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Plant-derived pesticides as sustainable alternatives for agricultural insect pest management with ecotoxicological considerations

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Abstract
The growing reliance on synthetic pesticides in intensive farming disrupts the ecosystem's natural equilibrium, affecting pest populations and diminishing essential interactions among organisms. Consequently, efforts in recent years have increased to develop safe and sustainable pest control methods as alternatives to synthetic pesticides. Plant-derived pesticides are viable substitutes for conventional pesticides. Although they may not always be highly effective, they pose less risk to the environment and are safer for humans and other living beings. Ecotoxicity probabilities were examined for plant components, including (–)-homopterocarpine, limonene, α-pinene, β-himachalene, and (E)-β-caryophyllene, with ratios above 0.50 indicating potential environmental risk. Predictions for skin irritation and corrosion showed confidence levels of 60, 50, and 70% for azadirachtin, resveratrol, and nimbandiol, respectively. It has been clearly demonstrated that these compounds can be used in agricultural insect pest management without causing environmental pollution. Given that the confidence levels were 50% or close to 50%, severe toxicity was unlikely. Based on the toxicity assessment, this study concluded that these compounds may be beneficial for managing insect pests in agriculture. This review provides information on the chemical makeup of plant-based pesticides, their mechanisms of action, and their significance in agricultural production. Plant-derived pesticides are effective in managing a wide range of crop pests, cost-effective, readily biodegradable, and operate through multiple mechanisms. Furthermore, their raw materials are readily accessible and exhibit low toxicity to nontarget organisms.

Keywords: Ecosystem, insect pest, Bio-pesticides, agriculture, crop protection

Introduction

Overview of Pest Management Challenges in Indian Agriculture

New developments and challenges continually reshape the field of pest management. Before the advent of synthetic pesticides, farmers and their predecessors relied on cultural and mechanical techniques based on experience [1]. The Green Revolution introduced technologies such as high-yielding crop varieties, chemical fertilizers, and synthetic pesticides from industrialized nations to developing countries, including India [2]. This marked a significant shift in pest management practices beginning in the mid-1940s. Following the introduction of Dichlorodiphenyltrichloroethane (DDT) in India, a range of synthetic pesticides, including Benzene Hexachloride (BHC), dieldrin, and 2,4-D, were widely used. These were hailed as "revolutionary tools" in agriculture for their user-friendliness, rapid response, and effective pest control. The initial success of these pesticides fostered strong confidence in synthetic solutions, leading to a rapid increase in their use. In India, pesticide application, which was approximately 70 g/ha in the 1960s, surged to 600 g/ha by the 1990s, with variation across crops and regions [3].

Agricultural products are continually threatened by various factors, and pest infestation is a significant issue. Synthetic pesticides are commonly used to manage pests [4]. However, overuse of these chemicals poses risks to human health, exacerbates climate change, and causes toxicity in non-target species, leading to biodiversity loss [5,6]. Additionally, many pesticides are not biodegradable, persist in the environment, accumulate in soil and groundwater, and cause pollution. Therefore, there is a need for environmentally friendly and sustainable alternatives [7]. Key characteristics of herbal pesticides include biodegradability, low toxicity, easy availability, and safety for human use [8,9]. Moreover, their market value is rising as consumers are willing to pay more for natural food products. Plant extracts and secondary metabolites are promising substitutes for synthetic pesticides and offer potential solutions for sustainable pest control [10]. Essential oils have recently garnered significant attention as viable and potent alternatives to synthetic pesticides [11]. This mini-review explores the use, benefits, and future prospects of plant-based pesticides for sustainable production in India.

Overuse of synthetic pesticides and their environmental impacts

Biopesticides, derived from natural sources, are used to manage or eliminate insects, weeds, and other harmful organisms that hinder plant development. They are typically categorized by mode of action and chemical composition [12]. However, overuse and inadequate regulation of pesticide application have led to numerous issues, including food contamination, environmental harm, and pollution of water, soil, and air [13,14]. Pesticide residues are present in fruits, vegetables, processed foods, and drinking water, posing significant health risks to humans. Agricultural practices and dietary exposure contribute to acute and chronic health issues, particularly in developing nations (Fig 1). Certain chemical pesticides are carcinogenic, cytotoxic, and mutagenic [15]. According to the World Health Organization (WHO) and the United Nations Environment Program (UNEP), approximately three million individuals worldwide suffer from pesticide poisoning annually, resulting in approximately 200,000 fatalities [16].

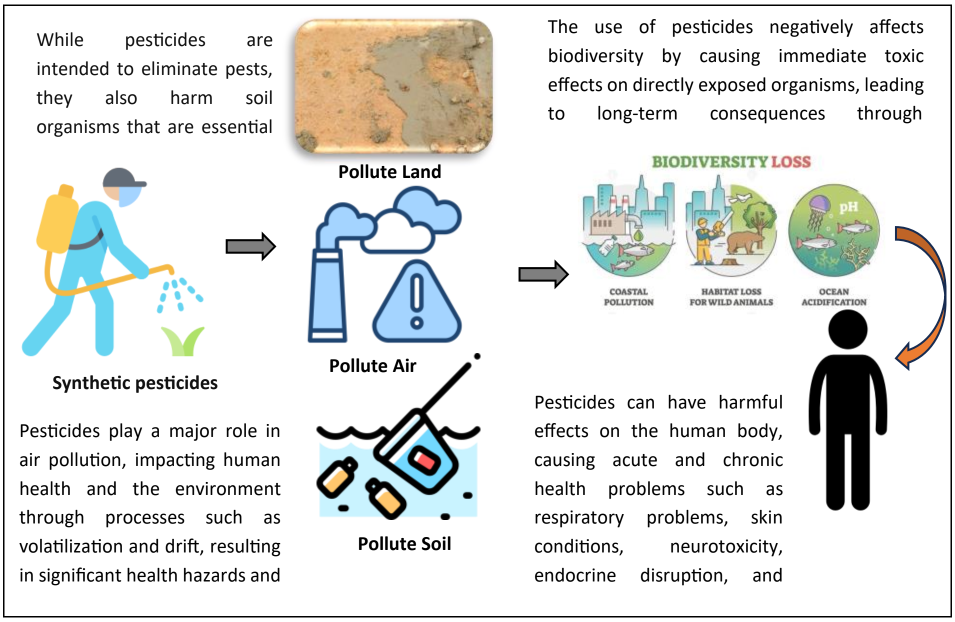

Fig 1: Pesticide pollution in the environment and humans

Pesticides are crucial for protecting crops from pests and enhancing agricultural yields. However, their use poses several environmental issues. Once applied, they rapidly disperse into the air, water, and soil [17,18]. Improper use or disposal can worsen these effects [19]. The toxic chemicals in pesticides persist in the soil for extended periods, gradually accumulating and affecting organisms vital to soil health, such as earthworms and microorganisms. This results in reduced soil fertility and disruption of the soil's natural ecological balance [20]. Additionally, pesticides can be carried over long distances by wind and, through rainfall and surface runoff, contaminate rivers, ponds, other water bodies, and groundwater. Pesticides released in this manner can lead to severe outcomes, ranging from minor environmental effects to the extinction of certain species [21]. Therefore, it is essential to adopt a balanced approach to pesticide use that protects human health and conserves the environment. Strategies such as Integrated Pest Management (IPM) are increasingly important for ensuring that agriculture remains sustainable and safe.

Importance of botanical pesticides

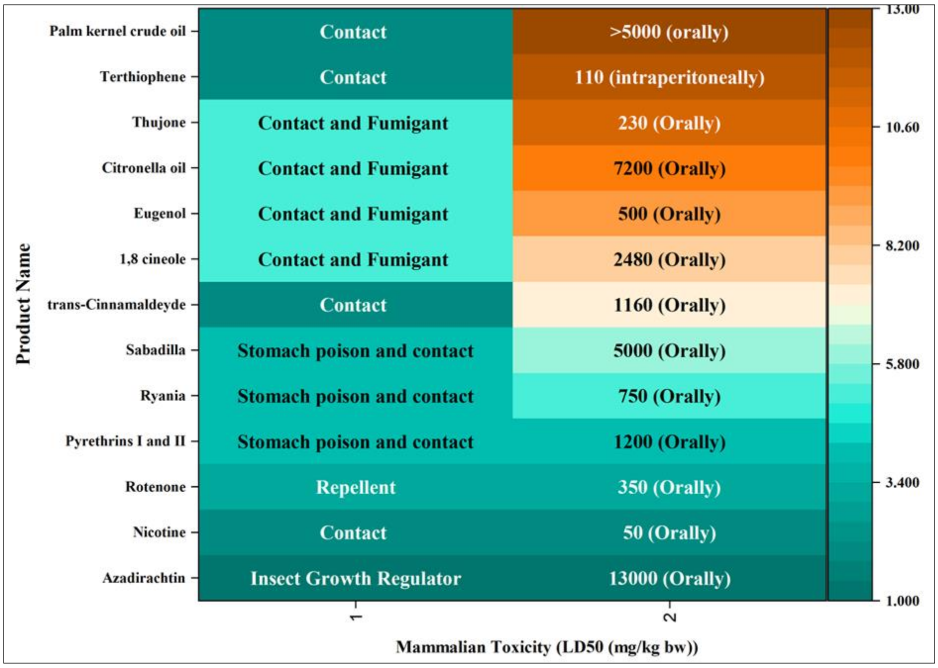

Fig 2: Toxicity and mechanism of plant-based natural insecticides

Plant-derived insecticides can affect an insect's respiratory, endocrine, or neurological systems in various ways. Additionally, pesticides are classified as fumigants, contact poisons, or stomach poisons based on their mode of entry into the insect. Figure 2 lists natural pesticides, detailing their toxicity and modes of action. The field of pest management is constantly evolving due to new developments and challenges. Biopesticides, derived from natural sources, are used to control or eliminate insects, weeds, and other harmful organisms that hinder plant growth. They're typically grouped by mode of action and composition. Biological pesticides are considered safe because you don't have to wait long to harvest crops after using them. Plus, they target specific pests, so beneficial insects and natural predators aren't harmed. Because they occur naturally in the environment, their raw materials are abundant and cost-effective, and various plant parts serve as food or feed [22]. Owing to their low toxicity, these pesticides are safe for both those who apply them and consumers. Therefore, biological pesticides can be seamlessly integrated into IPM systems, thereby reducing the need for synthetic pesticides and offering an environmentally friendly alternative. As natural raw materials break down rapidly, their environmental impact is minimal. Moreover, the short re-entry period ensures the safety of agricultural workers. Similarly, biological pesticides enhance soil fertility and maintain soil health by introducing specific microbial species [23].

Table 1 and Figure 3 present phytochemical compositions effective in managing various insect species. *Senecio palmensis* (11-Acetoxy-5-isobutyryloxysilphinen-3-one) acts as an antifeedant against decelomodarescent decelomaleate [24]. *Pterocarpus macrocarpus* [(–)-homopterocarpin] exhibits notable antifeedant activity against *S. litura* [25]. *Azadirachta indica*, which contains azadirachtin, nimbin, 6-deacetylnimbine, and nimbandiol, is effective as an insecticide against stored and field insect pests [26]. *Pinus strobus* (limonene) serves as an attractant for *Conophthorus coniferata*, whereas *P. strobus* (α-pinene) acts as an insecticide against *Oenocleus nigripes* [27]. *Cedrus theodora* (himachalol) is an effective insecticide against *C. analis* and *Musca domestica*, and *C. theodora* (β-himachalene) also exhibits insecticidal activity against these species [28]. *Zea mays* (β-caryophyllene) is an attractant for *Diaprotica virgifera* [29]. *Polygonum cuspidatum* (resveratrol) exhibits insecticidal properties against *H. armigera* [30]. *Lantana camara* (2,3-dihydrobenzofuran) exhibits strong insecticidal activity against Sitophilus oryzae and *T. ganium* [31].

Table 1: Major active plant phytochemicals against agricultural insect pests

S. No	Family	Scientific Name	Phytochemicals	Mode of Action	Target Insect Pest	References
1.	Asteraceae	*Senecio palmensis*	11-Acetoxy-5-isobutyryloxysilphinen-3-one	Antifeedant	*Leptinotarsa decemlineata*	[24]
2.	Fabaceae	*Pterocarpus macrocarpus*	(–)-homopterocarpin	Antifeedant	*S. litura*	[25]
3.	Lamiaceae	*Thymus vulgaris*	Thymol	Antifeedant	*Metopolophium dirhodum*	[24]
4.	Meliaceae	*Azadirachta indica*	Azadirachtin, nimbandiol	Insecticidal	Stored and field insect pest	[26]
5.	Pinaceae	*Pinus strobes*	Limonene	Attractant	*Conophthorus coniperda*	[27]
6.	Pinaceae	*P. strobes*	(–)-α–Pinene	Attractant	*Enoclerus nigripes*	[27]
7.	Pinaceae	*Cedrus deodara*	Himachalol	Insecticidal	*Callosobruchus analis* and *Musca domestica*	[28]
8.	Pinaceae	*C. deodara*	β-Himachalene	Insecticidal	*C. analis* and *Musca domestica*	[28]
9.	Poaceae	*Zea mays*	(*E*)-β-caryophyllene	Attractant	*Diabrotica virgifera*	[29]
10.	Polygonaceae	*Polygonum cuspidatum*	Resveratrol	Insecticidal	*H. armigera*	[30]
11	Verbenaceae	*Lantana camara*	2,3-dihydrobenzofuran	Insecticidal	*Sitophilus oryzae* and *T. castaneum*	[31]

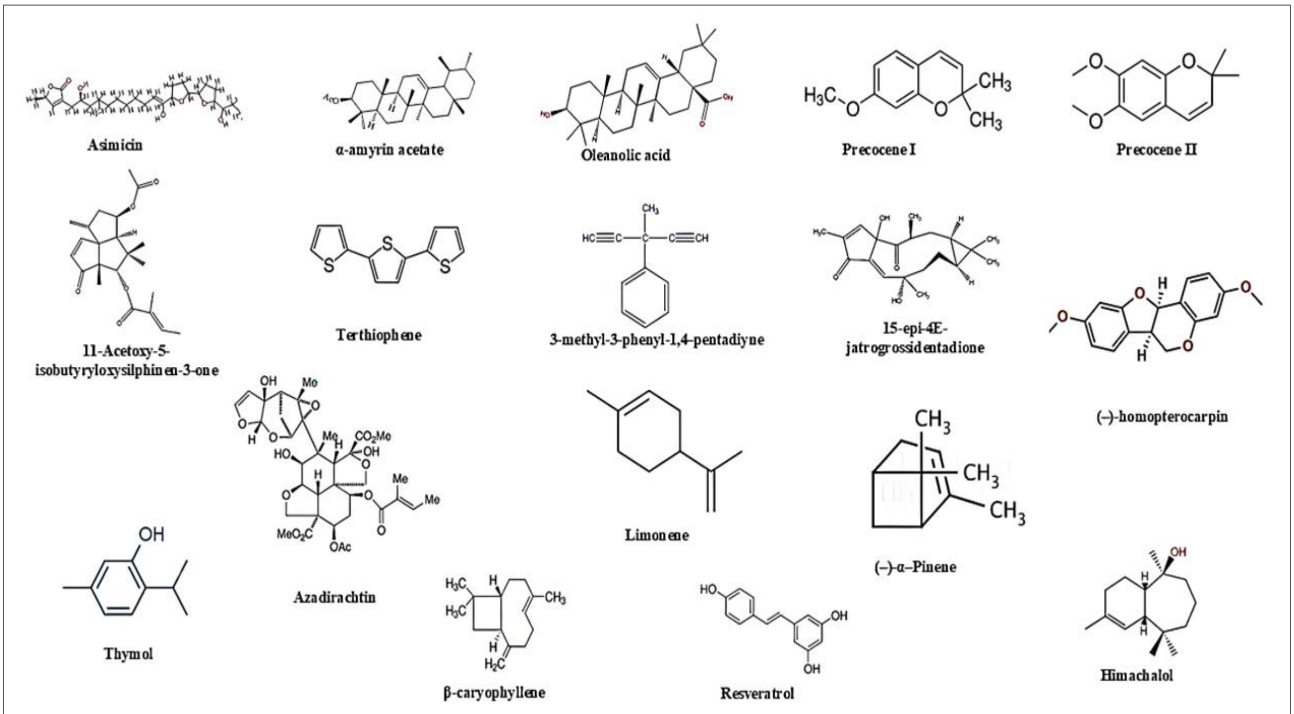

Fig 3: Major active phytochemicals against agricultural insect pests

Historical Context and Traditional Use of Botanical Pesticides

The earliest recorded use of plant-based pesticides dates to 400 BC in ancient Rome [32]. Pyrethrum (*Chrysanthemum cinerariifolium*), neem (A. indica), rotenone (Derris spp.), and sabadilla (*Schoenocaulon officinale*) are examples of plant pesticides with a long history [32]. In Croatia, Dalmatian pyrethrum flower powder has been used in homes and fields for many generations. In India, neem has been widely used since ancient times. Similarly, rotenone has been used in East Asia and South America, and sapodilla in Central and South America. With advances in chemical knowledge during the 19th and early 20th centuries, plant extracts such as nicotine (*Nicotiana tabacum*) and quassia (*Quassia amara*) became widely used [32]. Nicotine and its derivatives have been employed as contact insecticides and fumigants to manage pests such as aphids, thrips, and mites. Quassia has been recognized as an effective insecticide for aphid control since the 1880s. Regulatory restrictions on plant extracts and oils have eased in some countries, including India, Turkey, Uruguay, the United Arab Emirates, and Australia. However, the introduction of new plant pesticides remains challenging due to stringent standards in North America and the European Union [33].

Green Technology involving pesticides

In agriculture, a variety of chemicals are widely used to manage pests, prevent fungal diseases, and ensure consistent crop yields. Although pesticides significantly enhance yields, their overuse can lead to numerous issues. Consequently, it is crucial to monitor the Maximum Residue Limit (MRL), assess food safety, and enforce residue-control strategies. The persistent use of pesticides has harmful effects on soil, water, flora, fauna, and human health. Pesticides applied to crops often persist in food products and are ingested without being fully eliminated; they also contaminate water sources, posing a threat to aquatic life. Notably, because approximately 30% of a person's daily diet consists of fruits and vegetables, the likelihood of pesticide residues entering the body is heightened. Furthermore, food items can be contaminated with pesticides during processing. Residual pesticides are metabolized into compounds that can be highly toxic, leading to symptoms such as vomiting, headaches, respiratory issues, chronic illnesses, neurological disorders, and other health complications in humans. To mitigate these issues, several techniques have been used to remove pesticide residues from agricultural products. Traditional methods include rinsing with water, salt cleaning, peeling, cooking, drying, and chemical oxidation. These approaches are vital for enhancing food safety and safeguarding human health.

Challenges of botanical pesticides

Although botanical pesticides are effective against various agricultural pests, their use remains limited. The main reason is the limited availability of easily cultivated plants. Furthermore, these plants require large areas of land for cultivation, which may directly interfere with food crop production. Because large quantities of plant material are required to produce botanical pesticides, storage, preservation, and machinery costs are high. Because a single plant contains multiple active chemicals, it is difficult to identify and use them correctly. However, if plants with similar chemical components are used together, their pest control effects can be enhanced. Furthermore, small-scale farmers are unaware of the benefits of botanical pesticides; as a result, they are not widely used. Therefore, advanced extraction technologies and waste-disposal practices are required. Owing to the above challenges, most agrochemical companies are reluctant to produce botanical pesticides.

Toxicity assessment

The potential ecotoxicity of the chemical compounds listed in Table 2 was evaluated using the ProTox-3.0 online toxicity assessment tool. This involved using SMILES data for phytochemicals to determine their ecotoxicity ratings [34]. The ecotoxicity probabilities associated with plant components were examined. Certain chemicals previously documented in scholarly articles have inertness probability ratios exceeding 0.51, suggesting they might be relatively environmentally safe when used as pesticidal agents (Table 2). Conversely, other plant compounds, including (–)-homopterocarpine, limonene, α-pinene, β-himachalene, and (E)-β-caryophyllene, displayed ecotoxicity probability ratios above 0.50, indicating a potential environmental risk. Nonetheless, despite their potential for active toxicity, these phytochemicals are naturally volatile and do not persist in the soil for extended periods; therefore, their environmental impact is considered minimal.

Table 2: Phytochemicals exhibit varying probabilities of causing ecotoxicity

S. No	Name of the phytochemicals	Ecotoxicity	
		Active	In-active
1.	(–)-homopterocarpin	0.66	00
2.	Thymol	0.54	00
3.	Azadirachtin	00	0.68
4.	Limonene	0.67	00
5.	(–)-α–Pinene	0.78	00
6.	Himachalol	0.57	00
7.	β-Himachalene	0.70	00
8.	(*E*)-β-caryophyllene	0.68	00
9.	Resveratrol	00	0.55
10.	2,3-dihydrobenzofuran	0.65	00
11.	Nimbandiol	00	0.63

The toxicity of three negative phytocompounds (ecotoxicity) was assessed using STopTox (https://stoptox.mml.unc.edu/), a web-based toxicity prediction server that employs machine-learning (ML)-enhanced QSAR models [35]. Acute thermal toxicity analysis indicated that azadirachtin, resveratrol, and nimbandiol were toxic with confidence levels of 71%, 61%, 57%, and 61%, respectively (Figs. 4-6).

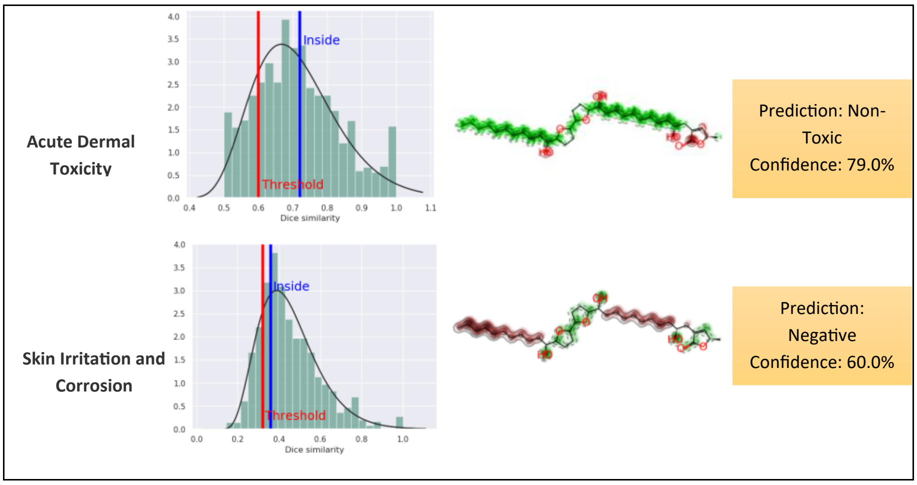

Fig 4: Predicted toxicity parameters and toxicity confidence levels for Azadirachtin

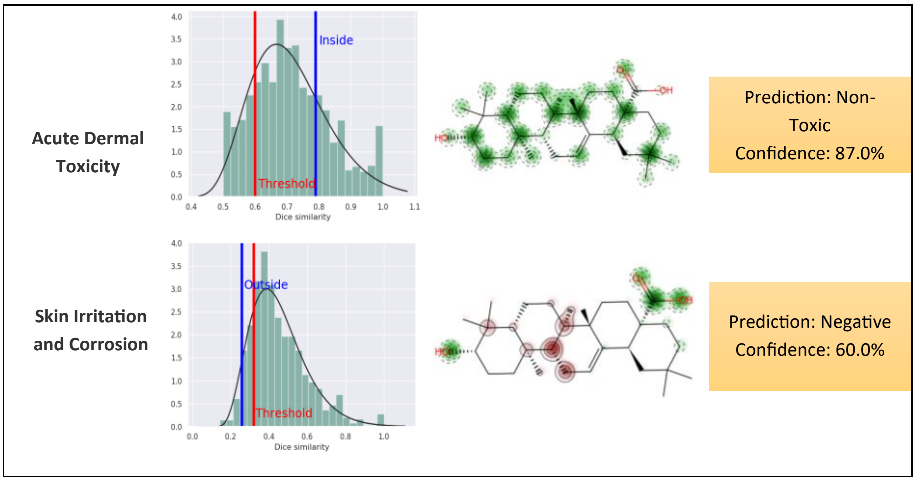

Fig 5: Predicted toxicity parameters and toxicity confidence levels for Resveratrol

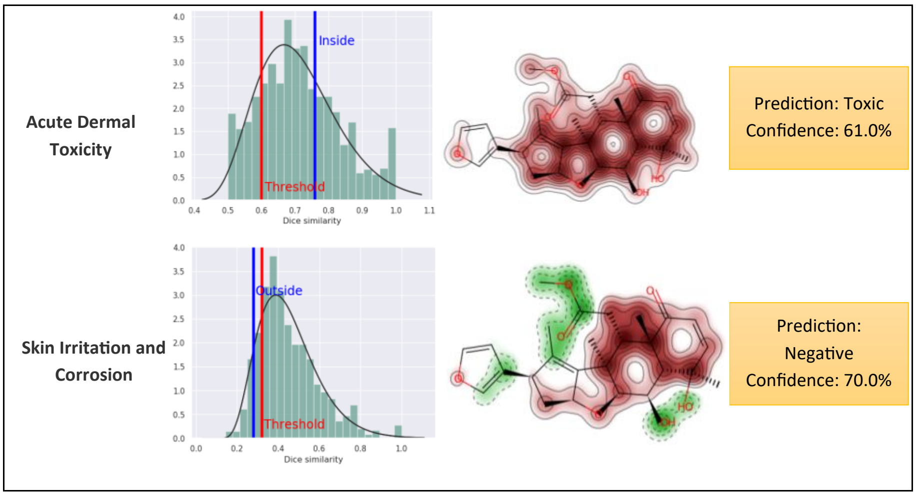

Fig 6: Predicted toxicity parameters and toxicity confidence levels for Nimbandiol

The predictions for skin irritation and corrosion indicated that azadirachtin, resveratrol, and nimbandiol had confidence levels of 60, 50, and 70%, respectively**.** It has been clearly demonstrated that these compounds can be used in agricultural insect pest management without causing environmental pollution. Given that the confidence levels were 50% or higher, severe toxicity was unlikely. Based on the toxicity assessment, this study concluded that these compounds may be beneficial for managing insect pests in agriculture.

Biopesticides often degrade quickly in the atmosphere, making them less efficient and stable than traditional pesticides. This limits their use, so they're often used alongside conventional pesticides to reduce chemical concentrations. Plant extracts, especially flavonoids, are promising sources of biopesticides due to their role in plant defense. Essential oils are also popular in ecological agriculture because they're biodegradable, diverse, target new molecules, and have low toxicity, helping achieve sustainable crop yields. Despite their potential, essential oils face challenges, including volatility and inconsistent effectiveness between the lab and the field. Nanoencapsulation can overcome these issues by improving the bioavailability, stability, and efficacy of these compounds. Overall, essential oils and plant-based products are promising for the future, and awareness of sustainable plant-based biopesticides should be promoted.

Conclusion and Future Prospects

The intensive use of synthetic pesticides in agriculture has failed to safeguard biodiversity, the environment, or human health. Currently, various horticultural and agricultural plants offer phytochemicals essential for pest control. By extracting and activating plant-derived pesticides with suitable solvents, production costs can be minimized, and issues related to storage and waste disposal can be addressed. Although producing botanical pesticides requires substantial raw materials, these plants can be grown on marginal lands unsuitable for food production, thereby avoiding competition with food crops. Additionally, chemical engineers and scientists can improve methods for identifying and utilizing plant compounds with insecticidal properties. By investigating production and extraction techniques using affordable solvents, costs can be reduced, making it easier for smallholder farmers to adopt safe pest-control solutions. There is a pressing need to broaden research on the use of plants with biologically active compounds for crop protection. Moreover, increasing adoption of organic-based pest control products within Integrated Pest Management (IPM) systems will boost exports of agricultural goods to niche markets, thereby bolstering international trade, food security, biodiversity conservation, environmental sustainability, and human health.

Authors Contribution

Sambasivam Suganya: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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