisopliae* or *B. bassiana* with cultural practices and limited chemical inputs can substantially lower grub densities and improve pod yield under IWGM modules (Bhut *et al.*, 2021b).

Entomopathogenic nematodes, particularly *Heterorhabditis indica* and *H. bacteriophora*, also exhibit bioefficacy against white grubs. These nematodes penetrate larval bodies and release symbiotic bacteria that cause rapid mortality. Laboratory and pot studies have reported high levels of grub mortality at increased inoculum rates, indicating their potential as soil-applied biocontrol agents. However, field performance is strongly influenced by soil texture, moisture availability, and application timing, which can limit consistency under rainfed conditions (Kaya and Gaugler, 1993; Kamaliya *et al.*, 2019; Chandel *et al.*, 2018).

Bacterial pathogens such as *Paenibacillus popilliae*, the causal agent of milky disease, are known to infect *Holotrichia consanguinea*, *H. serrata*, and *Leucopholis lepidophora*. These pathogens can provide long-term population suppression through natural epizootics. Nevertheless, their relatively slow mode of action and inconsistent field establishment restrict their use as standalone control measures, emphasizing the need for integration with other IWGM components (Chandel *et al.*, 2018).

In addition to microbial agents, natural predation by insectivorous birds contributes significantly to white grub regulation. Studies have shown that birds attracted during deep ploughing operations can remove 45-65% of exposed grubs, leading to meaningful reductions in population carry-over to subsequent crops. This highlights the importance of conservation biological control as a supportive element within IWGM (Parasharya *et al.*, 1994).

Overall, biological control under IWGM is most effective when implemented as part of area-wide, integrated modules that combine entomopathogens with cultural practices, organic amendments, and need-based chemical interventions. Such integration enhances control efficacy, reduces dependence on synthetic insecticides, and supports long-term ecological sustainability in groundnut-based production systems (Veeresh, 1988; Reddy, 2017; Bhut *et al.*, 2021b).

Seed treatment, soil, and bait formulations as IWGM tools

Seed treatment is a cost-effective, preventive strategy for managing white grubs in groundnut, particularly during early crop establishment. Insecticidal seed dressings create a protective zone around germinating seeds and developing roots, limiting grub feeding and establishment (Anitha *et al.*, 2006). Neonicotinoids such as imidacloprid and clothianidin have consistently demonstrated high efficacy. For instance, seed treatment with clothianidin 50 WDG (2-3 g kg^{-1} seed) or imidacloprid 17.8 SL significantly reduced plant mortality (≈5%), provided over 85% protection compared to untreated controls, and increased pod yield without affecting germination (Gangwar *et al.*, 2015; Patel *et al.*, 2018; Bhut *et al.*, 2021a). Chlorpyriphos seed dressing has also been effective against *Holotrichia* spp., with residues remaining below maximum permissible limits at harvest (Anitha *et al.*, 2006; Patel *et al.*, 2018). Integrating insecticidal seed treatments with fungicides or microbial antagonists can simultaneously control white grubs and soil-borne diseases like collar rot, resulting in higher economic returns (Bakhetia, 1983; Gaur *et al.*, 2017).

Soil application of insecticides is particularly important in endemic areas with high grub pressure. Granular formulations such as imidacloprid 0.3 G (15-20 kg ha^{-1}) and phorate 10 G (25 kg ha^{-1}) significantly reduce plant mortality and improve pod yields, with imidacloprid 0.3 G @ 20 kg ha^{-1} often identified as economically optimal (Bajya *et al.*, 2015). Soil drenching with newer formulations, including imidacloprid + fipronil WG, clothianidin 50 WDG, or chlorpyriphos 20 EC, consistently maintained plant mortality below 3% while enhancing yield performance (Patel *et al.*, 2020a; Chavan *et al.*, 2023).

Biological soil applications are gaining increasing emphasis within IPM frameworks. Incorporating entomopathogenic fungi such as *Metarhizium anisopliae* or *Beauveria bassiana* into the soil, particularly when enriched with organic amendments like vermicompost, neem cake, or castor cake, effectively reduces grub densities and enhances pod yields while simultaneously improving soil health (Chandel *et al.*, 2018; Patel *et al.*, 2022). Integrated IPM modules that combine chemical and biological soil treatments have been shown to be both effective and economically viable (Bhut *et al.*, 2021b; Patil *et al.*, 2025).

Bait formulations offer another targeted approach by attracting adult beetles during emergence and mating. Insecticide-treated organic baits reduce adult populations and subsequent egg laying, thereby limiting larval pressure (Pal, 1977; Veeresh, 1988). Recent IPM strategies combining aggregation pheromone traps with insecticidal or biological baits have further improved area-wide suppression of white grub populations (TNAU, 2015; Bhut *et al.*, 2021b).

Chemical insecticides within an IWGM framework

Chemical insecticides remain an important tactical component of IWGM, particularly in endemic regions where *Holotrichia* spp. can cause rapid and severe damage to groundnut crops. Within the IWGM framework, insecticides are applied judiciously, need-based, stage-specific, and in rotation, alongside cultural and biological measures to ensure long-term sustainability, environmental safety, and resistance management (IRAC, 2011; Reddy, 2017).

Among the most widely studied insecticides are neonicotinoids. Imidacloprid (17.8 SL, 600 FS, 0.3 G), when applied as seed treatment, soil application, or soil drenching, consistently reduces plant mortality and enhances pod yield across diverse locations (Anitha *et al.*, 2006; Gangwar *et al.*, 2015; Baloda *et al.*, 2021; Chavan *et al.*, 2023; Rao *et al.*, 2025). Similarly, clothianidin 50 WDG, applied as seed treatment or soil drench, provides high protection (>85%), low plant mortality, and favourable economic returns (Gangwar *et al.*, 2015; Patel *et al.*, 2020a; Bhut *et al.*, 2021a). Other neonicotinoids, including thiamethoxam and acetamiprid, have been evaluated, although their efficacy is comparatively lower (Singh *et al.*, 2012; Bhatnagar *et al.*, 2014).

Organophosphate insecticides also continue to play a role in soil-based IWGM interventions. Chlorpyriphos (20 EC, 10 G) has been widely used as a seed treatment, soil application, and for adult beetle management, effectively suppressing grubs while maintaining residue levels within permissible limits at harvest (Bakhetia, 1983; Anitha *et al.*, 2006; Bhut *et al.*, 2021b). Phorate 10 G and quinalphos 25 EC have similarly been effective as in-furrow or soil applications when timed to coincide with peak larval activity (Bakhetia, 1983; Gangwar *et al.*, 2015).

Recent studies underscore the advantages of pre-mix or ready-mix insecticides due to their multiple modes of action. For example, the pre-mix fipronil 40% + imidacloprid 40% WG, extensively evaluated in groundnut, consistently resulted in the lowest plant mortality (<3%), superior grub suppression, and higher pod yields compared to single-molecule treatments (Patel *et al.*, 2020a; Chavan *et al.*, 2023; Patil *et al.*, 2025). Granular premixes such as thiamethoxam 0.4% + bifenthrin 0.8% GR and thiamethoxam 0.9% + fipronil 0.2% GR also offer combined systemic and contact action for soil application, although groundnut-specific evaluations remain limited.

Among newer chemistries, chlorantraniliprole (18.5 EC) and flubendiamide (480 SC) provide moderate but stable control when applied to soil or as drench treatments (Mane and Mohite, 2014; Harsoliya *et al.*, 2024). Carbofuran 3 G, despite its high efficacy as a furrow application, is now discouraged due to environmental and regulatory concerns (Rao *et al.*, 2025).

Overall, IWGM studies emphasize that chemical insecticides are most effective when integrated with biological agents such as *Metarhizium anisopliae* and *Beauveria bassiana*. Such integrated approaches consistently achieve lower grub densities, higher yields, and improved benefit-cost ratios compared to chemical-only strategies, reinforcing the role of insecticides as a supportive, rather than standalone, component within sustainable IWGM systems (Bhut *et al.*, 2021b; Patil *et al.*, 2025).

CONCLUSIONS

White grub infestation remains a major biotic constraint to groundnut production in India, particularly in semi-arid regions such as Gujarat. Factors such as light-textured soils, erratic rainfall, and predominantly rainfed conditions create favourable environments for pest survival and recurrent outbreaks. This review highlights that IWGM, which strategically combines cultural, biological, mechanical, and judicious chemical interventions, offers a sustainable and climate-resilient approach to reduce pest damage, improve soil health, and enhance crop productivity (Veeresh, 1988; Gangwar *et al.*, 2015; Sharma and Reddy, 2020).

Effective suppression of white grubs in groundnut-based systems requires a time-sequenced, integrated strategy that targets multiple stages of the pest's life cycle. Key components of such a strategy include:

· ***Cultural and agronomic measures***: Repeated deep summer ploughing exposes and destroys carry-over larvae and pupae, reducing initial pest load. Crop rotation with non-host cereals (sorghum, pearl millet, maize), small millets, or fodder grasses, and avoiding continuous groundnut monocropping, disrupts the white grub life cycle and prevents population build-up. Synchronizing sowing with the onset of the monsoon avoids peak adult emergence, while very early pre-monsoon sowing (May-early June) should be avoided. Pruning preferred host trees (neem, ber, babul, *etc.*) and collecting adults for destruction, along with selective insecticidal spraying, reduces oviposition and local beetle densities.

· ***Mechanical and indigenous interventions***: Immediate reduction of adult beetle populations after the first monsoon showers can be achieved through mechanical collection, light traps, mating-disruption pheromone formulations, and indigenous methods such as mud-pot traps.

· ***Seed treatment***: Early-stage protection is achieved through insecticidal seed dressings, using imidacloprid 600 FS (2.0 ml kg^{-1} seed), clothianidin 50 WDG (2.0 g kg^{-1} seed), or thiamethoxam 30 FS (3.0 ml kg^{-1} seed). These treatments may be combined with *Metarhizium anisopliae* (4-5 g kg^{-1} seed) to reduce early-instar grub damage and improve crop establishment.

· ***Soil applications***: Immediate and sustained suppression can be attained through granular or drench applications of insecticides such as imidacloprid 0.3 G (10-12 kg ha^{-1}), chlorpyriphos 10 G (10-15 kg ha^{-1}), or phorate 10 G (10 kg ha^{-1}). Integration with biological agents, *Metarhizium anisopliae* or *Beauveria bassiana* (2.5-5.0 kg ha^{-1}, FYM-based) or entomopathogenic nematodes (*Heterorhabditis* / *Steinernema* spp., 2.5-5.0 × 10^9 IJs ha^{-1}), enhances long-term soil suppression.

· ***Organic, traditional, and cow-based amendments***: Soil or seed applications of neem cake, castor cake, vermicompost, Panchagavya, Beejamrut, Jeevamrut, and cow urine-based plant extracts improve soil health, enhance microbial activity, and directly suppress white grub populations. These inputs also complement biological agents, creating a soil environment unfavourable for larvae while supporting sustainable, eco-friendly pest management.

· ***Fertilizers***: Application of urea (≈50-100 kg ha^{-1}) during early crop stages can enhance grub mortality, likely through ammonia toxicity and adverse soil conditions, serving as a supportive component within IWGM.

· ***Monitoring and decision-making***: Regular field scouting between June and September, using visual inspection for wilting patches, soil sampling around affected plants, light traps, pheromone traps, and adult beetle counts on host trees, enables timely, informed IWGM interventions.

The synergistic integration of these IWGM components not only stabilizes yields under climatic stresses but also reduces dependence on chemical pesticides. As such, IWGM represents a cornerstone of sustainable, climate-resilient groundnut production systems in India, particularly for smallholder farmers in semi-arid regions (Bhut *et al.*, 2021b; Gangwar *et al.*, 2015).

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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