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Potato tuber moth (*Phthorimaea operculella* Zeller): biology, ecology, damage and integrated management – a modern review

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ABSTRACT

The potato tuber moth (PTM), *Phthorimaea operculella* Zeller (Lepidoptera: Gelechiidae), is a commonly dispersed oligophagous pest of potato and other solanaceous crops. Its economic importance is unusual because damage is expressed both in the standing crop and after harvest. Larvae mine leaves and petioles and, when tubers are exposed, penetrate through the eyes and create galleries inside tubers. This concealed feeding habit reduces the efficacy of contact insecticides and allows infestations to move from field to storage. Recent literature published between 2018 and 2026 shows a shift from reliance on conventional insecticides toward integrated pest management (IPM) combining cultural practices, monitoring, pheromone-based tactics, host plant resistance, biological control, botanicals, biorational compounds and molecular tools. Climate variability is also important because temperature influences development, generation number, seasonal activity and geographical suitability. Recent studies have prolonged knowledge of PTM pheromone receptors, the chromosome-level genome, gut microbiota, cultivar-dependent performance, entomopathogenic fungi, entomopathogenic nematodes, parasitoid and mite-based biological control, and novel botanical and nano-enabled interventions. This review synthesizes these developments, with particular emphasis on field-to-storage continuity, monitoring, biological and behavioral control, host resistance, emerging technologies and research priorities relevant to potato production in tropical, subtropical and hill environments. An integrated strategy based on healthy seed, deep planting and proper earthing-up, irrigation and field sanitation, timely harvest, storage hygiene, pheromone monitoring, conservation of natural enemies and selective use of registered insecticides is discussed as the practical framework for sustainable PTM management.

Keywords: Potato tuber moth, *Phthorimaea operculella*, Potato, Integrated pest management, Pheromone, Biological control, Host resistance, Storage pest, Botanicals, Climate change

1. Introduction

Potato (*Solanum tuberosum* L.) is a main food, cash and processing crop, but its production is constrained by a complex of insect pests. Among these, the potato tuber moth (PTM), *Phthorimaea operculella* Zeller, is particularly important because the same pest can damage foliage in the field and tubers immediately before harvest, during handling and in storage. The species is cosmopolitan in warm potato-growing regions and is associated with potato and several other solanaceous hosts. Recent global reviews continue to identify *P. operculella* as one of the major potato pests because its larvae feed within plant tissues and tubers, making control more difficult than for exposed foliar feeders (1,2,3,4,5).

The pest has four developmental stages—egg, larva, pupa and adult—and temperature strongly influences developmental rate and population growth. Females can oviposit on foliage, near stems and petioles, or on exposed tubers, particularly around eyes and cracks. Larvae initially mine plant tissues and may subsequently penetrate tubers. The most economically important damage is often associated with tubers because even a relatively small number of galleries can make fresh-market or seed potatoes unacceptable. Storage losses may become severe where infested tubers enter stores and conditions permit repeated generations (2,4,6).

The literature available from 2018 onward has broadened PTM research beyond conventional control. Climate suitability modelling, cultivar-dependent performance, pheromone chemistry and receptor biology, plant-insect chemical ecology, genome resources, microbiome studies, transgenic resistance, entomopathogenic fungi and nematodes, parasitoids and ectoparasitic mites have all received attention (7,8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18). At the same time, research on botanicals, plant powders, biorational insecticides and nano-formulations has attempted to reduce dependence on conventional synthetic insecticides (19,20,21,22,23,24,25).

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2. Taxonomy, distribution and host range

P. operculella belongs to Lepidoptera, family Gelechiidae. The species probably originated in the Andean region of South America along with potato and has subsequently spread to most major potato-growing areas. Contemporary reviews describe it as a cosmopolitan pest of potato and other solanaceous plants, including tomato and eggplant (1,3,5). In India, it has been reported from most potato-producing regions, with important field and storage problems in several states (6).

The host range is broader than potato alone. Laboratory work on potato, eggplant and tomato showed that host species can markedly affect fecundity, larval and pupal duration, mortality and total developmental period. Potato supported comparatively rapid development and greater fecundity in that study (26). The ability to survive on alternate solanaceous hosts has epidemiological significance because volunteer plants and weeds can maintain populations between potato crops.

Recent climate and niche studies suggest that temperature and host availability jointly influence potential distribution. A climate-and-host suitability analysis predicted spatial changes under future scenarios, emphasizing the importance of surveillance, movement of infested seed and storage-related pathways (8). A more recent ecological niche analysis also indicates that changing climatic conditions may alter the suitable area for *P. operculella* (27). These projections should be interpreted as scenario-based estimates rather than direct forecasts because climate models and host-distribution assumptions introduce uncertainty.

3. Biology and life cycle

The adult is a small, nocturnal moth. After mating, females oviposit on suitable plant surfaces. Eggs hatch into larvae that pass through several instars. The larva is the damaging stage: it mines between tissues in leaves and stems and can enter tubers through eyes or surface injuries. Mature larvae leave the feeding site and pupate in protected locations, including plant debris, soil-associated sites or storage structures. Adults emerge and restart the cycle. Development is strongly temperature dependent, so the number of generations varies among locations and seasons (2,3,6).

The thermal biology of *P. operculella* has also been investigated under cooler climates. Aryal and Jung (7) showed stage-specific differences in cold tolerance in a Korean population, with eggs and pupae showing greater cold tolerance than larvae and adults. Such findings help explain why overwintering success and population persistence can differ between climatic regions.

Recent host-performance experiments reinforce the importance of host genotype and tissue quality. Different potato cultivars produced different larval survival, feeding performance, pupal weight and oviposition responses (15,28). A 2026 study further showed that potato cultivar-associated phytochemicals can alter growth, feeding and life-table parameters of *P. operculella* (29). Thus, PTM population dynamics are determined not only by climate but also by plant chemistry and cultivar traits.

4. Damage symptoms and economic importance

PTM injury occurs in two interconnected phases. In the field, larvae form mines in leaves, petioles and stems. Foliar damage alone may not always translate into large yield losses, particularly when plants are vigorous; however, tuber infestation is economically much more serious. Larvae enter tubers through eyes, cracks or exposed portions and construct irregular galleries. Frass, webbing, discoloration and secondary decay may accompany the galleries. Infested tubers lose marketability and can become unsuitable for seed or processing.

The pre-harvest period is critical because tubers become increasingly exposed as foliage senesces, soil cracks develop and harvesting is delayed. Once infested tubers are moved into stores, the pest can continue development and complete additional generations. The field-to-storage continuum is therefore central to management: reducing field

infestation but ignoring store sanitation can permit rapid population recovery (3,6,19).

5. Environmental factors and climate change

Temperature is among the most important environmental variables affecting PTM development. Moderate warm conditions generally accelerate development, while extreme cold limits survival. Humidity, crop phenology, irrigation and canopy condition also influence oviposition and larval survival. The Indian review by Chandel *et al.* (6) summarized strong seasonal variation in PTM activity and emphasized the role of temperature and relative humidity.

Climate change can influence PTM through changes in overwintering success, generation time, population growth rate, crop phenology and geographical suitability. Rondon's updated synthesis highlighted climate variability as an important component of future PTM ecology (3), while Bhatnagar *et al.* (9) reviewed the broader implications of climate change for potato insect pests in India. Modelling studies should therefore be combined with local monitoring rather than used as stand-alone decision tools.

6. Monitoring and surveillance

Effective IPM begins with detection before tuber damage becomes extensive. Pheromone traps are useful for monitoring adult male flight and identifying periods of population buildup. The two principal components of PTM sex pheromone are 4E,7Z-tridecadienyl acetate (*PTM*₁) and 4E,7Z,10Z-tridecatienyl acetate (*PTM*₂). Recent work has improved understanding of pheromone formulation, field optimization and the molecular receptors involved in pheromone perception (12,13,30).

Monitoring should be integrated with field scouting. Particular attention is warranted near field edges, poorly earthed-up ridges, cracked soil, volunteer plants and fields approaching senescence or harvest. In storage, routine inspection of tubers, sanitation and trap-based monitoring can identify emerging infestations before they spread widely.

7. Cultural and preventive management

Cultural control reduces the opportunities available for oviposition, larval entry and population carry-over. Important measures include use of healthy seed tubers, adequate planting depth, proper ridging and earthing-up, irrigation where agronomically appropriate, removal of volunteer potato plants and solanaceous weeds, field sanitation, timely harvest and avoidance of prolonged tuber exposure after vine senescence (3,6).

Proper storage hygiene is equally important. Stores should be cleaned before loading, damaged and infested tubers should be removed, and storage structures should minimize moth entry. Rapid transfer of harvested potatoes into appropriate storage conditions reduces the period during which females can access exposed tubers. Plant-derived powders and botanicals have also been investigated as storage protectants (19,20).

8. Host plant resistance

Host plant resistance is attractive because it can reduce pest pressure without repeated pesticide application. Resistance can arise from morphological traits such as trichomes and tissue characteristics, or biochemical traits involving glycoalkaloids, phenolics and other secondary metabolites. Cultivar-based differences in PTM performance have been documented repeatedly (15,28,29,31).

A 2026 study comparing local and commercial potato genotypes reported associations between lower PTM preference and higher trichome density, trichome length, glycoalkaloids and phenolic compounds (31). Such relationships provide useful selection criteria for breeding, although correlations observed in laboratory or field screening must be validated across environments. Plant defense signalling is also complex. Li *et al.* (32) reported that enhancing herbivore-induced jasmonoyl-isoleucine increased resistance to beet armyworm but did

not similarly improve resistance to PTM, illustrating that host defence pathways can be pest-specific.

Biotechnological approaches are also being investigated. Salim *et al.* (18) developed potato lines expressing combinations of insecticidal genes and reported high larval mortality under experimental conditions. Such results demonstrate technical potential, but deployment requires assessment of agronomic performance, regulatory requirements, resistance management and environmental effects.

9. Biological control

9.1 Parasitoids

Parasitoid wasps can attack PTM eggs or larvae and have a long history in classical and augmentative biological control. Recent synthesis identifies numerous hymenopteran parasitoids associated with PTM and emphasizes *Copidosoma koehleri*, *Apanteles subandinus* and *Orgilus* species among important candidates (33). Conservation of parasitoids is particularly important where broad-spectrum insecticides can disrupt natural-enemy populations.

9.2 Entomopathogenic fungi

Entomopathogenic fungi offer opportunities for reducing chemical inputs. *Beauveria bassiana* has been investigated as an endophyte and as a direct biological control agent against PTM (17). More recent work has examined indigenous fungal isolates and storage systems. Song *et al.* (22) reported a sustainable storage-management system using entomopathogenic fungi together with an ectoparasitic mite. In 2026, Mei *et al.* (34) evaluated *Cordyceps fumosorosea* and reported pathogenicity across multiple PTM life stages, while also examining environmental suitability.

9.3 Entomopathogenic nematodes

Entomopathogenic nematodes (EPNs) can provide another biological option, particularly against susceptible pre-pupal and pupal stages. Laboratory and greenhouse experiments with *Heterorhabditis bacteriophora* and *Steinernema feltiae* showed activity against PTM and interactions with abamectin (16). A native *H. bacteriophora* isolate was subsequently evaluated in Turkey (35). Integration with compatible chemicals should be based on demonstrated compatibility because some insecticides can reduce EPN performance.

9.4 Ectoparasitic mites

Pyemotes zhonghuajia has emerged as a particularly interesting postharvest biological-control agent. Liu *et al.* (23) demonstrated lethal, sublethal and transgenerational effects on PTM, while subsequent work has examined host size and parasite density (36). These studies are important because postharvest PTM is difficult to manage once larvae are protected inside tubers.

10. Botanical and biorational management

Botanical products can act as repellents, antifeedants, oviposition deterrents, growth regulators or toxicants. Storage studies have evaluated plant powders and ethanolic extracts against PTM (19,20,24). More recent field work evaluated mineral oil, potassium salts of fatty acids and plant extracts of *Nicotiana glauca* and *Ricinus communis*; combinations of mineral oil and plant extracts reduced foliar damage and larval density and were associated with improved tuber production in the experimental system (21).

Novel nano-enabled formulations are also being explored. Abou El-Ela *et al.* (25) reported insecticidal activity of abscisic-acid-synthesized silver and copper oxide nanoparticles against PTM, accompanied by physiological and histological effects. Yeşilayer and Gülsoy (37) evaluated *Lantana camara* extracts and nano-silver formulations. These technologies remain promising but should not be regarded as field-ready alternatives without replicated field validation, residue assessment, non-target testing and regulatory evaluation.

11. Semiochemicals and behavioral control

Behavioral manipulation is especially relevant to PTM because adult moths use chemical cues to locate mates and hosts. Pheromone traps can support monitoring, while attract-and-kill, mating disruption or optimized lure formulations may eventually contribute to population suppression. Pan *et al.* (30) reviewed the chemistry and synthesis of PTM pheromones. Yan *et al.* (12) optimized field use, and Yan *et al.* (38) investigated pheromone analogues with the aim of developing alternative semiochemical tools.

At the molecular level, He *et al.* (13) identified and functionally characterized two putative pheromone receptors. This is important because receptor biology can support rational design of antagonists, agonists and other behavior-modifying compounds. A 2026 study on host volatiles and olfactory receptors further illustrates the emerging push-pull potential of plant-derived attractants and repellents (39).

12. Microbiome and genomic advances

Molecular tools are changing the understanding of PTM ecology. Zheng *et al.* (14) characterized midgut bacterial communities in relation to potato tissue consumed, opening questions about nutrition, detoxification and interactions between host plant chemistry and insect physiology. Song *et al.* (40) reported the complete mitochondrial genome, while Zhang *et al.* (41) produced a chromosome-level genome assembly. These resources provide a foundation for studying insecticide resistance, chemosensory systems, metabolism, adaptation and potential molecular targets.

Genome resources also strengthen future RNA interference, gene-expression and marker-assisted approaches. However, laboratory molecular discoveries should be linked to field phenotypes before being incorporated into operational IPM programmes.

13. Chemical control and insecticide resistance

Chemical insecticides remain important in many potato systems because of their rapid action and availability. Nevertheless, PTM presents a special challenge because larvae frequently feed inside leaves or tubers, reducing exposure to contact insecticides. Repeated use of the same mode of action can also select for resistance. Recent potato-IPM literature emphasizes that intensive potato production and reliance on insecticides contribute to resistance problems across pest complexes (4,42).

Chemical control should therefore be positioned within a resistance-management framework. Practical principles include monitoring before treatment, selecting products registered for the crop and target pest, rotating effective modes of action, respecting label dose and pre-harvest intervals, avoiding unnecessary repeated applications and protecting natural enemies. Chemical control should not substitute for cultural and storage sanitation measures.

14. Integrated field-to-storage management strategy

A robust PTM IPM programme should connect pre-planting, field production, harvest and storage. A practical sequence is: (i) use healthy, clean seed; (ii) maintain proper planting depth and earthing-up; (iii) eliminate volunteer hosts and field debris; (iv) use pheromone traps and regular scouting; (v) irrigate appropriately to reduce soil cracking where agronomically feasible; (vi) harvest promptly after physiological maturity rather than leaving exposed tubers in the field; (vii) remove damaged tubers before storage; (viii) maintain clean, moth-resistant stores; (ix) conserve parasitoids and other natural enemies; and (x) use selective registered insecticides only when monitoring indicates a need.

15. Research gaps and future directions

Although substantial progress, numerous gaps remain. First, locally validated economic thresholds for PTM are still limited, particularly for smallholder and hill production systems. Second, climate-based risk models need field calibration using long-term trap catches and infestation data. Third, resistance monitoring should be strengthened

where insecticide use is intensive. Fourth, biological-control agents require formulation, persistence and compatibility studies under commercial storage and field conditions. Fifth, cultivar resistance needs

multi-location validation because genotype $\times$ environment interactions may alter expression of resistance traits.

IPM component	Main action	Purpose
Preventive	Healthy seed; deep planting; ridging/earthing-up	Reduce access to tubers
Field sanitation	Remove volunteers and solanaceous weeds	Reduce carry-over hosts
Monitoring	Pheromone traps + field scouting	Detect adult activity and hotspots
Water/canopy management	Avoid excessive soil cracking and prolonged tuber exposure	Reduce oviposition opportunities
Biological	Conserve/release parasitoids; fungi; nematodes; mites	Reduce pest populations with lower chemical dependence
Host resistance	Use less susceptible cultivars where available	Reduce establishment and development
Biorational	Botanicals, oils and other selective products	Suppress pest with alternative modes of action
Chemical	Need-based, registered, mode-of-action rotation	Rapid suppression when thresholds/risk justify treatment
Storage	Sanitation, inspection, exclusion and appropriate conditions	Prevent multiplication after harvest

Future research should increasingly integrate pheromone monitoring, remote sensing, automated image-based damage detection, ecological forecasting and molecular diagnostics. Genome and transcriptome resources can support target discovery, while semiochemical research may enable more selective behavioral manipulation. Biological control should focus not only on laboratory mortality but also on mass production, field persistence, storage compatibility, non-target safety and farmer-level economics. For India, coordinated studies across plains, mid-hills and high-hill environments would be mainly valuable because temperature and cropping calendars strongly influence PTM phenology.

16. Conclusion

Phthorimaea operculella remains a major constraint to potato production because its larvae are concealed feeders and because the pest bridges the field-to-storage continuum. Literature from 2018–2026 demonstrates rapid expansion of research into climate ecology, cultivar resistance, pheromone biology, genomics, microbiomes and biological control, while botanical and biorational technologies are increasingly evaluated as complements to conventional pesticides. The most scientifically defensible management framework is therefore integrated rather than single-tactic: prevention and sanitation should reduce the initial population, pheromone monitoring should identify risk, resistant or less susceptible cultivars should be incorporated where suitable, biological and biorational options should be conserved or deployed where validated and chemical interventions should be selective, need-based and well-suited with resistance management. Future progress will depend on linking laboratory innovation with replicated field and storage validation, economic thresholds and practical farmer adoption.

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