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Natural Pesticides in Indian Agriculture Sector: A Minireview

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ABSTRACT

This systematic study explored the process of formulation, preparation and application of natural pesticide molecules in Indian agriculture with a focus on leveraging such pest management strategies instead of synthetic pesticides as cleaner alternatives. Natural pesticides developed from herbs and essential oils have been considered as environmentally safe options with target specificity due to increasing awareness about environmental health and insect resistance. It presents a review of classical and recent developments in formulation methods, their production techniques and regulatory system followed for natural pesticides along with an overview of the advantages and disadvantages of these pesticides in Indian agriculture. The review addresses some of the practical challenges, like scalabilty, economic feasibility and effectiveness across a range of irrigated crops and pest species. The small proportion of studies that evaluated natural

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pesticides mainly identified them as contributing towards sustainability, but there is little information on their effectiveness or cost–benefit potential compared to synthetic pesticides, highlighting the need for further research. Investing in more rapid need-based optimizations of formulation steps, enhancing access to market and other policies enabling natural pesticide promotion at work will soon be looked into place natural pesticides in Indian cropping systems.

Keywords: Formulation of natural pesticides; botanical extracts; microbial based organic pesticides; encapsulated method.

1. INTRODUCTION

The Indian economy stands on the pillars of agriculture, employing more than 50% of the population and contributing a sizable amount to the GDP. Because of its agricultural origins, crop protection measures to ensure food security remain vital. With population of India on rise, there is a need for agriculture sector to increase productivity and achieve consistent yield. Hence, pesticides now play a crucial role in this situation having become an important armoury of the farmers against various pests, diseases and weeds (Feng et al., 2018; Kumar et al., 2020). Pesticides came into extensive use during the Green Revolution beginning in the 1960s, which saw India go from a food-deficient to mostly self-sufficient nation in staple grains through the introduction of high-yielding crop varieties, chemical fertilizers and pesticides.

While pesticides are vital for boosting agricultural productivity, their pervasive employment has not been without its price. The chemical make-up of many pesticides has been causing serious global environmental and health concerns for decades now. The use of pesticides, though effective in pest control, has side effects and disturbs the soil health and biodiversity, as well as water quality. In some instances, residues of pesticides have lingered within food items leading to high public health fears for long term exposure to poisonous substances. In addition, the record demonstrates that exposure to pesticides can result in numerous incessant and intense health conditions for farm workers – respiratory problems, skin sicknesses, immune system muddling and even cancer in some instances. Pesticide management has emerged as an important aspect of agricultural policy, reflecting the complex interplay between pesticide use and agricultural production on one hand and environmental sustainability on the other. Pesticide consumption in India is not uniform across the states. Maharashtra, Uttar Pradesh and Punjab emerge as the biggest consumers of pesticides because widespread cultivation of crops such as cotton, sugarcane and rice require the use of more pesticides. In Haryana and West Bengal, where high-value crops are grown in intensive farming system, the annual pesticide consumption is also high (Singh, 2023; Wend et al., 2024). At the other end of the spectrum are states with lower pesticide use, either because of an absence of crops which generally require such chemical inputs or higher adoption rates over time for organic agriculture and other pest management alternatives – methods such as IPM that reduce reliance on synthetic pesticides. This variation in pesticide use across states reflects the diverse nature of Indian agriculture that is determined by climatic and soil conditions, insects and pest pressure as well as crop preferences. Due to current changes over the decades, researchers, policymakers and farmers have begun searching for safer substitutes in place of environmentally harmful chemical pesticides. The careless and overuse of chemical pesticides has caused soil and water pollution, as well as ecosystem disruption by targeting non-target organisms such as pollinators or natural pest enemies. Scarcity of resources and these adverse effects have raised alarm about the sustainability of chemical-intensive farming systems in the long term and made it obligatory to transform agricultural practices towards environmentally friendly systems (Gerwick & Sparks, 2014). The implementation of integrated pest management (IPM) strategies that thread together biological, cultural, and mechanical control techniques with minimal use of pesticides has been recognized as a viable solution to minimize reliance on synthetic chemicals without sacrificing yield. At the same time, public interest in organic agriculture (which abstains from synthetic inputs) and biopesticides (biologically based pesticides generally less harmful to non-target organisms with a reduced environmental impact), has increased. Targeted pest control with minimal environmental impact can be achieved through the use of biopesticides such as formulations based on neem, microbial agents like Trichoderma and *Bacillus thuringiensis* or plant-extracted compounds. With the realization of the potential of these alternatives, in India various initiatives have been taken up by the government to promote and practice sustainable agriculture. Encouraging farmers to move from conventional agriculture to organic is only sustainable if biopesticide production receives subsidies, awareness campaigns are done on the hazards of excessive use of chemicals and more research and development activities are carried out. In addition, the authorities have upgraded the regulatory framework to ensure that only approved pesticides are used and in amounts consistent with safety standards which re addresses issues related to pesticide residues in food products and environmental contamination. Today, India has made rapid advances in green revolution technology. This is largely due to economic factors; synthetic pesticides are generally less expensive, readily accessible, and provide an immediate and effective outcome. Small and marginal farmers, accounts for most of the agricultural workforce in India, they often do not have the financial resources to shift towards sustainable alternatives, which may bear higher upfront credits or require investment on education/ infrastructure. Moreover, unawareness and training regarding the need to reduce pesticide overuse and adopt alternative methods has created a culture of dependency on chemicals. In areas where pest pressure is severe and immediate control to prevent loss is necessary, sustainable options may be seen as inefficient or labor intensive. Additionally, the supply chain for biopesticides and other sustainable inputs remains largely fragmented and underdeveloped, leading to often-inadequate access, especially in remote rural areas. Absence of proper support systems, such as technical guidance and extension services incentivise farmers not to adopt integrated pest management or organic farming practices. In addition, the uneven implementation of regulations and widespread use of fake or low-grade chemical pesticides in the market make switching to a more sustainable agricultural system very difficult. Addressing these barriers requires a multi-faceted approach. Enhancing farmer education programs, expanding access to affordable biopesticides and establishing strong supply chains for sustainable inputs are all necessary pathways towards cutting reliance on chemical pesticides. Government policies should continue to encourage sustainability not just via subsidies but also by stimulating research and innovation to make biopesticides more efficient and cost-effective. Partnership among stakeholders (policy makers, researchers, private sector, and farmers) is needed to build an ecosystem for the large-scale adoption of sustainable pest control practices. By tackling these issues, India can strike a balance between agricultural production and environmental sustainability to promote health in both its human population and eco-systems for the long term. This report discusses state-wise pesticide consumption of pesticides in India identifying the reasons for excessive use in some states and overall trends behind the pattern of usage of pesticides in India. It discusses the positive and negative socio-economic and environmental effects of using pesticides. The report also examines how the government can take part in providing regulatory measures to control pesticide usage along with necessary incentives to practice sustainable agriculture, identifying major hurdles including regional imbalances, economic barriers, and inadequate infrastructure for alternative pest control strategies. This report provides an overview of the current situation of pesticide usage and its effects – to help stakeholders in identifying and developing solutions that equitably balance farming productivity with environmental sustainability, leading towards a more resilient agricultural ecosystem in India.

2. LITERATURE REVIEW

Natural pesticides are considered to be a sustainable alternative of chemical pesticides with the promise of decreased human health risk and lower environmental pollution, especially in the case of Indian agriculture. Formulations based on trees such as neem or pyrethrum are classic examples of successes, with a strong performance and natural origin. Nevertheless, continue with treatment protocols based on more recent developments in product formulation technique now exploiting extraction and stabilization systems to offer greater proof-of-efficacy. Even with all these innovations, however, scalability and cost continue to be major hurdles. Those challenges can be addressed, experts say — with improvements to supply chains and increased government incentives — if they're made in time for this production growth to ramp up. According to regulatory experts, natural pesticides encounter significant market entry hurdles largely due to protracted and complicated approval processes. To fix this, they argue more streamlined regulatory frameworks must be created to help farmers gain faster and easier access to safe and effective products. Interdisciplinary research, it is anticipated, will have a central role in changing the sector over the next months and years. Natural pesticides can become considerably more affordable and effective by combining green chemistry, biological controls, and machine learning. With more robust support from policy-makers and the industry, such initiatives could position natural pesticides as a valid replacement for chemical pesticides in the Indian agricultural landscape.

3. RESULTS

3.1 Formulation and Applications of Natural Pesticides

Natural pesticides are isolated and stabilized active ingredients derived from botanicals, essential oils and other natural sources with maximized efficacy often with designed synergies achieved through optimal mixtures (mixed synergy) or improved activity in combinations with adjuvants. These formulations are able to maintain and control pests with less impact on the environment, thus integral in sustainable pest management. Natural pesticides contain active ingredients that are often concentrated plant, fungus, or mineral derived substances. Surfactants or solvent is an integral part of pesticide formulation which enhances their spread, absorption and retention on plant surfaces leading to improved pesticides effectiveness. Different methods are used to maximise the effectiveness of these natural insecticides. The extraction method e.g. cold-pressing (essential oils) or solvent extraction (plant compounds), for instance, can have profound effects on the concentration and activity of active constituent's present. Moreover, based on the application requirements of each product, formulation strategies such as emulsions, powder and sprays are designed to facilitate ease in use and enhanced targeting four specific pests. Natural pesticides rely on natural ingredients, which can be especially valuable for organic farming systems that limited the use of chemical pesticides. Biopesticides can be used against various types of pests (insects, fungi and weeds) while leaving accompanying organisms such as pollinators, earthworms or soil microbes unharmed. Natural pesticides have multiple applications from field pest protection and post-harvest treatment to integrated pest management (IPM). Additionally, much demand for environmentally friendly alternatives to these chemical pesticides has resulted in formulation that is more potent and more lasting than traditional natural pesticides (e.g., some products exist with longer shelf life by using genetic engineering or incorporating nanotechnology).

In conclusion, the formulation and application of natural pesticides provide a practical and viable solution for sustainable agriculture, offering a safer and environmentally friendly alternative to conventional chemical pesticides. Such formulations can assist in lowering pesticide residues on food and are also necessary for ecosystem health, forming an integral part of modern integrated pest management.

Fig. 1. Benefits of using natural pesticides

From botanical extracts: Bio-pesticide formulation means developing the natural/bio agents in such a way, that they are easy to apply and effectively prevent the pest. Active ingredients sourced from nature, such as plant extracts (Table 1) microbial cultures or beneficial insects are combined with stabilizers, surfactants and carriers to promote efficacy and shelf life. The bio-pesticides are made to suit the needs of application with regards to liquid or powder, and granules during the formulation processes. Novel methods of microencapsulation and hence nano encapsulation especially can be employed to purposely shield the biomolecules from environmental degradation as well as increase delivery specificity. Formulation is essential design of bio-pesticides ensures that they are safe, efficacious and friendly to the environment

Table 1. List of plants and their targeted pests

Name of plant	Target pathogen
Cinnamon spp	*Staphylococcus aereus*, *Escherichia coli*
Lantana camara	*Klebsiella pneumonia, Escherichia coli*
Satureja hortensis spp	*Bacillus cereus*, *Candida kruzei*
Thymus vulgaris	*Erwinia amylovora*, *Eschrichia coli*, *Staphylococcus aureus*, *Bacillus cereus*
Satureja hortensis spp	*Bacillus cereus*, *Candida kruzei*
Azadirachta indica	*Helicoverpa armigera*, *Spodoptera litura*
Ocimum sanctum	*Aspergillus niger*, *Pseudomonas aeruginosa*
Allium sativum	*Phytophthora infestans*, *Botrytis cinerea*
Curcuma longa	*Aphids*, *Whiteflies*, *Mealybugs*
Eucalyptus spp	*Alternaria spp.*, *Helminthosporium spp*
Mentha arvensis	*E. coli*, *Klebsiella spp.*, *Candida albicans*
Pelargonium graveolens	*Houseflies*, *Mosquito larvae*
Neem (*Azadirachta indica*)	*Fusarium spp.*, *Aspergillus spp.*
Garlic (*Allium sativum*)	*Alternaria spp.*, *Helminthosporium spp*
Syzygium aromaticum	Candida albicans, *E. coli*, *Klebsiella spp.*
Chrysanthemum cinerariifolium	*Houseflies*, *Mosquito larvae*
Zingiber officinale	*Fusarium spp.*, *Aspergillus spp*
Lemon grass	*Staphylococcus aureus*, *E. coli*

Botanical pesticides (Table 1) hold promise as sustainable alternatives to synthetic pesticides, considering the issues of non-target toxicity and environmental pollution posed by synthetic chemicals. They highlight the advantages of botanical pesticides such as biodegradability, cost-effectiveness, and lower toxicity to non-target organisms (Naik et al., 2020). Nonetheless, they point out the problem of formulation and little chemical information as barriers to wider uptake. The current study highlights the relevance of further research in phytochemical profiles and insecticidal modes-of-action for sustainable pest management (Lykogianni et al., 2021). Methods of extracting botanical pesticides from *Pelargonium graveolens* (geranium) using supercritical fluid extraction (SFE). Extraction conditions (pressure and temperature) optimization is performed to improve the yields, selectivity, and bactericidal activity of the extraction. The CO2 extracts are compared with those obtained by maceration and hydrodistillation as to their insecticidal and antifungal activities. They observe that CO2 extracts have important insecticidal activity (particularly at 9 MPa and 50 °C), whereas antifungal effects are enhanced with increasing volatile concentrations. This study demonstrates the promise of CO2 extracts as potent and eco-sustainable botanical pesticides. The use of bio-based liquid formulations from *Brassica carinata* for pest control in citrus orchards were used in southern Italy (2015). The study, from 2011 on, looked at pests like aphids, mites, scales and whiteflies. In conclusion, these natural formulations were found to be effective, indicating that plant-based pesticides may provide a comparatively safe alternative to chemical agrochemical pesticides. These bio-based products also proved to be good candidates for the development of integrated pest management and organic farming strategies, in line with European Commission directives on promoting safer alternatives and reducing risks associated with chemical pesticides (Benfatto et al., 2015). Hernani & Yuliani, (2023) explored the dynamic changes of some physical characteristics of natural biopesticides based on rice husk liquid smoke during 6 months storage time. The laboratory study was of emulsified concentrate (EC) formulations: F1, F2 and F3 and assessed pH, specific gravity, particle size and phase separation. pH and specific gravity were more stable while particle size increased and PDI was a triplet, independent variable. All of the formulas experience phase separation in either F1 or F2 which are less separate than F3. According to the study, these biopesticides can also be preserved for 6 months with little change in their physicochemical properties, indicating that such products could be applied directly or ready for future control of insect pests via sustainable pest management.

Microbial based natural pesticides: Natural pesticides based on microbial use effective microorganisms, such as bacteria, fungi and viruses to control pests in a sustainable and environmentally friendly way compared to synthetic chemicals. One of the classic examples is *Bacillus thuringiensis* (Bt): a bacterium that produces proteins toxic to insect larvae, especially moth caterpillars, without affecting beneficial insects or humans. For example, *Beauveria bassiana*, which can infect all insects by penetrating under their skeleton and causing death. These biopesticides are specific for certain pests and interfere with their life cycle through inhibiting growth or death. They are highly specific in nature, and therefore do not harm non-target organisms which makes them a suitable candidate for pest management. Also, microbial-based pesticides are suitable for organic farming due to their origin from the nature as well as minor environmental hazardous factors. Increasingly used in Integrated Pest Management (IPM) systems, they have implications for sustainable agriculture by providing an alternative to chemical pesticides, thereby contributing to environmental friendliness and biodiversity. These deliver an environmentally friendly approach to pest control, which aligns globally for the need of sustainable and more resilient agricultural practices. Machalova et al., (2015) reported that microbe-based biopesticides have recently gained in portrait proportions, especially among scientists and farmers interested in sustainable agriculture These biopesticides play a significant role in Indian agriculture because crop losses of 30–40% are common; the use of these compounds has been demonstrated to contribute positively to food grain production, particularly in several tropical countries (Tripoli & Schmidhuber, 2018). Kumar et al., (2021) studied the synthetic recognition of *Bacillus thuringiensis* (Bt) as a biopesticide and biofertilizer. As a pest control agent and plant growth-promoting microbe, the integration of Bt into transgenic crops such as Bt cotton and maize has provided both improved crop yields and an increase in pest resistance in agriculture (Moretti et al., 2002). Recent focuses on soil health by Effective Microbes (EM) formulations to increase crop productivity, grain yield and alter the growth response of crops such as rice, soybean and okra under abiotic stress. Their review highlighted the eco-compatibility of EM formulations, providing evidence that EM can be used as a sustainable agricultural input. Together, these papers underscore the importance of microbial-based biopesticides in enhancing crop production, moderating stresses and reducing environmental hazards of chemical pesticides to be a requisite for sustainable agriculture in future.

Nano encapsulation: Nano encapsulation encloses active pesticide ingredients in nano-sized carriers, improving stability, targeted delivery, and controlled release. This method enhances natural pesticides by protecting active compounds from degradation, reducing doses needed, and minimizing environmental impact. Nano-carriers like liposomes and polymers enable gradual, targeted release, improving efficacy while reducing risks to non-target organisms. Nano encapsulation also boosts pesticide solubility and adherence, making it a valuable tool in sustainable agriculture practices. Nanotechnology for environment-friendly neem-based pesticides (Charpe, 2023) discussed the advantages of nano-encapsulation to overcome problems such as photo-degradation, short efficacy and slow action in neem-based pesticides. The use of nanoparticles stabilizes neem oil and also minimizes environmental toxicity of the oil, thereby averting development of resistance in pests and prolonging its utility for pest management. It also has economic benefits that reduce the number of applications used. For example, the chapter by (Cooper & Dobson, 2007) on nano emulsions of pesticides illustrates the advantages of these novel formulations with regard to increased stability, effectiveness and environmentally benign characteristics. Their performances can be affected by pH, ionic strength and oil-water ratio. Nano emulsions with their ability to improve bioactivity, penetrate in addition being ecological substitutes for pesticide delivery systems (Souto et al., 2021) also studied nano-encapsulation of savory essential oil (*Satureja hortensis*) in biopolymers for bioherbicides. The herbicidal activity of *Amaranthus retroflexus* was enhanced by all three encapsulated formulations when compared to the unencapsulated formula, with 100% weed control occurring at 48 h for Arabic gum and Persian gum/gelatin and after 48 h with Persian gum. Ecological and hydrophilic formulation of a widely used insecticide, acephate: A nano-encapsulation complex developed by (Choudhury et al., 2012) which were characterized by DLS (dynamic light scattering) (90 nm)/SEM/TEM and FTIR spectra (120 nm) which enhanced formulation as a farmer-friendly pesticide delivery system. The problems that arise with chemical insecticides including toxicity, resistance and pollution therefore recommending Eucalyptus extract in nano capsules as a safer alternative. Identification of main components by GC-MS (1,8-cineole: 70.94%) The nano capsules were characterized showing a mean particle size of 380 nm and a zeta potential of −26.36 ± 5.31 mV. The highest efficacy was shown at 48 hours with an LC50 of 14.93 mg/ml, and therefore tests were performed on the basis of this time for efficacy determination. The efficacy of the nanocapsules is greater than that of conventional therapy and has less impact on the environment, according to the study (Khoshraftar et al., 2019). In another study (Adak et al., 2020) have developed nano scale emulsions of eucalyptus oil (EO) with the aim to provide a safer alternative to chemical pesticide for storage pest attack in rice. At the same time, they demonstrated lower lethal concentrations (LC50) than pure EO against *Sitophilus oryzae* and *Tribolium castaneum*, which prove their potential efficacy together with safety as an agrochemicals producer.

Essential oil based natural pesticides: These Plant oil-based natural pesticides, like neem, peppermint and eucalyptus are being used more frequently because of their natural modes of action and environmental advantages. The bioactive compounds contained in these oils such as terpenes and phenols disrupt the metabolism, nervous system, or reproductive cycle of pests. These natural alternatives are biodegradable, leaving no or less toxic residues in the environment compared to synthetic pesticides and pose minimal hazards to humans, animals and beneficial insects such as pollinators. Essential oil-based pesticides demonstrate broad spectrum efficacy against many insects, fungi, bacteria and nematodes. Examples include neem oil, which can limit insect feeding and reproduction, or eucalyptus oil, known for its potent antimicrobial activity. They play a special role in organic and sustainable agriculture because it fits within the framework of sustainable practices, as they minimize reliance on synthetic chemicals and promote soil health and crop production. These pesticides have a number of benefits and are renewable, inexpensive, abundant and can be used in an integrated pest management system. The growing consumer demand for agricultural products free from pesticide residues combined with recent tighter environmental legislation has made natural pesticides an important part of sustainable agriculture and anti-agrochemical pollution strategies. Further additions to research and policy support would enhance their use and development. Neem oil is used for agricultural pest control and as mosquito repellent Ghosh et al., (2021) described the preparation of neem oil micro emulsions which were made stable, safe and economical. Their study also involved molecular docking of neem oil component nimbin, which showed the best binding to the odorant binding proteins and may be an important step towards safer alternatives for mosquito repellence. Growing food without destroying the environment in particular, pollution by excess use of agrochemicals and development of resistant populations of pests. It stresses the role of biopesticides in pest management as a more secure substitute for chemical pesticides. On the other hand, biopesticides are hindered by short storage-life and sensitivity to light. The present review explores the efficacy of neem oil as a novel plant extract for enhancing crop protection and then discusses gaps, challenges, and future perspectives in developing sustainable crop protection practices (Estefania et al., 2016). Eucalyptus, (genus Eucalyptus), any of several hundred species of evergreen trees native to Australia and the source of a wide variety of products—including essential oil, gum, pulp, and timber. It is targeted to the eucalyptus leaf-eolium, which is extensively used in food, perfume and medicine. The oil is emphasized by the broad-spectrum of biological activity of many natural products such as antimicrobial, fungicidal, insecticidal, herbicide, acaricides and nematicide (Batish et al., 2008). Their study highlights the potential use of eucalyptus oil as a significantly natural environmentally friendly pesticide to overcome the high harmful effects on environment and health due to extensive use of synthetic pesticides. A study by (Khodeir et al., 2013) evaluated the effectiveness assessment of garlic oil (*Allium sativum*), eucalyptus oil (*Eucalyptus globulus*) and their combinations with two organophosphorus pesticides (Dimethoate 30% and Pestban 48%, Eq100 L./fadden for controlling the piercing-sucking insect pests of Faba bean (*Vicia faba*) under field conditions during 2011/2012 winters. During the study it revealed that garlic oil is the most effective pesticide on leafhoppers and planthoppers with 68.09% followed by Dimethoate and Pestban. In the case of aphids, garlic oil proved again to be in the top with 90.96% control but in both groups, relatively more lowest level was determined for eucalyptus oil. The study also looked at the side effects of such treatments on insect predators, including true spiders and minute pirate bugs (*Orius* sp.), indicating that natural oils had lesser impact on these beneficials as compared to chemical pesticides.

Ngegba et al., (2022) evaluated the efficacy of neem and garlic oil based biopesticide formulation (NGOE) in the control of destructive pest of watermelon. Results from the study provide evidence that NGOE can suppress specific pests, including leaf beetles and ants, while increasing beneficial insect activity. It also increased fruit yield, which demonstrates the possibility of sustainable pest control. Mockute & Judzentiene, (2004) reported that essential oil formulations of rosemary (*Rosmarinus officinalis*) and thyme (*Thymus herba-barona*) were explored as a potential alternative approach for controlling insect pest. Microencapsulation of these oils was performed and tested on gypsy moth larva. These proved to be highly effective with very high toxicity levels and over 98% encapsulation efficiency. The formulations proposed a feasible substitute for synthetic pesticides by providing environmental safety and controlled release of target relevant pest control. Mishra et al., (2019) analysed the composition of essential oils from *Tanacetum vulgare* (tansy), in Vilnius District, Lithuania. The oils obtained from leaves and inflorescences exhibited four chemotypes, all of them being: camphor; α-thujone; 1,8-cineole; and artemisia ketone. Principal components consisted of camphor, α-thujone and 1,8-cineole that differed by the respective chemotypes. In comparison to leaf oils, inflorescence oils were found to contain a larger proportion of oxygenated mono terpenes. Moreover, the chemotypes of oils exhibited differences in chemical compositions that can affect their application for pest control or others.

Production and standardization: Natural pesticides are produced by extraction of bioactive compounds from plant, microbial, or mineral sources using steam distillation, solvent extraction and fermentation methods. Commonly used have included essential oils, plant extracts, microbial formulations and mineral-based compounds. Because these compounds can be highly variable in concentration depending on the extraction method, plant species and environment, standardization processes are important to ensure consistency and efficacy. Standardization usually relates to the quantitative assessment of active substances and setting standards for its quality. These may include High Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometer (GC-MS) and Fourier transforms infrared spectroscopy (FTIR). These techniques for identifying and quantifying bioactive ingredients Moreover, in most cases regulatory authorities demand validation for sustainability, safety and environmental impact. It helps in maintaining the quality of batches to be used which means you will know how much effective and safe your pest control application might be. Clear standards increase product credibility and stimulates a broader use in organic and integrated pest management (IPM) systems (Tabana et al., 2020) provided a comprehensive review on the use of botanical insecticides (BIs) as eco-friendly substitutes to synthetic pesticides. While they consist of the sustainable and non-toxic breakdown, the acceptance of these phytochemicals is hampered by unpredictable pesticide activity due to variations among species. The review highlighted the necessity of standardization, quality control and bio-enhancement to file for wider agricultural usage. Walia, (2021) in their studied eco-safety benefits of botanical pesticides compared to chemical pesticides. The exception to all of this is microbial pesticides, which have difficulties with efficacy and cost. Hereby the review particularly highlighted need for regulatory frameworks which integrate New Approach Methods (NAM) that has enough scientific pedigree to justify assessment methods of microbial formulations and thus safety towards human health (Saberi et al., 2018) provided a literature review regarding the application of botanical pesticides, providing a historical record from ancient cultures to modern times and the increasing interest in this type of pesticide due environmental and health consequences of synthetic pesticides. Biodegradable options from botanicals (such as alkaloids, terpenoids and essential oils) are providing alternatives. Although they have great potential, the market share of botanical pesticides is still low (~1%). The authors highlighted the importance of more detailed reverse pharmacology studies in order to improve successful identification of pest control botanicals given increasing global threats from persistent, long-term effects of many chemical pesticides.

Table 2. Efficiency and application of each type of natural pesticides

Natural Pesticide Type	Effectiveness	Target Pests	Application Considerations
Botanical Extracts	Moderate to high	Insects, fungi	Depends on extraction method and concentration
Microbial-based	High for specific targets	Insects, fungi, bacteria	Requires specific conditions for microbial activity
Nano-Encapsulation	High, with controlled release	Insects, fungi, mites	Improved stability, requires advanced formulation
Essential Oils	Moderate to high, short-lived	Insects, mites and fungi	Often volatile, frequent reapplication needed

3.2 Supply Chain

The natural pesticide supply chain consists of sourcing raw plant or microbial raw materials, extraction, formulation and stringent quality control for consistency in bioactive compounds. After production, products are stored and delivered with care to preserve efficacy. The challenge, as always, is twofold: compliance with regulations and the seasonal constraints involved with raw materials. Much of this demand comes from organic and sustainable farming, resulting in an environmentally friendly, efficient supply chain that is required to keep those products consistent and effective (Gozali et al., 2024) addressed block chain technology and its potential for improving supply chains in the pesticide market. The study concludes that the block chain can greatly reduce risk and improve data security. Using simulation examples, they show that the incorporation of block chain enhances transparency, trust and cooperation between stakeholders which results in lower operating cost and improved efficiency in the entire supply chain. You can see this more in areas like traceability and sustainability, where block chain allows for the real-time tracking of products from farm to fork. This makes it easier to verify product origins and movement along any part of the supply chain as well as compliance with food safety regulations and reducing incidences of fraud. The findings show that adoption of Block chain, in addition to improving its practical functionality, can create a more resilient and transparent pesticide supply chain. In a related vein, (Thongni et al., 2023) explored the transformative potential of block chain in the agri-food sector highlighting its use in improving transparency and traceability while decreasing transaction costs. In the conversation, they talk about financial savings from block chain and procurement processes. One example that is cited, is the block chain pilot by the World Food Programme at refugee camps, which proved how it could simplify procurement and help reduce costs so that assistance can be delivered with greater transparency to those who are in need. Their research encourages additional investigation into how block chain can be leveraged to maximize the organizational, economic and social potential within agri-food supply chains (Reddy et al., 2024) conducted an extensive study about global supply chain problems, focusing on the aspects of transparency, security and complexity of international trade that can be solved using block chain. According to them, the block chain technology can facilitate supply chains by decentralization, trustlessness and immutable system of tracking goods & transaction which reduces fraud rates and strengthens data fidelity. At the same time, they expected there to be hurdles to implementing block chain. More interoperable block chains are necessary yet the study indicates there are challenges that require to be overcome if we want to integrate block chain technology more seamlessly across new areas of society in the future, needing further studies. Examining Bharat Rasayan Ltd., an Indian agrochemical company, (Sarkar & Kshirsagar, 2014) conducted a similar study in the context of supply chain management where he details its product portfolio, demand projections driven by crop land and pest pressure and sales channels among other aspects. They have multiple channels to reach the market like direct sale, retail stores, e commerce and cooperatives where they do tie-ups. In his Ph.D. dissertation, Shetty illustrates how agrochemical companies can utilize multi-channel distribution and advanced analytics to optimize their supply chain, improve customer penetration, and tackle demand forecasting and product availability issues. Collectively, these studies highlight the disruptive capability of block chain across different sectors from agriculture to agrochemical, via operational efficiency, traceability and sustainability measure improvements. Block chain could be used to solve a lot, underpinned by the need for transparency and cost reduction in complex value chains (both locally and globally).

Usage in Indian agricultural sector: Natural pesticide use is an integral part of sustainable agriculture, and if promoted/entrenched to help augment the manifolds benefits of organic farming in Indian agriculture. Indigenous farming practices have historically utilized plant-based pesticides (e.g., neem, turmeric and other botanicals), which reduces chemical residues on crops and improves soil health. Microbial solutions (biofertilizers and biocontrol agents) complement these plant-based products for a holistic pest & diseases management.

Supported by government initiatives like the subsidy for bio-pesticides and an emphasis on Integrated Pest Management (IPM) policies, farmers have embraced natural pesticides. This would also be in line with India's natural resource management for sustainable development that meets the national priorities and current global challenges like food safety, environmental pollution, and loss of biodiversity. Implementing these IPM tactics minimizes dependency on synthetic chemicals while enhancing climate resilience and pest outbreak control, paving a way towards sustainable agriculture for the long term.

Nevertheless, its numerous advantages are outweighed by immediate issues of high production cost, low distribution and adoption among farmers. Yet these challenges can be overcome with strategic funding in research, public-private partnerships, and supply chain enhancements. Over the long term, natural pesticides are a part and parcel of India achieving its objective of producing safe food as also ecologically sustainable agriculture Tertsegha et al., (2021) recommend the use of botanical pesticides as natural and less harmful substitutes for chemical fertilizers in agriculture during developing countries which assure sustainable agricultural practices without environmental detriment and lower health vulnerability. Natural pesticides provide a safer, more environmentally friendly alternative for pest control with reduced toxicity for farm workers, consumers and non-target organisms; an effective solution in global regions suffering the devastation of synthetic pesticides (Abhilash & Singh, 2009). The green revolution, while enhancing food production in India, has also been linked to health risk arising out of exposure to pesticides (Gentz et al., 2010). Regulatory and applicatory technology improvements are critical to control environmental pollution and related health hazards associated with pesticide pollution disturbances (Carson, 1962). The demand for increased food production needs to be balanced against efforts to reduce risks posed by pesticides, and better regulatory frameworks could help achieve this balance, according to a University of California, Davis, study that reviews the latest science on pesticide regulation. Zero Budget Natural Farming (ZBNF), a farming system aimed at reducing dependence on external chemical inputs and maximizing local resources in India, using more of the sustainably managed facilitates (Jain et al., 2024). Although they recognize its promise, they say there is skepticism among scientists about claim that it can be used at scale and long term, underscoring the need for more research. Chakraborty et al., (2023) provided a review of expanding biopesticides in India due to impetus by the Government, which has led to an increase in production as well as demand for these products. They highlight that biopesticides are eco-friendly and are therefore excellent substitutes to synthetic pesticides, moving us closer to sustainable farming (Okrikata et al., 2022). Drawing on spatial analyses of pesticide use in India, (2024) examine inequities by region and crop type and provide recommendations for better regulations to adjust pesticide application fundamental to be both fairer and effective. Pest management approaches underscore the need to move towards less chemical-dependent measures (Shetty, 2023) attribute the challenge to soil health in natural farming as due to the beneficial microbes present, and further narrate indigenous method of plant-based soil improvement. They emphasize that the government should foster these sustainable agricultural activities to counter the degradation due to synthetic chemicals. In conclusion, given the environmental and health problems associated with synthetic pesticides, these studies together indicate an emerging potential for sustainable agricultural practices in India either through biopesticides, natural farming or improved pesticide regulation. These alternatives, combined with sustained support from the government, provide exciting avenues toward environmentally friendly, health-supporting agricultural systems capable of providing food security in an environmentally sustainable way.

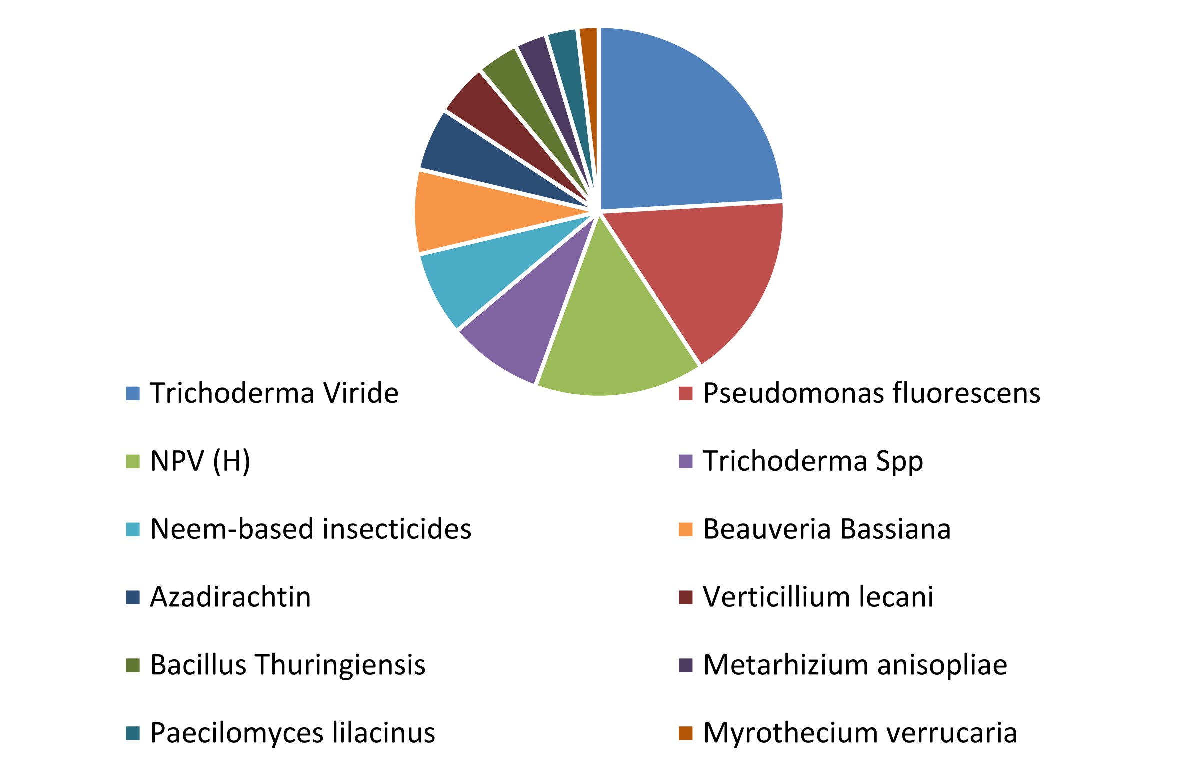

Fig. 2. Most popularly used natural pesticides

4. CHALLENGES AND FUTURE DIRECTIONS

Natural pesticides encounter challenges in production, standardization and adoption to the market. But season and geographic location can change the concentration of some bioactive compounds, and thus disrupt uniformity. Scalability is further limited by production costs and reduced shelf life. There is also limited awareness among farmers, which affects the wide deployment in mainstream agriculture. Future perspectives are focused on the establishment of innovative extraction and nano encapsulation technologies with enhanced stability and optimized bioavailability. If these natural pesticides had more of a broad spectrum, research could help make them viable against synthetic chemicals. To make the transition into conventional agriculture, natural pesticides will need increased government support, farmer education and the formation of protocols for standardization. In their elaborated summary, (Gupta et al., 2023) discussed the biopesticide potentials of natural compounds explaining modes of action and interaction mechanisms, and commercialisation challenges. This chapter points to the urgent need for research to address obstacles in market acceptability and technology advancement, for safer, sustainable alternatives to synthetic pesticides. Duke et al., (2002) viewed the larger version of these challenges that are due to the relatively poor discovery of phyto toxins from plant sources, a focus on non-pathogenic microbes rather than on plant pathogens, and the bioassay-directed isolation step that is highly demanding in terms of labour. Our future directions are to use current chemical characterization technologies and novel approaches to accelerate herbicide discovery, and also explore new plant-derived compounds that have been relatively unexplored. The change could open the door for more efficient and long-lasting herbicidal applications. A potent method of discovering new applications for well-known Natural products (NPs) is the development and application of innovative biological screens, which significantly increases the likelihood of discovering lead structures. Furthermore, it is commonly known that only a small percentage of soil microbes have been successfully cultivated and their NPs assessed for biological activity 430 Additionally, only a small portion of the genetic potential for secondary metabolites has been expressed and assessed among those that have been grown. Although the use of NPs for agricultural pest management dates back thousands of years to the early Greek and Roman eras, industry must re-engage with 21st-century technology in order to fully grasp its potential.

5. CONCLUSION

The transition from non-sustainable to sustainable farming systems can be achieved by leveraging the potential of natural pesticides, particularly those derived from botanicals and microorganisms. These solutions offer numerous advantages, including biodegradability, specificity in targeting pests, and reduced toxicity to humans and the environment compared to synthetic pesticides. However, achieving widespread adoption and commercialization of these products requires addressing several significant challenges. One major hurdle is the variability of phyto chemicals in plant-based pesticides, leading to inconsistent efficacy. This variability, coupled with high production costs, limits their competitiveness against synthetic alternatives. Furthermore, navigating complex regulatory requirements, such as the stringent European Union crop protection standards, adds an additional barrier for natural pesticides to gain entry into established agricultural markets. Addressing these challenges requires enhanced standardization and quality control to ensure consistent performance and safety.Natural pesticide formulations typically consist of bioactive compounds, essential oils, and microbial agents. Innovative approaches, such as hybrid formulations and nano-encapsulation, have improved their usability by enhancing stability, controlled release, and effectiveness. These advancements highlight the need for intensified research efforts, including reverse pharmacology and high-throughput screening, to identify novel bioactive compounds with superior efficacy.

Additionally, policy changes are crucial to support the adoption of natural pesticides. Governments can play a vital role by incentivizing research and development, promoting sustainable farming practices, and simplifying regulatory pathways for natural products. Public-private partnerships and investments in infrastructure for production and distribution can also address scalability and cost challenges. By aligning on standardization, regulations, and broader market acceptance, natural pesticides hold immense potential to mitigate the adverse environmental impacts of chemical pesticides. These alternatives could contribute significantly to global efforts for sustainable agriculture, safeguarding ecosystems while ensuring safe and sustainable food production. With the right policies and continued innovation, natural pesticides could serve as a cornerstone for achieving environmentally responsible farming practices worldwide.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (Chat GPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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