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Botanical Insecticides for the Management of *Spodoptera litura* in Cotton Agro-ecosystems: Mechanisms, Efficacy and Future Directions

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Abstract-: The paradigm shift towards Artificial Intelligence (AI) is now able to produce creative works and technological inventions with only The escalating resistance of agricultural pests to conventional synthetic insecticides and the associated ecological risks have intensified interest in plant-derived biopesticides for sustainable crop protection. Among destructive polyphagous pests, Spodoptera litura poses a persistent threat to cotton agro-ecosystems due to its high reproductive potential, wide host range, and capacity to develop insecticide resistance. Botanical insecticides represent an ecologically compatible alternative owing to their diverse bioactive phytochemicals and multi-target modes of action. This review critically examines the insecticidal potential of three botanicals—Parthenium hysterophorus, Murraya koenigii, and Pongamia pinnata—with an emphasis on their phytochemical composition, bioactivity against S. litura, and underlying mechanisms such as antifeedant activity, growth inhibition, and disruption of insect physiological processes. The review synthesizes available experimental evidence, evaluates their applicability in cotton-based integrated pest management (IPM) systems, and identifies key research gaps including formulation development, field-level validation, and synergistic interactions among plant metabolites for improved pest suppression.

Keywords—Botanical insecticides; Spodoptera litura; Parthenium hysterophorus; Murraya koenigii; Pongamia pinnata; Cotton agro-ecosystem; Integrated pest management; Phytochemicals

1. INTRODUCTION

Spodoptera litura (Fabricius) is a polyphagous tobacco caterpillar and ranks among the most devastating pests affecting agricultural production in tropical and subtropical regions [1]–[3]. In cotton agro-ecosystems, severe infestations of this pest can result in massive defoliation and substantial reductions in crop productivity, thereby causing significant financial losses to farmers [4]–[6]. Traditionally, *S. litura* has been managed through the intensive use of synthetic chemical insecticides [7]–[10]. Although these pesticides offer rapid control, their indiscriminate and repeated application has led to numerous ecological and agronomic problems, including widespread environmental contamination [11]–[13], toxicity to non-target organisms, and the rapid emergence of insecticide resistance in pest populations [5], [14].

Over the past few decades, the drawbacks associated with conventional chemical pesticides have prompted the exploration of alternative pest management strategies that are both environmentally sustainable and cost-effective. Integrated Pest Management (IPM) has emerged as a holistic approach integrating biological, cultural, mechanical, and chemical methods to effectively control pests while minimizing ecological disruption [14], [15]. Within the IPM framework, botanical insecticides have gained considerable attention due to their biodegradability, reduced environmental persistence, and comparatively lower toxicity to beneficial organisms [5], [16], [17].

Botanical insecticides are derived from plant secondary metabolites, including alkaloids, terpenoids, flavonoids, and phenolic compounds, which exhibit insecticidal, antifeedant, growth-regulating, and oviposition-deterring properties [18], [19]. These compounds often possess multiple modes of action, significantly reducing the likelihood of rapid resistance development in insect populations. Numerous plant species have been investigated for their pesticidal properties; however, only a limited number have been extensively studied for their

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potential against *S. litura* in cotton agro-ecosystems [16], [19]. Among these, *Parthenium hysterophorus*, *Murraya koenigii*, and *Pongamia pinnata* have emerged as promising sources of bioactive phytochemicals with substantial applications in pest management [20]–[22]. Extracts from these plants contain diverse metabolites capable of disrupting insect feeding behavior, physiological processes, and development [23], [24]. Therefore, exploring their insecticidal efficacy and mechanisms of action contributes significantly to the development of sustainable pest management strategies for cotton cultivation. This review provides an overview of the biology and damage potential of *S. litura* and highlights the phytochemical composition and insecticidal activity of these selected botanicals in managing this economically important pest.

II. BIOLOGY, FEEDING BEHAVIOR, AND DAMAGE CAUSED BY SPODOPTERA LITURA

S. litura is a widely distributed lepidopteran pest belonging to the family Noctuidae. The species is highly endemic to tropical and subtropical agricultural regions, including India, China, Japan, Southeast Asia, and parts of Oceania [25], [26]. *S. litura* has become a primary pest in multiple cropping systems because of its remarkable adaptability and wide host range [27].

Taxonomic Classification of *Spodoptera litura* [28]

Kingdom: Animalia
Phylum: Arthropoda
Class: Insecta
Order: Lepidoptera
Family: Noctuidae
Genus: *Spodoptera*
Species: *litura*

The pest is highly polyphagous, reported to attack over 150 plant species across more than 45 botanical families. Key host crops include cotton, soybean, groundnut, tobacco, castor, sunflower, and various vegetables [29]–[32]. This broad host range enables the insect to survive and reproduce year-round across different agro-ecological environments, elevating its threat level in agricultural systems.

S. litura undergoes a life cycle comprising egg, larval, pupal, and adult stages. Female moths lay egg masses on the underside of leaves, usually covered with protective scales. Upon hatching, early instar larvae feed gregariously on leaf tissues, scraping epidermal layers and forming characteristic window-like patches [33]-[35]. As the larvae develop, they become increasingly voracious and disperse across the crop canopy. Later instars consume extensive amounts of foliage and may also feed on tender stems, buds, and reproductive organs [16], [32]. Larval feeding results in severe defoliation, significantly reducing the plant's photosynthetic capacity. Under favorable conditions, the pest has the potential to destroy between 25% and 100% of a crop during severe outbreaks[36]–[38].Its high reproductive capacity, rapid development, and ability to migrate among host plants further aggravate its economic impact.

The extensive use of chemical insecticides to control *S. litura* has induced resistance against multiple pesticide classes [39], [40]. Resistance mechanisms include target-site alterations and enhanced detoxification via metabolic enzymes such as cytochrome P450 monooxygenases, esterases, and glutathione S-transferases [41]. These adaptive responses diminish the effectiveness of conventional insecticides and complicate management [25], [42]. Consequently, there is an urgent need to incorporate environmentally friendly, plant-derived alternatives into sustainable pest management programs [6], [29], [30], [38].

TABLE I: PHYTOCHEMICAL CONSTITUENTS AND INSECTICIDAL PROPERTIES OF SELECTED BOTANICAL PLANTS AGAINST SPODOPTERA LITURA

Plant species	Major bioactive compounds	Reported insecticidal activity	Reference
Parthenium hysterophorus	Parthenin (sesquiterpene lactone), phenolic compounds	Antifeedant activity, larval toxicity, growth inhibition in lepidopteran pests	[6], [32], [46], [47] , [60]
Murraya koenigii	Carbazole alkaloids, flavonoids, terpenoids, essential oils	Feeding deterrence, larval mortality, oviposition deterrence	[29], [51], [52]
Pongamia pinnata	Karanjin, pongamol, furanoflavonoids	Larvicidal activity, growth disruption, enzyme inhibition	[5], [19], [55], [57], [63], [66]

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III. PHYTOCHEMISTRY AND BIOACTIVE COMPOUNDS OF SELECTED BOTANICAL INSECTICIDES

Natural plant-derived insecticides are increasingly recognized as vital components of green pest management [25]. Their pesticidal efficacy is largely driven by diverse secondary metabolites naturally produced as defense mechanisms against herbivores and pathogens [14]. These compounds include alkaloids, flavonoids, terpenoids, phenolics, and essential oils, which exhibit insecticidal or behavioural effects against insect pests [38], [41].

Parthenium hysterophorus, an invasive weed, contains numerous bioactive compounds, notably the sesquiterpene lactone parthenin, its principal toxic constituent. Studies confirm that *P. hysterophorus* extracts possess potent insecticidal and growth-inhibitory properties against agricultural pests [6], [32]. Purified parthenin exhibits significant toxicity toward the diamondback moth (*Plutella xylostella*), recording an LC50 value of 1709.42 mg L^{-1} at 96 hours [44]. The allelochemicals present in this plant facilitate its invasive success while simultaneously serving as a powerful natural pesticide [45], [46].

Murraya koenigii, commonly known as curry leaf, is another rich source of bioactive phytochemicals [47]. The leaves contain carbazole alkaloids, flavonoids, terpenoids, and essential oils known for diverse biological activities [48],[49]. Extracts demonstrate promising insecticidal and antifeedant activities against pests [29]. For instance, hexane extracts of *M. koenigii* leaves exhibit a concentration-dependent feeding deterrence against fourth instar *S. litura* larvae, significantly increasing antifeedant indices with higher concentrations [50]. Essential oils and carbazole derivatives isolated from the leaves also show substantial antifeedant activity against fifth instar larvae (ED50 ~130 mg mL^{-1}) [51].

Similarly, *Pongamia pinnata* is widely recognized for its pesticidal potential. The plant contains active furanoflavonoids, primarily karanjin and the flavonoid pongamol [52], [53]. These constituents display insecticidal, antifeedant, and growth-regulating effects [5], [54]. Extracts of *P. pinnata* demonstrate strong toxicity against *S. litura*, confirming its utility as an effective botanical pesticide source [55], [56]. The phytochemical diversity within these plants offers multifaceted modes of action, including feeding disruption, growth inhibition, hormonal interference, and direct tissue toxicity. Such complex mechanisms are invaluable in delaying pest resistance and promoting sustainable control [57], [58].

TABLE II. REPORTED INSECTICIDAL EFFICACY OF PLANT EXTRACTS AGAINST SPODOPTERA LITURA

Plant species	**Extract type / solvent**	**Target insect stage**	**Reported bioactivity**	**Reference**
Parthenium hysterophorus	Crude plant extract	Larvae	Significant toxicity and feeding inhibition	[32]
Parthenium hysterophorus	Parthenin compound	Lepidopteran pests	LC50 = 1709.42 mg L^{-1} against Plutella xylostella	[46]
Murraya koenigii	Methanol leaf extract	Third instar larvae	Mortality 75.6–94.5%; LD50 223.5–313.4 ppm	[29]
Murraya koenigii	Hexane extract	Fourth instar larvae	Antifeedant index increased from 13.72 to 60.77	[51]
Pongamia pinnata	Methanolic seed extract	Larvae	High larval mortality up to 94.5%	[29], [57]
Pongamia pinnata	Seed oil formulation	Larvae	Enhanced insecticidal activity and field potential	[62], [66]

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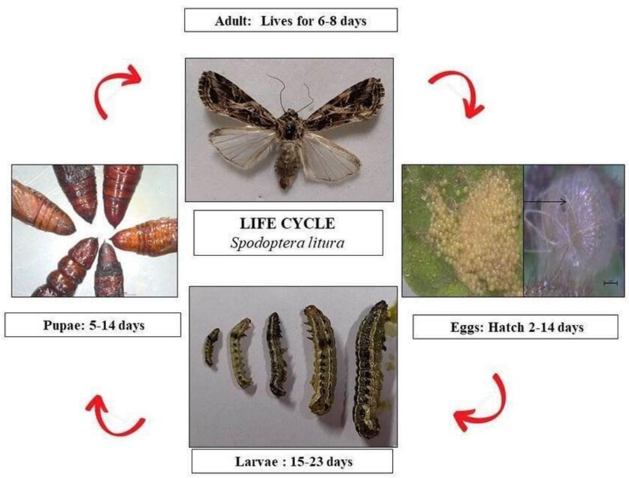

Fig. 1. Life cycle o*f Spodoptera litura showing egg, larval, pupal, and adult* stages [68].

IV. INSECTICIDAL ACTIVITY AGAINST SPODOPTERA LITURA

Extensive experimental studies have validated the insecticidal properties of *P. hysterophorus*, *M. koenigii*, and *P. pinnata* extracts against *S. litura* [32]. These extracts showcase a broad spectrum of bioactivities, including larval mortality, feeding deterrence, and growth/oviposition inhibition.

P. hysterophorus extracts exert quantifiable toxicological effects on *S. litura* larvae [59]. Among crude extracts of various herbaceous plants, *P. hysterophorus* displays particularly notable toxicity [32]. While purified parthenin possesses an LC50 of 1709.42 mg L^{-1} against *P. xylostella*, crude extracts occasionally exhibit even higher relative toxicity [44], suggesting synergistic interactions between the multiple phytochemicals present [4].

Research highlights that *M. koenigii* significantly impacts *S. litura* behavior and survival. Methanolic leaf extracts caused considerable mortality (75.6%–94.5%) when tested against third instar larvae at concentrations of 250 to 1000 ppm (LD50: 223.5–313.4 ppm) [60], [29]. Hexane extracts simultaneously serve as potent antifeedants against fourth instar larvae; the antifeedant index scales proportionally from 13.72 at a 1% concentration to 60.77 at 5% [49]. Furthermore, these extracts suppress pest populations by reducing oviposition in gravid female moths.

Extracts obtained from *P. pinnata* reflect comparable efficacy. Methanolic seed extracts tested at 250 to 1000 ppm generated larval mortality reaching up to 94.5%, matching the LD50 range of *M. koenigii* [29]. The pesticidal effects are largely attributed to karanjin and pongamol disrupting insect physiological processes [19]. Field evaluations of pongam oil, occasionally combined with other botanical preparations like panchagavya, further validate its practical application against *S. litura* [61].

Comparative solvent studies indicate that methanolic extracts of *M. koenigii* and *P. pinnata* generally exhibit greater insecticidal activity than acetone extracts [62], establishing that solvent polarity is critical for optimal phytochemical extraction [29]. Hexane extracts excel specifically in isolating compounds with high antifeedant properties [49]. Maximizing bioactivity thus depends heavily on the chosen extraction technique. Ultimately, the versatile actions of these botanicals position them as highly viable, environmentally sustainable alternatives to synthetic insecticides within cotton pest management frameworks [63], [64].

TABLE III. MECHANISMS OF ACTION OF PLANT-DERIVED PHYTOCHEMICALS AGAINST SPODOPTERA LITURA

Phytochemical compound	**Plant source**	**Mechanism of action**	**Physiological effect on insect**	**Reference**
Parthenin	*Parthenium hysterophorus*	Antifeedant and metabolic disruption	Reduced feeding and impaired larval development	[6], [47], [60]
Carbazole alkaloids	*Murraya koenigii*	Neurotoxic activity and feeding deterrence	Disruption of neurotransmission leading to paralysis	[11], [52]
Karanjin	*Pongamia pinnata*	Insect growth regulator	Disruption of molting hormones (ecdysone/juvenile hormone)	[5], [55], [63]
Pongamol	*Pongamia pinnata*	Digestive enzyme inhibition	Reduced nutrient assimilation and larval	[28], [55]

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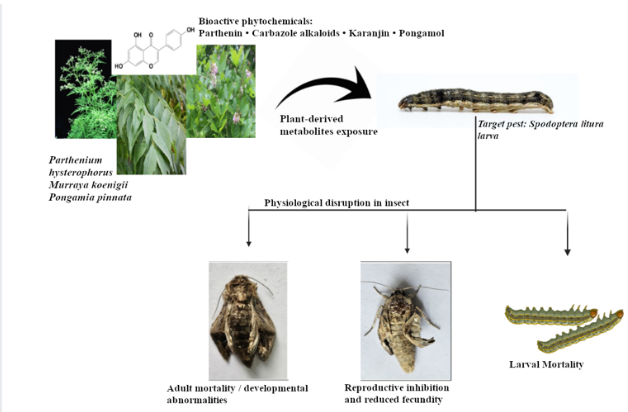

Fig. 2. Proposed mechanisms of action of plant-derived insecticidal compounds against *Spodoptera litura.* Bioactive phytochemicals such as parthenin from *Parthenium hysterophorus*, carbazole alkaloids from *Murraya koenigii,* and karanjin and pongamol from *Pongamia pinnata* interact with the larval physiology of *S. litura* [5], [11], [20], [55]

V. MECHANISMS OF ACTION OF PLANT-DERIVED INSECTICIDAL COMPOUNDS

Plant secondary metabolites have naturally evolved to defend against herbivorous insects and microbial pathogens. They exert profound biochemical and physiological impacts, including neurotoxicity, hormonal disruption, digestive enzyme inhibition, and structural cuticle damage [67], [68]. Because of these varied actions, plant-derived insecticidal compounds are highly valuable for managing resilient pests like *S. litura* [38], [69], [70].

Parthenin, heavily studied in *P. hysterophorus*, acts primarily as a powerful antifeedant, restricting nutrient intake and leading to starvation [6], [32]. Furthermore, sesquiterpene lactones like parthenin can interfere with cellular proteins and metabolic enzymes via alkylation reactions, disrupting physiological pathways and culminating in impaired growth and mortality [45].

In *M. koenigii*, carbazole alkaloids and essential oils drive feeding deterrence and neurotoxicity. Essential oils demonstrated an ED50 of approximately 130 μg mL^{-1} for feeding deterrence in fifth instar *S. litura* [51]. Beyond feeding inhibition, carbazole alkaloids exert neurotoxic effects by interfering with insect neurotransmission, causing paralysis and death [71].

The toxicity of *P. pinnata* is driven by karanjin and pongamol [54], [72]. These furanoflavonoids act analogously to insect growth regulators (IGRs) by altering the delicate balance between ecdysone and juvenile hormone, effectively inhibiting the molting and metamorphosis processes required for development. Additionally, these compounds inhibit digestive enzymes in the insect gut, directly impairing nutrient assimilation [19].

Overall, the multi-mechanistic nature of these botanical insecticides—combining antifeedant, neurotoxic, and hormonally disruptive properties—generates synergistic effects that substantially reduce the likelihood of pest resistance [9], [67].

VI. APPLICATION OF BOTANICAL EXTRACTS IN COTTON IPM PROGRAMS

Integrating botanical insecticides into Integrated Pest Management (IPM) practices is crucial for reducing synthetic chemical reliance in cotton agro-ecosystems [3]. Botanicals like *P. hysterophorus*, *M. koenigii*, and *P. pinnata* align perfectly with IPM principles due to their biodegradability, minimal environmental persistence, and safety regarding non-target organisms [68], [74], [75]. Beyond direct mortality, the strong antifeedant properties of these extracts actively shield cotton crops from severe defoliation [49]–[51].

Furthermore, botanical insecticides display excellent compatibility with biological control agents. Synergistic interactions have been demonstrated between plant extracts and microbial pesticides, such as *Bacillus thuringiensis* (Bt). *P. pinnata* extracts fortified with *B. thuringiensis* subsp. Kurstaki significantly increased *S. litura* mortality [55], [76]. Botanicals can also weaken insect immune systems, rendering them more susceptible to entomopathogenic fungi and naturally occurring predators [24].

To overcome field limitations such as rapid photodegradation and volatility [23], [77], [78], advanced formulation techniques like microencapsulation and nanotechnology are being rapidly adopted. Encapsulated *P. pinnata* seed oil has achieved enhanced stability and sustained karanjin release, markedly improving insecticidal duration and efficacy [65], [79]. Nanotechnology-based delivery systems further optimize bioavailability and targeted release [77].

While laboratory results strongly advocate for these botanicals, widespread adoption in cotton cultivation necessitates extensive large-scale field trials to optimize application methodologies, assess economic feasibility, and ensure consistency[78].

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Nevertheless, the pronounced ecological advantages firmly establish botanical biopesticides as vital assets for future sustainable agriculture [27], [79].

VII. RESEARCH GAPS AND FUTURE PROSPECTS

Even though the insecticidal effects of *Parthenium hysterophorus*, *Murraya koenigii*, and *Pongamia pinnata* against *Spodoptera litura* have been demonstrated by several studies, significant knowledge gaps still exist that limit the extensive application of these botanical insecticides in cotton pest management initiatives.

A major limitation is the lack of studies examining the combined or synergistic effects of these botanical extracts. The majority of current studies have focused on individual plant species; however, the combination of phytochemicals from multiple plants may enhance pesticidal efficacy and broaden the spectrum of activity against insect pests. Synergistic interactions among different plant metabolites have been reported in some botanical formulations and may result in improved pest control efficiency while reducing the required concentration of individual compounds [8]. Therefore, future research should investigate the development of multi-plant formulations involving *P. hysterophorus*, *M. koenigii*, and *P. pinnata*.

Another significant research gap is the limited number of field-scale studies evaluating the performance of botanical insecticides under natural agricultural conditions. Most existing studies have been conducted under laboratory or greenhouse conditions, which may not accurately represent the complexity of field environments where factors such as temperature fluctuations, rainfall, ultraviolet radiation, and pest population dynamics can influence pesticide efficacy [43], [80].

Standardization of extraction and formulation processes also represents a major challenge in the development of commercial botanical insecticides. The chemical composition and biological activity of plant extracts can vary considerably depending on factors such as plant genotype, geographic origin, harvesting stage, plant part used, and extraction solvent [33], [36]. Establishing standardized extraction protocols and quality control measures will therefore be essential to ensure consistent efficacy and facilitate regulatory approval for commercial products.

In addition, the development of advanced biopesticide formulations represents an important future direction. Technologies such as microencapsulation, nanoemulsions, and controlled-release systems can improve the stability and bioavailability of botanical compounds, thereby enhancing their effectiveness under field conditions. These innovations may help overcome some of the limitations associated with conventional botanical extracts, including rapid degradation and limited residual activity.

Finally, molecular-level investigations into the mechanisms of action of plant-derived insecticidal compounds against *S. litura* are required. Although general mechanisms such as antifeedancy, neurotoxicity, and growth inhibition have been reported, detailed studies are needed to identify the specific molecular targets and biochemical pathways affected by these phytochemicals. Understanding their interactions with detoxification enzymes, hormonal pathways, and neural receptors could facilitate the development of more effective botanical insecticides and help predict potential resistance mechanisms.

Addressing these research gaps will be essential for translating promising laboratory findings on botanical insecticides into practical pest management strategies for cotton production systems. Continued research in this field may ultimately reduce dependence on synthetic pesticides and promote more sustainable agricultural practices.

VIII. CONCLUSION

The rising issues related to the control of the polyphagous pest *Spodoptera litura* in cotton agro-ecosystems underscore the essential need for the development of sustainable and environmentally friendly pest management strategies. Excessive use of synthetic insecticides has contributed to severe ecological problems such as pesticide resistance, environmental pollution, and adverse effects on non-target organisms. Plant-derived botanical insecticides such as *Parthenium hysterophorus*, *Murraya koenigii*, and *Pongamia pinnata* therefore represent promising alternatives for sustainable pest management.

These plants contain a variety of bioactive phytochemicals such as parthenin, carbazole alkaloids, karanjin, and pongamol, which exhibit multiple modes of action including antifeedant activity, neurotoxicity, disruption of insect growth and development, and inhibition of digestive enzyme activity. Such multifaceted mechanisms reduce the likelihood of resistance development in pest populations while effectively suppressing larval feeding and survival. Moreover, their compatibility with

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integrated pest management strategies, including biological control agents and microbial pesticides, further enhances their potential application in cotton cultivation.

Although these findings have shown promising laboratory results, further research is required to translate these outcomes into practical agricultural solutions. Large-scale field trials, standardized extraction and formulation protocols, and advanced delivery systems such as nanoformulations are necessary to improve the stability, efficacy, and economic feasibility of botanical insecticides. In addition, deeper molecular-level investigations into the interactions between plant metabolites and insect physiological pathways will help optimize their pesticidal potential.

Overall, the integration of plant-derived insecticidal compounds into cotton IPM programs represents a viable pathway for reducing reliance on synthetic pesticides while promoting environmentally sustainable crop protection. Continued interdisciplinary research involving phytochemistry, entomology, and formulation science will be crucial in harnessing the full potential of these botanicals as next-generation eco-friendly pest management tools.

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