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INSECT PEST MANAGEMENT UNDER NATURAL FARMING: A REVIEW

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ABSTRACT

Insect pest management remains a central challenge to sustainable agriculture. The increasing dependence on synthetic pesticides during and after the Green Revolution has caused serious ecological, economic, and health concerns. Natural farming, particularly the Zero Budget Natural Farming (ZBNF) system popularized by Subhash Palekar in India, offers a sustainable, self-reliant, and eco-friendly alternative that minimizes external chemical inputs. This review synthesizes recent scientific findings and traditional ecological knowledge on natural pest management approaches, emphasizing botanical formulations, microbial inoculants, soil health restoration, and biodiversity-based strategies. Evidence suggests that natural farming enhances plant resistance, supports beneficial arthropods, reduces pest outbreaks, and maintains ecological balance while improving soil fertility and farm profitability. Despite promising outcomes, scientific validation, standardization of formulations, and large-scale field trials remain crucial to optimize these methods under diverse agro-ecological conditions.

***Key words**:* Natural farming, Pest management, eco-friendly agriculture, Zero Budget Natural Farming (ZBNF), Sustainable agriculture

Introduction

Ecological imbalance, pest resistance, soil degradation, and environmental contamination have been some of the crisis brought on as a result of over relying on chemical pesticides since the Green Revolution in the 1960s (Byrnes, 1990; Colbourn and Thornton, 1978). Extensive monocropping in conjunction with the usage of synthetic inputs has disrupted the natural predatorprey relationship, hence increasing susceptibility of pests, and increasing the input expenses of the agricultural producer (Ayansina & Oso, 2006; Lena & Rao, 1997).

As the term is found by Subhash Palekar (2014, 2016) within the framework of Zero Budget Natural Farming (ZBNF), natural farming reformulates the practical conceptualization of agriculture: depending on on-farm resources such as cow dung, cow urine and plant-based preparations to maintain soil fertility, as well as various pests. The philosophy is consistent with the philosophy of Do Nothing Farming described by Fukuoka, (1978), which emphasizes cooperation with ecological processes, but not aggression.

As recent studies (Badiyala and Sharma, 2020; Shakywar *et al.*, 2024) emphasize, natural pest management involves a multiplied approach that is a combination of seed decoction, microbial inoculants, and botanical pesticides (e.g. Neemastra, Agniastra, Dashparni Ark). These inputs do not only help to keep away pests like insects, but also help renew the soil microbial diversity and ecological stability 2. The Concept of Natural Pest Management.

Ecological Foundations and Philosophy

Natural pest management (NPM) is a key pillar of the Natural Farming (NF) paradigm, which represents a transition to an input-intensive approach to pest control in favor of an ecological approach, which functions in consonance with the natural environment. Instead of a total annihilation of insect pests through artificial intervention, NPM is focused on the ecological balance, biodiversity, and stability such that the numbers of pests do not reach the point when they are harmful to the economy (Paoletti, 1999; Doran *et al.*, 1996).

The predominant traditional pest control that is mainly ortho, rylon, and dibenzo-pinacolate-like insecticides, herbicides, and fungicides has created a general disturbance to the ecosystem, pest evolution, and resistance (Ayansina and Oso, 2006; Byrnes, 1990). Counter to this, NPM uses biological regulation, cultural methods, agricultural soil management and botanical additions in an effort to restore the self-composing ability of the ecosystem. This method acknowledges that every pest species has its natural predators, and presumes that they all play their ecological roles in an agro ecosystem (Glick and Bashan, 1997).

NPM is philosophically based on the ideas of Do Nothing Farming by Masanobu Fukuoka (1978) which promotes the idea of little human action in the natural processes. The ecological partnership that Fukuoka viewed in farming was the foundation of the implementation of these principles by Subhaswati Palekar in his development of the ecological farming model named Zero Budget Natural Farming (ZBNF) in India (Palekar, 2014, 2016). The philosophy of Palekar states that the agriculture practice must conform to the laws of nature, but not to substitute them with the man-made interventions. Therefore, his model will not embrace the use of chemical fertilizers and pesticides but encourages the use of native cattle, botanical extracts, and microbial inoculants as the alternatives that are sustainable.

Ecological pest control in such a construct is therefore the result of ecological restoration of the ecological processes interrupted by chemical dependence. When an agrocosystem works well, the predators, parasitoids, pollinators, and decomposers coexist with the crop plants sharing checks and balances, which exclude the pest outbreaks. This is interfered by the use of toxic chemicals which kill useful species and destroy biota in the soil. Hence, NPM tries to reconstruct the web of life within the agricultural systems, that is, ecological processes are at the fore which are used to manage pests as compared to using external control measures (Andow and Hidaka, 1998).

Principles of Natural Farming and Their Role in Pest Management

There are a total of four pillars on which the natural farming model as described by Palekar (2016) is based: Beejamrutha, Jeevamrutha, Mulching (Achhadana), and Whapasa. All these are important towards the holistic inhibition of pests and the creation of pest-resistant cropping systems.

Beejamrutha

Scientific name: *Bacillus thuringiensis* (Bt). The bacterium Bacillus thuringiensis (Bt) offers protection against seed predation caused by pests like bacilli, thistles, and vine borers (2008) Bacillus thuringiensis (Bt) is a bacterium that has been shown to provide chickens with protection against seed predation by such pests as bacilli, thistles and Beejamrutha serves as the structural part of managing pest in natural farming systems, which is aimed to control the pathogen and pests which infest at a seed or seedling level. It is made by the use of cow dung, cow urine, lime and soil all made of the indigenous (desi) cattle. Such formulation seeds have been shown to be inoculated with useful microbes that protect against the attacks of the unhealthy fungi, nematodes, and insects (Sreenivasa *et al.*, 2010). Another ingredient of Beejamrutha, cow dung, harbours antagonistic microorganisms including the species of Bacillus, *Pseudomonas*, and *Trichoderma* which inhibit the growth of pathogenic fungi by other mechanisms of competition and antibiosis (Kloepper, 1993; Chen *et al.*, 1995). Cow urine is also a source of nitrogenous compounds and antibacterial enzymes, lime is a disinfectant, which neutralises deleterious microorganisms. Treatment of the seeds through the application of Beejamrutha causes the seeds to be covered by a microbial film which invokes systemic acquired resistance (SAR), a physiological condition which does instruct an increase in defensive responses in a plant. This conditioning of the immune system at an early stage boosts its ability of the plant to tolerate the attack of insects at the vegetative growth stages (Glick, 1995; Nileema and Sreenivasa, 2011).

Jeevamrutha

Co-exists with Beejamrutha as one that feeds the soil of life. Jeevamrutha, a microbial culture, is fermented, prepared using cow dung, cow urine, jaggery, pulse flour and a small portion of soil, and is contaminated with bacteria, fungi and actinomycotes. These microorganisms disintegrate organic matter, solubilisate nutrients and also release growth-promoting substances which indirectly enhance plant immunity (Lazarovits, 1997). In Jeevamrutha, microbes (including, but not limited to Azotobacter, Rhizobium, and phosphate coatitor bacteria) improve the quality of nutrients indispensable to herbivores and the production of secondary metabolites to prevent herbivory (Rodriguez & Fraga, 1999). Also, useful microbes secrete volatile organic compounds (VOCs) which serve as natural repellents against insects. The soils that are treated with Jeevamrutha possess a complex rhizosphere microbiome able to synthesize enzymes such as chitinase and protease to wear insect exoskeletons and eggs (Shaikh and Gachande, 2015). As a result, the soil turns to be biologically active which helps in plant health besides naturally controlling pests.

Mulching:

Another key concept of natural farming is called Mulching or Achhadana and has far-reaching ecological effects in the way of controlling pests. Farmers protect the soil by introducing it with crop remnants, straw, or live cover, which help them keep the soil wet, control temperature, and lower soil erosion. More to the point, mulching helps to create a favourable environment to useful organisms like earthworms, spiders as well as predatory beetles that consume insect pests (Paoletti, 1999). The process of mulching inhibits the growth of weeds; these weeds are the alternative pest hosts. The organic material that is retained decomposes to produce the humus that feeds the soil life. Nitrogen fixation occurs through the use of live mulches (usually leguminous intercrops such as cowpea or clover) and creates a house to natural enemies of pests. These intercrops emit chemical signals which disorient or deter pests referred to as allelopathy. Taking this, the mulching technique can serve as a soil-management tool and as a pest control method that is based on the idea of ecological design in natural farming.

Whapasa

Whapasa is the practice of keeping the air and moisture in the soil pores at the most optimum level in a way where oxygen and water exist simultaneously. Over irrigation/ compaction causes anaerobic environment encouraging root diseases and insect pests, whereas heavy dry soils cause plants to get stressed making them more vulnerable to herbivory (Doran *et al.*, 1996). Whapasa promotes healthy root development and aerobic microbes activity through moderate irrigation and use of organic-matter. Roots contained in a fresh microchildren community give off biochemical cues which might then repel or dishearten pests yet promote more effective nutrient- uptake. Thus, Whapasa is a preventive ecological process which maintains soil and root health which is the basis of pest resistance.

Role of Biodiversity and Cropping System Design

Biodiversity forms the entire structural and functional basis of pest control in natural farming regimes. Monoculture situations generate an evenly dispersed habitat that facilitates high-rise growth of the populations of pests. Heterogeneous crops systems on the other hand, like intercropping, mixed and crop rotation, break cycles of pests, decrease the availability of hosts, and support the predator-prey relationships (Andow, 1998).

Palekar (2016, 2014) is a proponent of the idea of mixed cultivation of monocolds and dicolds, which include cereals intercultivated with legumes to maintain the balance of soil nutrients and increase ecological diversity. This diversity does not only help in maintaining the fertility of the soils, but also acts as the bane of host location by confusing the pests through visual and olfactory senses. Planting aromatic or deterrent plants like marigold (*Tagetes* spp.), basil (*Ocimum* spp) and coriander (*Coriandrum sativum*) will bring a natural predator (parasitoid wasps, ladybird beetles, and lacewings) that feeds on soft-bodied pests like aphids and jassids (Fukuoka, 1978; Glick and Bashan, 1997).

Field bundines and buffer strips that contain flowering herbs are ecological reservoirs of useful insects, which therefore preserve their occurrence even following a decrease in population of the pests. Such structural diversities determine self-sustaining self-control biological systems that reduce gene dependency on chemical insecticides. Biodiversity management therefore does not exist on the fringes rather it forms part of a core principle of natural pest management, as it directly associates ecological complexity with pest suppression.

Natural Pest Management as a Holistic System

Natural pest management (NPM) has transitioned to a collection of heterogeneous agronomic activities, instead of a coherent conceptual model, which is based upon the own agroecosystem Dynamics (Badiyala and Sharma, 2020). Modern researchers believe that the paradigm is the basis of a series of complementary interactions between soil biota, plant physiological processes, and overall biodiversity measures, but not a number of isolated interventions (Shakywar *et al.*, 2024). The focus of this discussion is the identification that combined application of microbial inoculant Beejamrutha and Jeevamrutha enhances the stomata-based biochemical defense mechanisms of plant, thus decreasing the use of external pesticide inputs (Badiyala and Sharma, 2021). At the same time, an out-of-field ecological defenses intervention like mulching and intercropping represents agronomic practices that are effective at reducing the population of insects by altering the habitat and diversifying the resource base (He *et al.*, 2019; Zhang *et al.*, 2021). It has been recorded that botanical extracts, such as neemastra, Agniastra, Brahmastra, and Dashparni Ark, demonstrate a strong insecticidal effect and have low non-target toxicity (Singh & Mehta, 2018; Liu *et al.*, 2020). The sequence of these strategies creates a self-reinforcing functional cycle, where the presence of high levels of soil microbial activity facilitates plant vigor, which, in its turn, leads to the existence of beneficial arthropods that help to control the outbreak of pests (Nair and Anil, 2015).

Review of Literature

Natural pest management literature in natural farming has developed as a conglomeration of folk ecological functionality combined with scientific substantiation of these practices. During the last forty years, studies have increasingly driven to the forefront the vitality of ecological balance, microbial diversification and biochemicals found in plants as primary regulators of the pest population without synthetic additions. The philosophical and practical basis of natural farming was given through early works, as Fukuoka (1978). The principle of his Do Nothing Farming is that agriculture which imitates natural ecosystems is the most sustainable and productive. Experimental tests in Japan conducted by Fukuoka showed that yields were at least as good as that of conventional systems when natural food web and soil structure was intact and there was no use of fertilizers or pesticides. This idea served as an inspiration to the Indian adaptation of natural farming written by Subhash Palekar, specifically his Zero Budget Natural Farming model of other popular natural farming methods that combines native cattle-made inputs and agroecological concepts (Palekar, 2014, 2016).

The scientific interest in the restoration of natural farming as a system found its way back to India since the ecological drawbacks of the Green Revolution had been noted. The accruing degradation of the environment by chemical inputs which include soil and groundwater contamination, destruction of the productive microflora, and bioaccumulation of harmful chemicals in food chains had already been foreshadowed by researchers like Byrnes (1990) and Colbourn and Thornton (1978). This was further worsened by heavy metal contamination as Wolnik*et al.* (1983) and Sauerbeck (1991) suggested that the ecological imbalance was also caused by interference with soil enzymes and the symbiosis of microbes. The latter results highlighted why there was an urgent requirement of low input, biologically safe pest management options, which led scientists to investigate organic and natural methods.

The modern literature on natural pest management has highlighted the fact that pest management in natural agriculture systems is a biological and ecological process, but not a chemical procedure. Research works by Shakywar *et al.* (2024) point out that the natural farming system incorporates various preparations of plants, including Neemastra, Agniastra, Dashparni Ark, and Brahmastra, which are also made using the locally presented botanicals, cow dung, and cow urine. These extracts are also highly concentrated with secondary metabolites, such as azadirachtin, nicotine, capsaicin, allicin and many phenolic compounds, which have insecticidal, repulsive or antifeedant effects. Examples include the loss of hormonal balance by neem-based preparations to insects in molting and reproduction (Hooda, 1997), the presence of alkaloids in tobacco and chili extracts that disorient the nervous system of the insect pests. The socio-economic aspect was also pointed out by the same study, indicating that such formulations can be like they have been prepared at farm so minuscule costs, and they are hence conspicuous to the zero budget philosophy.

In line with these bio-chemical methods, microbial biochemicals like Beejamrutha and Jeevamrutha have come into the forefront as an essential biological instruments in the management of natural pests. They do not just cycle the nutrients as they also lower the immunity of plants to the indirect suppression of pests. Studies by Sreenivasa *et al.* (2010) demonstrated that application of maize crops using Beejamrutha and Jeevamrutha enhanced the germination, root strength and output besides decreasing the pests attacks. The cause of these effects was considered to be the growth of plant growth-promoting rhizobacteria (PGPR) like *Pseudomonas fluorescens* and *Bacillus subtilis* that grow in the rhizosphere and produce antifungal and antibacterial compounds (Kloepper, 1993; Chen *et al.*, 1995). In addition, such microbes cause systemic acquired resistance (SAR) in the plants triggering the ecogenesis of the pathogenesis-related proteins, phytoalexins and phenolic compounds that increase the defensive response of the plant to insect feeding (Glick, 1995; Lazarovits, 1997).

To add on to this, natural inputs to the soil also enable soil microflora to stimulate the long-term resilience of the cropping systems. Research by Doran *et al.* (1996) and Shaikh and Gachande (2015) was able to demonstrate higher mineralizations of nutrients, structural stability and biomass of microbes in biologically active soils, which have increased crop resistance to pest damage. The presence of soil with abundant organic components and micro-life also offers nutritional benefit, but chemical signals, to discourage pest population. As an example, certain soil bacteria emit volatile organic compounds (VOC) that away herbivorous insects, whereas others are able to competitive with nematodes that feed on roots by secretion of enzymes like chitinase and protease (Rodriguez & Fraga, 1999).

The interaction between soils that have been studied biologically and those studied in relation to plant physiology, as well as pest ecology, is a common motif in the literature. According to the findings of a study conducted by the authors of this paper, the tomato plants sprayed with Jeevamrutha had increased chlorophyll, nitrogen and total phenolic content, which was associated with reduced incidence of the leaf-eating caterpillar (Nileema and Sreenivasa 2011). Various studies in the ecological agronomy back this connection between the plant nutrition and pest resistance whereby it is believed that the nutritionally balanced plant is unlikely to be attacked by the insect (Suslov, 1982; Glick and Bashan, 1997). Plants that are healthy and maintained under equal conditions of microbes have lesser volatile compounds that attract herbivores and thus lower the rate of colonization of pests.

Although microbial inoculants and botanicals are the biochemical and biological components of natural pest management, the ecological component lies at the habitat management and biodiversity. The article by Andow and Hidaka (1998) is still considered as being seminal in terms of proving that diversified crop systems contain more natural enemies than monocultures. This statement is consistent with the results of Paoletti (1999) who found that recycling of organic matter and conservation of soil biota by mulching provide microhabitats to such predators as spiders, ground beetles, earwigs. Having self-sustaining nature these natural enemies control the pemporary population by predation and parasitism. In Indian settings, the principles of Fukuoka have been implemented through the application of intercropping whereby legumes and aromatic plants have been incorporated as a result of cereals and vegetables to offer nutrient balance and to scare off insects (Neera *et al.,* 1992). Badiyala and Sharma (2020) explained the effects of live mulch e.g. cowpea and marigold to improve biodiversity, reduce soil evaporation, and parasite vectors by increasing the presence of parasitoid wasps and ladybird beetles.

Palekar has further developed these ideas as a system of four pillars of natural farming, Beejamrutha, Jeevamrutha, Mulching and Whapasa in which the soil biology, moisture balance and biodiversity work together to reduce pest pressure (2016). Whapasa, which is the maintenance of the best levels of air-water balance in the pores of the soil, makes the roots healthy, and eliminates the environment that encourages the development of pests. In anaerobic environments that result in overirrigation, which is common in chemically intensive systems, microbial activity and root-rot pathogens strengthen and the plants are vulnerable to insect infestation (Doran *et al.*, 1996). The stability of natural farming environment presented by the focus on minimal tillage and controlled irrigation promotes the stability of soil ecology and consequently the reduced rate of pest outbreaks.

A number of studies have even tried to measure the ecological and agronomic benefits of natural pest-management practices. Shubha (2014) and Nileema and Sreenivasa (2011) found an improvement in the yield and less pest occurrence in okra and tomato under the application of Jeevamrutha, respectively. Experimental studies by Shaikh and Gachande (2015) have verified that organic liquid manures enhanced the enzymatic activity of the soil and nurtured by the natural control mechanisms of pests. Indigenous formulations developed by Palekar (2014) have been tested in various agro-ecological situations in India and the results have shown a consistent reduction in the required pesticides that do not involve a loss of yield. Despite these promising results, the majority of researchers note that, in order to standardise the methods of preparations and determine the biochemical consistency of the formulations, like Neemastra or Dashparni Ark, long-term and multi-location validation is required (Rodriguez & Fraga 1999; Shakywar *et al.,* 2024).

Among the literature, the issue of environmental and health impacts of natural pest management stands out clearly. Arguing that syndrome of dependence on synthetic pesticides is one of the conditions that leads to the restoration of the ecosystem, increases in the purity of groundwater and decreases human contact with carcinogenic chemicals, Byrnes (1990) and Barabasz *et al.* (2002) proposed their thesis. The model of Palekar, as it does not require the introduction of chemicals at all, is in line with these environmental safety goals. In addition, natural pest management promotes a closed bioeconomy, where waste biomass and cow by-products are used in a cyclic way and thus, a closed nutrient loop is formed (Palekar, 2016; Shakywar *et al.* (2024).

At the international scale, the HDRA (1990s) guide to Natural Pest and Disease Control offered initial operational models that farmers should follow in using biological and botanical alternatives to chemicals. It has written about neem, garlic, chilli, and marigold and other plants preparations, focusing on their accessibility to farmers and their safety to the environment. These practices are echoed in the formulations of Palekar later and the argument is strengthened that ecological knowledge can lead to pest control that can be done using local and renewable practices.

The challenges and research gaps are, however, also identified in the literature. Numerous studies admit that, the natural farming systems have shown evident advantages in the aspect of pest control, maintenance of yields as well as environmental safety, but they are not scientifically standardised (Mattina *et al.,* 2003; Rodriguez and Fraga, 1999). The cow-related variability of the inputs and microbial charge, as well as the local environmental factors influences the reproducibility of outcomes. In addition to this, the majority of experiments have been done on a small scale and comparative data across regions are still limited. Shakywar *et al.* (2024) thus propose a combination of the old methodology with new biotechnological instruments to define microbial populations and detect active compounds that cause pesticides.

The literature that was reviewed arrives to a single conclusion that natural pest management is a multidimensional, ecologically friendly alternative to the use of chemicals in managing pests. The pests are controlled by the life cycle of connected interactions involving plants, soil microbes and other useful organisms through natural farming which also regulates the health of the soil and ecologic equilibrium. The variety of the literature related to this subject, where the indigenous work of Palekar is complemented by the contemporary microbiological explanations, substantiates the entire idea that the control of the pests is possible through the methods of nature-friendly work that do not endanger the environment but instead maintain the productivity of the farms, ensure the environmental safety, and guarantee the economic welfare of the farmers.

Mechanisms of Pest Suppression under Natural Farming

The natural farming techniques of controlling insect pests have a solid basis in the complex interconnection of biological, biochemical, and ecological processes that interact as a self-regulating agroecosystem. However, in contrast to the application of synthetic insecticides to control pests, which is based on chemical pest control, natural pest control, also carried out under natural farming, is based on ecological interactions between microorganisms of the soil, plants, insects, and the overall agroecosystem. These interactions develop direct and indirect pest suppression that are sustainable, economical and environmentally harmless.

Neemastra, Agniastra, Brahmastra, and Dashparni Ark are some of the botanical formulations used in the control of pests in natural farming at the biochemical level. These preparations are based on plants that grow in the surrounding that are pesticidal in nature, cow urine and cow dung, which serve as natural solvents and microbial enhancers. The effectiveness of these botanicals is attributed to the existence of active constituents like azadirachtin, nimbin, nicotine, allicin, capsaicin and saponins that possess various insecticidal and repellent properties. Neem-based products such as Neemastra are especially useful in interfering with the hormonal system of insect pests, thus, preventing the molting, oviposition, and reproduction (Hooda, 1997). As research mentioned by Shakywar *et al.* (2024) shows, Neemastra controls have a strong impact on the prevalence of aphids, whiteflies, and jassids, and they also prevent pests that are living in the soil due to the residual effect. Likewise, Agniastra which includes chili, tobacco, garlic and neem have been reported to have been effective as a broad-spectrum bio-insecticide, which targets a variety of sap-sucking and chewing insects by disrupting their nervous systems. The extract of ten varieties of plant leaves called Dashparni Ark gives a blend of repellency and antifeedant effects hence a multi-pest protection.

These botanical preparations have synergistic activity with valuable microbes on top of their chemical action. The base ingredients used (cow dung and cow urine) have high microbial populations of Lactobacillus, Actinomycetes, *Pseudomonas*, Bacillus. When used on crops they do not only provide insecticidal substances, they also facilitate the proliferation of friendly microorganisms on the surface of the plant. The production of enzymes and secondary metabolites by these microorganisms inhibit the growth of pathogenic fungi and bacteria indirectly decreasing the pest pressure by keeping the plants healthy. The urine of cows is especially significant in this respect because it is rich in urea, phenols, and uric acid that have natural antibacterial and antifungal properties, and also increase the protective properties of plants (Shaikh and Gachande, 2015).

The microbial and physiological level is crucial in the use of Beejamrutha and Jeevamrutha in pest suppression by improving soil health. The inoculants of microbes brought in through these inputs enhance the cycling of nutrients, the growth of roots and general vigor of the plants which induce the systemic resistance (ISR) to insect pests. This process is associated with plant defense pathway activation that leads to the synthesis of biochemical compounds such as phytoalexins, peroxidases and phenols which render the tissues of the plants less palatable to insects (Glick, 1995; Chen *et al.*, 1995). According to Sreenivasa *et al.* (2010), crops treated with Jeevamrutha suffered less infestation by shoot borers and leaf miners mostly due to the healthy crop plants that had well-developed roots that could withstand and recover insect attacks more effectively. In addition, the useful microorganisms related to Jeevamrutha, like *Pseudomonas fluorescens* and *Trichoderma harzianum*, also secrete chittinolytic and proteolytic enzymes that can in direct relation destroy the exoskeletons of the insect larvae and egg, an added biological means of pest control (Rodriguez & Fraga, 1999).

The pests are also regulated by the ecological balance of soil that is preserved in the natural farming systems. The regular application of organic materials by mulching and using microbes improves the food web of soil, sustaining the predators like nematophagous fungi, predatory mites, and earthworms that indirectly regulate the population of the pests. Soils that are healthy and full of microbial life are less vulnerable to outbreaks of pests since they maintain a dynamic balance between the pests and the natural predators. Doran *et al.* (1996) and Paoletti (1999) emphasized the fact that soils which have large microbial biomass and organic carbon facilitate the cycling of nutrients and release of biochemical signals that discourage herbivory. The improvement of the soil biodiversity, hence, serves as an ecological insurance system, so that the population of pests is kept in control by the system of natural predation and competition.

Ecologically, the ecological control of mulching, intercultural, and companion planting enhances the biological mechanisms of control. The practices offer shelter, food and breeding grounds to useful insects' ladybird beetles, lacewings, spiders and parasitic wasps (Andow & Hidaka, 1998). Natural farming systems regulate the top-down pests and avoid the rapid population explosion that is characteristic of the monocultural systems relying on chemicals by continually cycling natural enemies to control pests. Badiyala and Sharma (2020) noted that intercropping of marigold and basil in vegetable systems had significant impact on aphid and whitefly incidence on plants through attracting predatory insects and poor scent perception of the host plant. These ecological methods do not work by killing the pests but by keeping the equilibrium of the population and as a result, both the pests and the predators coexist at sustainable levels.

The second important pest-suppressive mechanism of natural farming is based on the biophysical characteristics of the soil-plant interface. Whapasa practices, among others, guarantee sufficient aeration and moisture content, which consequently support the aerobic microbial population that is vital to the wellbeing of plants. Soils that are over-irrigated and anaerobic embrace pathogens that are related to pests, as well as straining vegetation, which exposes them to insect attacks. The idea of natural farming keeping the balance of Whapasa helps to avoid this imbalance, which results in the environment where plants have a chance to reveal their natural defense (Palekar, 2016). Similarly, mulching minimizes fluctuations in soil temperature and growth of weeds so that the pest have few places to go.

Lastly, natural pest management is also resilient due to the integration of various ecological and biochemical processes. Although botanical extracts are direct deterring agents, microbial inoculants and soil based biological activity offer long term stability. The effect is synergistic, that is, a multilayered defense system biochemical deterring the plant surface, microbial resistance in the rhizosphere, and ecological control by the biodiversity in the ecosystem level. This is very different to the single-target, and very narrow mode of action of the synthetic pesticides that frequently causes pest resistance and environmental disturbance.

The findings of Shakywar *et al.* (2024) confirmed that the effective collaboration between plants, microbes, and soil organisms is due to their working as a unit that creates synergy and results in effective natural pest suppression. This replenishment of the life in the soil and ecological networks converts the farms into a chemically dependent system to self-sustaining biological systems. Pest management in natural farming is in essence not a process of responding to pest destruction but a proactive process of restoring the ecosystem. It creates a balance between production and the environment, showing that productivity and sustainability can be attained when the natural defense mechanisms that nature has are supported instead of being killed.

Empirical Evidence of Efficacy

Empirical studies regarding natural farming systems give a growing evidence that ecological and biological approaches of pest management, are not only eco-friendly but also effective in agronomy. During the last 20 years, various field and laboratory research has reviewed the effectiveness of natural pest management systems such as cow-based microbial formulations, botanical pesticides, and habitat management methods and their effects on pest control, crop production, and soil condition. The results are always that these practices applied as an integrated system bring about the same pest control as with the use of chemicals, and without sacrificing the cost they enhance the soil fertility and increase the cost efficiency.

The application of the Zero Budget Natural Farming (ZBNF) in the Indian state of Himachal Pradesh, Karnataka, Andhra Pradesh, and Maharashtra, is one of the most widely reported examples of natural pest management effectiveness. Badiyala and Sharma (2020) have carried out large-scale field experiments in Himachal Pradesh to determine the effects of different natural farming inputs on cereal and vegetable crop pests. Their findings indicated that with the application of the formulations of Neemastra and Agniastra on crops, the reduction of pest infestation was 70-90 percent of the untreated control plots. It is interesting to note that the decrease was made without any synthetic input of pesticides and crop production did not decline or grow slightly. It was also reported by farmers that natural inputs, which were made out of locally sourced materials such as neem leaves, cow urine, and cow dung saved a lot of money that would have been spent on agrochemicals, and this caused the net farm income to be high.

More evidence of effectiveness is provided by microbial based soil treatments. Sreenivasa *et al.* (2010) also noticed a high increase in pest resistance as well as crop yield of maize fields treated with Beejamrutha and Jeevamrutha. The research indicated that treated plants were found to have stronger root systems, thicker stems and had more chlorophyll content which translated to be more resistant to stem borers and leaf miners. The authors explained this resistance by the fact that the microbiology of the soil became better and that the enzymes of plant defense like peroxidases and polyphenol oxidases were also activated. This is similar to a relating study on tomato crops conducted by Nileema and Sreenivasa (2011), who found the use of Jeevamrutha not only raised the fruit yield by 22 percent compared to the control but also suppressed whitefly and fruit borer infestation by more than 60 percent, which also indicated the relationship between soil biological activity and pest suppression.

On the biochemical scale, botanical pesticides that are prepared following the principle of natural farming have been shown to have high insecticidal and repulsive effects. Shakywar *et al.* (2024) contrasted the efficacy of various natural pest management preparations such as Neemastra, Brahmastra, and Dashparni Ark in various crops, such as cotton, tomato, and okra. The findings showed that Neemastra which was extracted using neem and cow urine had the greatest level of control on sap-sucking insects, including jassids, aphids and whiteflies, with a 80 per cent suppression rate two applications later. A blend of ten local vegetable extracts by the name Brahmastra was found to be very effective in case of pod borers and caterpillars and also Dashparni Ark was found to be highly effective in deterring pests that eat leaves. The results of these experiments showed that naturally grown botanicals do have the potential to compete with the effectiveness of commercial bio-pesticides provided that they are adequately fermented and applied at the right time.

Long term ecological gains of natural pest management have also been registered. Research in Karnataka and Maharashtra by Shaikh and Gachande (2015) showed that repeated Jeevamrutha use after consecutive seasons increased soil microbial counts, improved the level of organic carbon, and minimized the rate of occurrence of major insect pests. This is in support of the claim that natural farming is effective in suppression of pests not simply due to simple toxicity, but due to reorganization of the farm ecosystem into a biologically sound structure less susceptible to pest outbreaks. Both natural systems were characterized by large population sections of useful insects like ladybird beetles, lacewings, parasitic wasps, and this method confirms that the technique creates a natural predator prey equilibrium (Andow and Hidaka, 1998).

Evaluations of large-scale farmer participatory research of more than 600,000 farmers indicated that natural farming plots had a lower pest incidence and input costs of up to 50 percent, and yields of major crops, including paddy, maize, and groundnut, were not less and sometimes greater. The independent assessments by agricultural universities established that the pesticide application rate in conventional plots was four times more than in natural farming plots but damage to pests was always less in the latter owing to higher plant vigor and better predators.

Food quality and environmental safety testing are other facts. Wolnik *et al.* (1983) and Barabasz *et al.* (2002) recorded that natural farming produce had insignificant traces of chemical residues and heavy metals as opposed to conventional produce. This implies that natural pest management not only helps to suppress populations of pests but also helps in provision of safer food and healthier ecosystems. These results have helped to make natural farming an option to addressing the twin problems of pest control and environmental depreciation during the post green revolution period.

On the whole, the empirical research is united by one common idea: the natural pest management is scientific and effective. The system obtains a steady pest control, reduction in costs, and ecological restoration through combination of microbial inoculants, botanical pesticides and ecological habitat enhancement. All these results confirm the assertion that natural farming is a resilient self-sustaining system of pest control that can make the traditional system of agriculture oriented towards ecological regeneration.

Comparative Advantages over Chemical Control

The comparison between the natural pest management and the chemical pest control is not only about the difference in the inputs but the essential difference in the philosophy of agriculture and ecological influence. Compared to the situation when chemical pest management looks at the elimination of the pest by immediate external intervention using synthetic methods, natural farming focuses on prevention and ecological equilibrium by using biological and environmental controls. The comparative advantages of the latter can be applied to various spheres environmental sustainability, cost-effectiveness, soil health, human safety, and long-term productivity.

The greatest benefits of natural pest management can be observed in an ecological perspective, as this is a method that has the potential to restore and sustain the biodiversity of agricultural ecosystems. Synthetic pesticides are very widespread, especially organophosphates and carbamates which not only eliminate target pests but also kill beneficial organisms (pollinators, decomposers and natural predators) (Byrnes, 1990; Andow and Hidaka, 1998). Such thoughtless practice disrupts the ecological balance and results in the revival and resistance of pests. By comparison, natural means of pest control, such as neem extracts, cow-based preparations and microbial inoculants, maintain useful insect populations, and increase the abundance of predators like ladybird beetles, lacewings, and parasitoid wasps. Research by Shakywar *et al.* (2024) and Badiyala and Sharma (2021) had verified that the biodiversity indices in natural farming plots was always high compared to the conventional ones, the ratios between predators and their prey stabilized at sustainable levels. The strategy, therefore, changes the pest control into a friendly ecological interaction.

Naturally, natural pest management has astonishing benefits to the small-scale farmers, in terms of economics. In normal farming systems, synthetic pesticides and fertilizers contribute 4060 per cent of input expenses (Byrnes, 1990). Natural farming as opposed to it is solely dependent on the on-farm low-cost resources like cow dung, cow urine, and plants found locally. The pest control formulations such as Neemastra or Dashparni Ark can be prepared at the insignificant expense of farmers, which have left them in need of commercial agrochemicals and market fluctuations. Empirical field research of Himachal Pradesh and Andhra Pradesh (Badiyala & Sharma, 2020; RySS, 2021) reveal that natural farming lowers the total costs of cultivation by approximately half and does not affect or even increases the yield. This is in line with the vision of Palekar (2016) of zero budget agriculture that seeks to see self-reliance instead of external dependency to improve the economic sustainability of the rural livelihoods.

The comparative advantages of natural pest management are also long-term due to the soil health advantages. Repeated use of pesticides is also observed to interfere with the soil microbial diversity, slow down the enzyme activity and also prevents the recycling of food (Barabasz *et al.*, 2002). The consequences of these effects are reduced fertility and structural degradation that predisposes one to pests and illnesses. On the other hand, the natural sources of farming inputs such as Jeevamrutha and Beejamrutha replenish microbial life in the soil, replenish organic carbon and enhance physical properties of the soil (Sreenivasa *et al.*, 2010). Doran *et al.* (1996) and Paoletti (1999) have found that in natural management soils, earthworm density, aggregate stability, and nutrient retention is increased which results in plant vigor and resistance to pests. Therefore, natural pest management deals with the factors contributing to the occurrence of pests, which include nutrient imbalance and disturbance of the ecology, as opposed to the treatment of the symptoms using chemicals.

The benefits of natural pest management are unquestionable in both human and environmental health. World Health Organization (WHO) estimates close to one million pesticides poisoning cases involving approximately 20,000 deaths every year and this is in developing nations where they are still using dangerous pesticides (HDRA, 1990s). The natural pest management will remove this danger completely, since the non-toxic, biodegradable materials are not harmful to human beings, animals and the environment. Surveys by Wolnik *et al.* (1983) found that produce of natural farming systems has insignificant amount of chemical residues, thus, it is safer to consume and export. Moreover, natural pest management will cut down green house gas emissions

Table 1: Comparison of natural pest management with Chemical Pesticides.

Aspect	Natural Farming	Chemical Pesticides
Cost	Minimal, locally produced inputs	High recurring input cost
Ecological impact	Maintains biodiversity, safe for pollinators	Kills beneficial insects, causes resistance
Human health	Non-toxic	Carcinogenic, causes poisoning
Soil fertility	Enhanced microbial life	Declining fertility, residue accumulation
Sustain-ability	Circular, self-reliant	Input-dependent and unsustainable

that come with the production and transportation of pesticides and this will enhance climatic resilience.

Overall, natural pest management presents a superiority of multidimensionality vis-a-vis chemical pest management. It is ecologically rehabilitative, cost effective, socially accommodative, and environmental friendly. It is regenerative and all-encompassing as it helps to improve soil health, biodiversity, and human health at the same time in comparison to industrial agriculture. The comparative evidence substantially confirms the fact that the pest control in natural farming is not a substitute of the chemical practices, but a global change towards the ecological harmony and sustainable fruitfulness.

Challenges and Research Gaps

Nevertheless, even though natural pest management (NPM) has gained increased acceptance as a viable and ecologically friendly alternative to chemical control despite its growing popularity among researchers and practitioners, a number of challenges and gaps in the literature persist in restricting the application and scientific validation of this approach. The main hurdle associated with this problem is the absence of standardization and quantification of natural ingredients like Neemastra, Jeevamrutha, and Dashparni Ark. Their composition, microbial content, active biochemical levels, and the preparation methods of cow dung are significantly different based on the source of cow dung, plant species, and the local climatic condition (Shakywar *et al.*, 2024). This variability tends to give uneven outcomes in different regions and is thus challenging to come up with consistent scientific data of efficacy.

Insufficiency of long term, controlled field research comparing natural pest control with conventional systems is another type of limitation. The literature that is available is mostly short term or localized demonstrations and in many cases with no experimental design and purely in farmer field conditions. This has resulted in the fact that there is no coherent quantitative information available on pest suppression, yield performance, and ecological impact (Rodriguez & Fraga, 1999). Mechanistic research with molecular and biochemical techniques is also necessary to find out either the active compounds or the microbial species that are underlying the pest suppression effects and also to determine their interaction pathway in the plant-soil-microbe continuum.

Most agricultural extension services are still skewed to the chemical input sector, which does not provide much technical training on how to prepare and apply natural formulations to farmers (Badiyala and Sharma, 2021). In addition, natural crops lack clear certification, which makes it difficult to motivate the market. To fill these gaps, it is necessary to conduct research togetherness between the traditional ecological knowledge and the modern biotechnology coupled with governmental support on standardization, training and marketing. The challenges will be overcome not only to enhance the scientific basis of natural pest management but also to speed up its introduction as an alternative to mainstream thinking on sustainable agriculture.

Future Prospects

Natural pest management of the future is in interface between the ancient ecological knowledge and the current scientific breakthrough. Developments in microbiology, molecular biology and analysis chemistry can be critical in the identification and characterisation of the bioactive compounds and useful microbes found in the natural formulation e.g. Jeevamrutha, Neemastra, and Dashparni Ark. This kind of scientific validation would allow drawing up standard preparation steps, which would guarantee uniform effectiveness in different regions and types of crops.

In addition, biotechnological and ecological modelling tools could assist in decake the complicated relationships among the soil microbes, plants and pests and result in proactive systems of pest epidemics and optimal utilization of natural contributions. On the policy level, adoption will be increased by promoting farmer education, participatory research networks, and market incentives of naturally grown produce. Credibility and consumer confidence will also be enhanced by setting up certification and quality assurance systems on the natural inputs.

Finally, natural pest management presents a way of achieving climate-resilient, low-input, and regenerative agriculture, which complies with the sustainable food systems and biodiversity preservation objectives of the world. The next task is to integrate these practices on an interdisciplinary level, and natural farming can become a scientifically sound and internationally accepted model of farming.

Conclusion

Natural agriculture has a holistic approach to pest control. It enhances the synergist effects of botanical pesticides, non-harmful bacteria and ecological design, hence reducing the reliance of synthetic chemicals, and promoting the sustainability of the soil and vegetative health over the long term. The effectiveness of such a strategy is supported with the empirical data in the Indian and global settings; however, strict research and standardisation remain inevitable. Natural pest control is beyond farming, it is a paradigm shift that should seek the restoration of the balance between crops, soil, biodiversity, food security, and ecological stability.

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