



REVIEW ARTICLE

Enhancing ecological integrity and resilience: The use of biocontrol agents and botanicals for sustainable plant disease management in *Jhum* systems of Nagaland

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Abstract

Shifting cultivation (*Jhum*) is a common farming method in the Northeastern hill areas of India. *Jhum* system of farming is traditionally prevalent throughout the hilly regions of Nagaland. *Jhum* is frequently misrepresented as being environmentally destructive. The multilayered diversity in the *Jhum* system, however, serves as the ecological basis for disease suppression in *Jhum* fields. At the genetic level, farmers keep and use landraces and traditional types of rice, maize, beans and millets, many of which have built-in resistance to pathogens that are common in the area. Diversity at the species level, such as co-cultivating functionally complementary crops like legumes (which fix nitrogen (N), aromatic herbs (which repel pests) and root crops (which stabilise soil), adds spatial heterogeneity that limits the capacity of pests and pathogens to disseminate efficiently. The vertical layering of the plant structures and uneven field shapes make conditions less like monoculture, which stops the movement of insects that carry diseases and the spread of fungal spores through the air. These actions together create an environment of systemic stability that protects the agroecosystem from both living and non-living stressors. Combining these native ecological strategies with scientific research findings on eco-friendly disease management approaches investigating the effectiveness of biocontrol agents and botanicals in controlling plant pathogens pertinent to the crops of Nagaland provides a comprehensive view of the resilience of *Jhum* systems. In this context, laboratory and field trials executed to evaluate the biocontrol agents like *Trichoderma* spp. and plant-based treatments from the area against important crop pathogens by various researchers are reviewed here. Combining modern science with traditional ecological knowledge, biological control techniques can improve disease resistance and promote sustainable agriculture practices in traditional *Jhum* farming systems.

Keywords: agroecosystem resilience; biocontrol; crop diversity; disease suppression; shifting cultivation; sustainable agriculture; *Trichoderma*

Introduction

Nagaland, the 16th state of the Indian Union, is in the far Northeastern region of India, between 25°10' N and 27°4' N and 93°15' E and 95°20' E. The state has a land area of about 16579 km². The topographic variation of the land ranges from 100–3826 m above sea level. Nagaland is a narrow, hilly strip running from Southeast to Southwest, forming part of the Northern extension of the Arakan Yoma mountain range of Myanmar. It shares borders with Assam to the West and North, Myanmar to the East, Arunachal Pradesh to the Northeast and Manipur to the South. The terrain is largely mountainous and rich in natural resources. The state experiences a predominantly monsoonal climate with high humidity. Annual rainfall averages between 70 and 100 inches (in) (1800–2500 mm), concentrated mainly between April and September, though rainfall is relatively low in April and May. Strong winds from the Northwest are common in February and March. Summer temperatures range from 21–35 °C, while winter temperatures generally stay above 4 °C (40 °F), though frost is common at higher elevations. The average annual temperature ranges from 18–20 °C in the higher elevations and from 21–35 °C in the lower regions. Humidity remains high across the state.

The climate of Nagaland varies from tropical to sub-tropical to temperate, supporting a rich diversity of flora and wildlife. Four major soil orders have been found in the state, viz., inceptisols, ultisols, entisols and alfisols. The soils of the state are primarily inceptisols, which cover 66 % of the land. These soils are mostly fine clay, clay, loam and fine loamy clay and are very common near riverbeds. About 23.8 % of the land is made up of entisols and alfisols, which make up 7.3 % and 2.9 % (1). This mix of different weather conditions with combination of different soil types creates an ideal environment conducive to the proliferation of plant diseases. Climate change, changes in farming methods, shift toward more intensive farming and introduction of new types of crops make it harder to control plant diseases. Disease surveys carried out in collaboration with the State Department of Agriculture in Dimapur and Peren districts from 2011–12 and 2013–14 found several serious threats to important food and cash crops (2). *Jhum* paddy was found to be highly vulnerable to blast disease, underlining the continued importance of traditional rice varieties for their genetic resilience. Growing *Colocasia* faces significant challenges because of leaf spot or blight, which is mostly caused by oomycetes like *Phytophthora* blight. Wilt disease hampers ginger production, while anthracnose has become a common problem for bean crops.

Nearly 70 % of the population in Nagaland relies on agriculture for their livelihood. Many farmers in Nagaland continue to practice shifting cultivation. Locally known as *Jhum*, this system is an age-old, indigenous agricultural practice that forms the subsistence livelihood, driven by geographical and social imperatives which are almost a direct response to the challenging mountainous topography. *Jhum* land covers an area of 160000 ha which is nearly 10 % of the state's total geographical area and 35.50 % of the total cropped area. In *Jhum* cultivation, forest land is cleared to grow crops for a short period, after which the land is left fallow to regenerate, demonstrating its deep connection with the surrounding forest ecosystem. The total forest cover spans 870000 ha and represents 52 % of its geographical area (Table 1). The state consists of 17 administrative districts, inhabited by 17 major tribes along with other sub-tribes. Each tribe is distinct in character from the other in terms of cultivation practices besides customs, language and dress. The average annual *Jhum* area cultivated per household can be anywhere from 0.5–2.5 ha.

Agricultural practices in the state, especially among *Jhum* communities, are profoundly based on traditional ecological knowledge and they usually don't use synthetic chemical inputs. This cultural orientation has substantial ramifications for the management of plant diseases, which frequently merges traditional agricultural methods with integrated disease management (IDM) methods. The use of chemical fungicides and pesticides is mostly in lowland areas with more intensive farming and is still limited, both in terms of size and where it is used. Recent data shows that the use of pesticides in Nagaland has one of the lowest amounts in India, with only 7.83 t of solid pesticides and 10319 L of liquid pesticides. This is less than 0.5 kg ha⁻¹, which is lower than the national average of 0.6–0.7 kg ha⁻¹ (3). These low levels of pesticide use show that people in the area are not only subsistence-oriented, but also the way agriculture works in the area and the way community norms and state- policy frameworks at the national level that make it less likely that people will use chemical fertilisers and pesticides. These factors collectively contribute to the continued reliance on ecologically sustainable practices in plant health management. This systemic avoidance of agrochemicals establishes *Jhum* as an "organic-like" farming process, relying on traditional and plant-based methods to control seasonal pests and diseases (4–9). The avoidance of synthetic chemicals in *Jhum* also naturally aligns with global organic agriculture criteria.

The different types of cultivation predominantly practised in Nagaland beside *Jhum*, include wet rice terrace cultivation (WRTC), alder-based farming system and *Zabo* cultivation system. *Jhum* cultivation is however, the most common, as it is practiced throughout Nagaland, whereas WRTC is primarily concentrated in Kohima, Phek and the plain areas of the state, including Dimapur

Table 1. Area under different land use in Nagaland

Land use	Area (in ha)	Percentage of total geographical area
Forest area	870000	52.00
Net sown area	450000	27.00
<i>Jhum</i> cultivation/Fallow land	160000	10.00
Non-agricultural uses	110000	7.00
Barren and uncultivable land	70000	4.00

Source: Anon., 2025. Nagaland Statistical Handbook 2025, Directorate of Economics & Statistics, Government of Nagaland.

and Chumoukedima districts. Alder tree-based farming system is largely practised by tribes of Angami, Chang, Yimchunger, Chakesang and Konyak while *Zabo* cultivation is an original farming system, native of Kikruma village under Phek district. The term *Zabo* meaning system of impounding of water, is a distinct water harvesting technique through rain-water for meeting the needs of drinking and irrigation purpose.

Jhum represents a complex agroforestry model essential for regional food security. Expert analysis in terms of land use dynamics and conservation challenges shows that *Jhum* is a complex, ecologically integrated system that is naturally set up for sustainable plant disease management and the conservation of agrobiodiversity (9–12). The intrinsic sustainability of *Jhum*, especially when overseen with adequately extended fallow periods, gives real environmental benefits (13). Studies have shown that organic farming systems like the *Jhum* can store significantly more carbon (C) than traditional, chemically intensive practices, demonstrating its ecological significance in C cycling (14, 15).

This research offers an agroecological evaluation of resilience mechanisms in the *Jhum* cultivation system. It shows how farmers in Nagaland use genetic, species and structural diversity through practices like multi-cropping and nutrient management, fallow rotation, seed selection, wood ash application and minimal tillage, as main ways to control plant diseases without using chemicals. This kind of structural complexity makes *Jhum* fields more stable and able to adapt to changes in the environment. The research additionally combines real-world data on the use of biocontrol agents and botanicals to assess their effectiveness against major phytopathogens that detriment crops in Nagaland.

Agroecological systems for disease prevention in *Jhum*

The main way that *Jhum* protects itself from widespread disease outbreaks is through its structure complexity and high agrobiodiversity, which makes it hard to set up the same host populations that usually cause disease pathways based on monoculture.

Avoiding disease by growing many different crops and using the *Jhum*scape

Jhum cultivation is characterised by a multi-cropping system in which staple cereals such as rice and maize, along with a wide range of pulses, millets, oilseeds and vegetables like pumpkin, beans, colocasia, tomato, cucurbits, chillies etc. There can be as many as 50 different types of plants and crops in one *Jhum* field that has been identified (16). This agroecological structure plays a significant role in both diversity in crops and diets, which is a key part of local food security and resilience in nutrition. Also, growing more than one crop in *Jhum* is a way to protect the environment. The spatial and species complexity of this system forms a kind of biological camouflage that makes it harder for pests and pathogens to find their hosts. This setup makes it harder for insect vectors to move around and for airborne particles to spread fungal spores and oomycetes, which lowers the chance of large-scale disease outbreaks that are common in systems with only one type of crop. The alder-based *Jhum* cultivation in Khonoma, Nagaland, is an example of the high level of biodiversity in *Jhum* system, where researchers have found and documented up to 57 different types of food crops, showing a lot of biological protection against agricultural failure (17). In monoculture, on the other hand, a pathogen or pest can quickly spread through the whole field because all the plants are the same type (a single crop

with similar genes). This makes it easy to spread disease, which causes large-scale epidemics.

In varied plant communities, exemplified by traditional *Jhum* systems, spatial heterogeneity is very important for keeping pests and diseases from spreading. The plants of the same species that are spaced apart from each other collect less pathogen inoculum because pathogens and their vectors encounter increased challenges in locating and transferring between good hosts. As a result, disease outbreaks are less severe in mixed cropping systems, compared to single-crop systems (18). Rice is often grown in *Jhum* landscapes, grown along with maize, legumes, Job's tear (*Coix lacryma-jobi* L.), sorghum and several other vegetables that grow in the ground. This setup not only enhances functional crop diversity but also makes physical barriers that stop the spread of viruses and bugs that are harmful to plants. People often plant *Coix lacryma-jobi* in patches on rice fields. The long, hollow stems of the plant make whistling sounds when the wind blows, which produces a sound that deters birds and rodents (19).

Additionally, the incorporation of specific intercrops in *Jhum* system helps inhibit the spread of harmful weeds and other hosts of pathogens. Many plant diseases have a wide range of hosts and survive the off-season by colonising wild and common weed hosts. Thatch grass (*Imperata cylindrica* (L.) Raeusch.) is one such weed common in *Jhum* fields, where it competes with paddy for nutrients and light and also serves as an alternative host for pests like the brown planthopper (*Nilaparvata lugens*). This threat is reduced by growing plants such as cassava (*Manihot esculenta* Crantz), sesame (*Sesamum indicum*) and soybean (*Glycine max* (L.) Merr.), whose deep root systems improve soil quality. It has been reported that their exudates inhibit the growth of *I. cylindrica*. Thus, multi-cropping in *Jhum* not only makes the environment more resilient but also provides effective, low-input methods for controlling pests and weeds based on local agroecological knowledge systems.

Nutrient-driven disease avoidance and alder-based *Jhum* system (*Alnus nepalensis* D. Don)

Soil-borne pathogens such as *Rhizoctonia* spp., *Fusarium* spp., *Verticillium* spp., *Sclerotinia* spp., *Pythium* spp. and *Phytophthora* spp. are significant threats to crop growth and production, potentially causing 50–75 % yield loss for many crops (20). In contrast, *Jhum* farmers have developed a highly stable agricultural system through their deep understanding of the growth requirements of each crop component. Their practices ensure the efficient use of sunlight, soil nutrients and the natural complementarities among crops (21). In *Jhum* cultivation, the primary crops include rice, followed by maize, millet, Job's-tears and small millets. Vegetables commonly grown are legumes, potatoes, pumpkins, cucumbers, yams, tapioca, chilies, beans, onions and taro (arum). By cultivating a diverse range of crops with varying planting and harvesting times, as well as different growth patterns, they optimise nutrient use from various soil layers and capture sunlight more effectively, leading to improved resource utilisation.

The symbiotic relationship between rhizobia and legumes is well-known for its role in biological nitrogen (N) fixation, which not only enhances plant growth but also reduces disease incidence across various crops. Rhizobia are effective in controlling the growth of soil-borne plant pathogenic fungi, including those from genera such as *Fusarium*, *Rhizoctonia*, *Sclerotium* and *Macrophomina*. This antagonistic activity is primarily due to the production of antibiotics,

hydrocyanic acid (HCN), mycolytic enzymes and siderophores under iron limiting conditions (22, 23). The alder-based *Jhum* farming system, practiced by various tribes viz., Chakhesang, Chang, Yimchunger, Konyak and notably the Angami tribe in Khonoma village, represents a highly evolved form of shifting cultivation. The integration of the N fixing alder tree (*A. nepalensis*) is a critical adaptation engineered to correct nutrient-deficient soil, particularly in areas facing short fallow periods. The success of alder system is predicated on both mechanical and biological enhancements to soil function. The practice of pollarding ensures continuous tree regeneration while supporting a multilayered cropping canopy. Integrating alder (*A. nepalensis*) into *Jhum* cultivation helps rejuvenate the land, due to the beneficial symbiotic relationship between alder and the actinobacterium *Frankia* and cultivates a diverse and competitive soil microbiome. Crucially, the N-fixing capability of the tree leads to enhanced nutrient status, characterised by significantly high levels of available N, moderate phosphorus (P) and potassium (K) and a high soil organic carbon (SOC) content (24, 25). The strong microbial community engages in biological antagonism, effectively suppressing key soil-borne pathogens and making the plant's immune system stronger. Antagonistic compounds that fight pathogen (26) and help reduce plant diseases (27) with *Frankia* are well known. The main contribution of alder system to disease management is indirect ecological control. By making the soil more competitive biologically, the system lowers pathogen virulence and makes it less likely that inoculum will survive in the environment, effectively eliminating the need for chemical soil fumigants. This structural strength makes sure that the system stays stable and healthy for the environment in the long run.

Disease avoidance through physical sterilisation

The first step in *Jhum* is to clear a patch of forest and then burn it, using slash and burn methods to get rid of plants and debris that have built up. Even in the second year of *Jhum*, it is common to cut off the top layer of soil along with plant debris and burn the leftover straw from harvested crops. This process is not just for getting the land ready but plays an important role in preventing disease. The heat sterilises the soil temporarily and kills all the microbial pathogens in the soil, which leads to the removal of harmful microorganisms and insects, providing a cleaner, immediate planting environment. Burning process has the potential to destroy plant disease inoculum, like existing sclerotia and plant residues where sclerotia grow, as well as plants that serve as alternate hosts. It also eliminates insects like arthropods, which are responsible for spreading plant pathogens (28, 29). Burning and slashing followed in the *jhum* system helps in control of weeds, soil-borne pathogens and other diseases of crops (30).

The high soil temperatures generated by fire can directly damage cell structures, effectively killing soil biota (31, 32). Burning rice stubble is known to reduce inoculum levels of pathogens such as *Sclerotium oryzae* (stem rot), *Curvularia lunata* (black mould) and *Corticium sasakii* (sheath blight). A 10 cm layer of surface litter burned during *Jhum* can destroy nematodes down to a depth of 9 cm (18). Fire can raise soil temperatures at the surface and sometimes at deeper layers, to levels lethal for microorganisms, with lethal temperatures for soil microbes being as low as 60 °C for 1 min (33). It is widely accepted that a large proportion (60–95 %) of the nutrients in tropical forest ecosystems are stored in the above-ground biomass (34). These nutrients are released into the soil

through burning, making them available for crop cultivation. The alkaline ash produced increases soil pH, reducing soil acidity and the toxicity of aluminium (Al) and manganese (Mn). Given that many areas of the Northeast region have acidic soils, shifting cultivation helps neutralise the soil, making it more suitable for crop growth. It was also reported that the traditional practice of vegetation slashing and burning can have positive impact on tropical soil which sustains crop yield during cropping with reference to phase in *Jhum* lands. Furthermore, the burnt biomass produces nutrient rich ash (35). This ash acts as an immediate natural fertiliser, enhancing soil fertility and significantly, decreasing soil acidity by raising the pH. This immediate nutrient boost helps crops overcome early stress, reducing vulnerability to common seedling diseases during the crucial establishment phase (36–38).

Avoiding disease by managing fallow land and rotating pathogens

The fallow periods are an important part of the *Jhum* cultivation process and are a well-known way to bring soil health back and control plant diseases. Farmers traditionally know that letting fields go fallow allows the soil regain its fertility, which helps manage plant diseases in an indirect way. During the fallow period, the natural soil nutrients are restored and the structure of the soil gets better. Weeds and pests are not actively managed during this time, which can help reduce their population over time.

Fallowing is scientifically recognised to diminish the accumulation of soil-borne pathogens and pests by breaking up their life cycles so that disease vectors in the soil can naturally decline. Letting fields go fallow helps get rid of pathogen residues and stops their spread by removing host tissue from them, since the decay of infected plant material removes the pathogen. Extended fallow periods also help with nutrient cycling and organic matter accumulation, which leads to healthier plants and more microbial biomass, possibly reducing the occurrence of diseases (39–41). Additionally, the composition of the soil microbiome is recognised to change during ecological succession (42), probably affecting how well nearby plants grow. For example, the number of harmful fungi tends to go down over time in abandoned farmland (43). The efficacy of the temporal control by fallowing confirms soil quality by increasing the length of the fallow period that significantly increases key soil quality index (SQI) components, including SOC, available nitrogen, phosphorus and potassium (NPK). A fully recovered soil environment, characterised by a high SQI, intrinsically fosters greater pathogen resilience (44–47).

Disease avoidance through seed selection and storage practices

Seeds are chosen from the best early harvests in newly cultivated *Jhum* fields because they are adapted to local conditions and demonstrate optimal yield, resilience and resistance to disease and pests. Seeds are preserved by sun-drying, while others are stored in baskets made from bamboo, rattan or cane by the farmers. Maize cobs, millets and similar crops intended for seed use are bundled together and hung from the roof beams of the kitchen or sometimes hung outside to sun-dry. Additionally, seeds are often stored in the kitchen above the fireplace, placed in special rectangular bamboo tiers tied and hung in baskets. Smaller seeds are either smeared onto a piece of cloth for sun-drying before storage or kept in hollowed calabashes with corn husk lids. Some seeds, such as cotton, cereals, maize and pulses are mixed with ash and charcoal before storage or placed between layers of wood ash for preservation. Paddy grains

dried on bamboo mats in the hot sun are kept in specially made bamboo containers that are usually kept near the kitchen. Granaries are also built to store paddy, using bamboo structures made locally in the area with bases raised higher around 1–2 feet above the ground.

While seeds are being stored, they can be attacked by different pathogens and saprophytes. Seeds can serve as passive vectors of pathogens in conducive environmental conditions which are then passed on to growing plants. Many pathogens do well when seed moisture content is in equilibrium with relative humidity between 65 % and 90 % (48). This can be avoided by drying seeds properly before storing them. Sun-drying seeds is a traditional and effective method practiced by the farmers to reduce moisture content. The sun heats the seeds and the air around them, which speeds up water evaporation and bringing the moisture levels down to safe levels. Not only is this method cost-effective, but also environmentally friendly, as it relies on solar energy and produces no carbon-dioxide (CO₂) emissions. Also, farmers often mix seeds with wood ash before putting them away for storage. Wood ash is known for its antimicrobial ability, which prevents the growth of bacteria and fungi (49,50).

The storing seeds above the fireplace, exposing them to smoke, has long been practised by the farmers. It's well known that smoke has antimicrobial properties that help reduce infections caused by bacteria and fungi. The substances in wood smoke come from the polymers in the wood, which undergo chemical reactions that are caused by heat and involve gasified moisture and intermediates. Extensive research has documented the composition of wood smoke, with more than 400 compounds found in wood smoke or smoke flavours from different sources (51–53). The importance of acids and carbonyls in the antimicrobial effects of liquid smoke was emphasised (54). Moreover, numerous researchers have noted the antimicrobial properties of phenolics and acetic acid. acid and carbonyls in different amounts (53, 55, 56).

Avoiding disease by using wood ash

In *Jhum* cultivation, farmers often plant cucurbits, chillies and beans in certain places where twigs, branches and other organic residues have been collected and burned. Consequently, ash-enriched soil enhances seed germination and promotes vigorous plant growth. Crops grown in these burned areas usually exhibit a lower incidence of diseases compared to those grown in unburned areas. Farmers also use foliar application of wood ash by spreading it on crops and soil. The light dusting of ash over the leaf surface and around the base of the plant on the soil surface has been reported to be effective (57). Wood ash has a lot of different nutrients, such as calcium (Ca), K, P, magnesium (Mg) and other important trace micronutrients that are needed in small amounts for plants to grow well. This means that using wood ash can help make the soil more fertile and helps plants grow healthy (58). The high amount of K of wood ash is known to help crops immune systems, making them more resistant to diseases. Wood ash also has antimicrobial properties and helps keep insects like aphids and pod borers away by acting as a natural pest repellent (59). Its application can create an environment less suitable for many plant pathogens because of its alkaline nature and presence of minerals like Ca and K (59).

Disease avoidance through minimum tillage practices

Farmers adopt minimum or zero tillage practices in *Jhum* cultivation. Minimum tillage minimises soil erosion, improves

drainage and water holding capacity and increases levels of microbial and earthworm activity. Additionally, it is less expensive, requires less energy and is more convenient. It also increases organic matter content on the surface and over the years gradually improves the soil nutrient reserves. In minimum tillage, seeds are often sown by dibbling method, which enhances quick germination without getting infected by soil borne pathogens. Moreover, minimum tillage reduces injury to the roots of crop plants caused by mechanical tillage or hand weeding, reducing the opportunities for opportunistic pathogens to infect. It also reduces the spread of pathogens by tillage practices (18).

In no-tillage systems, crop residues are left on the surface of the soil. The residues may become a food source for pathogens or alter the physical environment occupied by both the host and its pathogens. Changes in the microflora and increased microbial activity under conservation tillage may lead to biological control of diseases by antagonism or by competition. It was suggested that antagonists may be introduced as living seed treatments, particularly for soil-borne disease control under reduced tillage systems (60). For cereal crops, root disease incidence decreased with reduced tillage and new disease problems with take-all, *Rhizoctonia* root rot and *Pythium* root rot have not been developed at this time (61).

Harnessing biocontrol agents and botanicals

The overview of the effectiveness of biocontrol agents against diverse plant pathogens under Nagaland conditions are presented under Table 2. The research on biocontrol agents for management of plant pathogens, both soil-borne and foliar, is dominated by *Trichoderma* species, reflecting their established role as potent antagonists. The effectiveness of the biocontrol agents, *Trichoderma asperellum*, *T. harzianum*, *T. virens* and *T. afroharzianum* range from moderate (around 46–57 %) to high (above 70 %). *T. asperellum* recorded 72.96 % inhibition against soil-borne pathogens such as *Rhizoctonia solani*, *Fusarium oxysporum* and *Sclerotium rolfsii*, while *T. harzianum* suppressed *Alternaria brassicicola* in cabbage with 88.88 % efficacy. Various species of *Trichoderma* viz., *T. harzianum*, *T. asperellum* and *T. virens* showed consistent inhibition of *Alternaria alternata*, *Phytophthora drechsleri* and *Sclerotium rolfsii* in pigeon pea. Besides *Trichoderma*, the other promising bioagents included in various research works are *Pseudomonas fluorescens*, *Paraburkholderia insulsa*, *Acremonium cellulolyticus* and *Bacillus subtilis*, though their effectiveness was found to be lower compared to *Trichoderma*. Experiments conducted against the collar rot pathogen of French bean with *Paraburkholderia insulsa* recorded only 30.30 % inhibition, while *Pseudomonas fluorescens* inhibited pathogen by 87.55 %. *Acremonium cellulolyticus* showed 73.30 % inhibition against multiple pathogens, which is a significant amount, highlighting its potential as an alternative biocontrol option.

The study also stresses how different crops reacted. The pathogens affecting king chilli, *Fusarium* sp. and *Colletotrichum capsici* were suppressed by *T. harzianum* and allied species with effectiveness of about 74 %, while the stem canker pathogen of dragon fruit was reduced by *T. virens* by 63.34 %. Similarly, the pathogens affecting groundnut (wilt) and (stem rot) were effectively managed by *T. asperellum* with over 70 % inhibition.

The variability in effectiveness across pathogens and crops highlights the importance of pathogen-specific screening and

integrated approaches for sustainable disease management in Nagaland.

Botanicals are regarded as safe and eco-friendly option for plant disease management. The efficacy of botanicals against major plant pathogens under Nagaland conditions is depicted in Table 3. Garlic bulb extract is recorded to be the most consistent and potent botanical, achieving complete inhibition (100 %) against *Sclerotium rolfsii* and *Alternaria brassicicola* (cabbage pathogens) and showing strong activity (78.25 %) against *Alternaria tagetica* (marigold pathogen). Garlic extracts significantly reduced the pathogens causing wilt in cherry tomato, with *in vivo* trials confirming reduced disease incidence.

Neem-based botanicals also demonstrated broad-spectrum activity, with 78.02 % inhibition against cabbage blight pathogen and 66.23 % against groundnut wilt pathogen. Neem oil at 0.2 % was particularly effective against chilli anthracnose, reducing disease severity to a minimum PDI of 19.49. Other botanicals such as *Polyalthia longifolia* (73.56 % against chilli anthracnose), *Datura stramonium* (67.09 % against tomato early blight) and eucalyptus leaf extract (in combination with tea and neem, 75.28 % against tomato early blight) further indicate the effectiveness botanicals against fungal pathogens.

Botanicals, like garlic and neem, are good for the environment and can be used instead of chemicals fungicides. Their *in vitro* efficacy, coupled with encouraging *in vivo* outcomes, renders them a significant component of integrated disease management strategies.

Conclusion

The *Jhum* agroecosystem of Nagaland represents a sophisticated Indigenous model of sustainable plant disease management. Rooted in ecological complexity and traditional knowledge, *Jhum* farmers maintain crop health without synthetic chemicals, relying instead on multi-cropping, agroforestry, shifting cultivation cycles and ethnobotanical remedies. These practices create structural and temporal diversity that suppresses pathogens and pests, while ongoing phytochemical research validates the effectiveness of many traditional plant-based treatments.

A distinctive feature of alder-based *Jhum* is its ability to generate positive biotic feedback loops. Incorporating *Alnus nepalensis* enriches soil fertility through nitrogen (N) fixation and organic matter accumulation, fostering diverse microbial communities that naturally suppress soil-borne diseases. Such interactions highlight biodiversity as a long-term defence and underscore the importance of conserving local genetic resources as biological insurance for farming communities.

When Indigenous ecological strategies are integrated with modern science, the resilience of *Jhum* systems becomes even more apparent. Recent studies in Nagaland confirm the efficacy of local biocontrol agents, particularly *Trichoderma* spp., in suppressing fungal pathogens, enhancing plant growth and improving soil health. Similarly, botanical extracts from culturally significant plants demonstrate strong antimicrobial properties, reinforcing the relevance of traditional knowledge.

This synthesis of Indigenous practices and scientific innovation strengthens disease resistance, safeguards biodiversity

Table 2. Effectiveness of biocontrol agents for the management of plant pathogens under Nagaland condition

Sl. No.	Disease	Pathogen	Crop	Biocontrol agent	% effectiveness <i>in vitro</i>	Reference
1	Blast	<i>Pyricularia grisea</i>	Rice	<i>Aspergillus flavus</i> <i>Geotrichum candidum</i> (rice endophyte)	68.50 63.44	(62)
2	Brown spot	<i>Bipolaris oryzae</i>	Rice	<i>Pseudomonas fluorescens</i> (rice rhizosphere)	73.33	(63)
3	Leaf spot and flower blight	<i>Alternaria tagetica</i>	Marigold	<i>Trichoderma harzianum</i>	46.82	(64)
4	Leaf blight	<i>Exserohilum turcicum</i>	Maize	<i>Trichoderma</i> sp. (maize phylloplane)	64.04	(65)
5	-	<i>Rhizoctonia solani</i> , <i>Fusarium oxysporum</i> , <i>Sclerotium rolfsii</i> , <i>Sclerotinia sclerotiorum</i>	-	<i>Trichoderma asperellum</i>	72.96	(66)
6	-	<i>Sclerotium rolfsii</i>	-	<i>Trichoderma harzianum</i>	52.59	(67)
7	-	<i>Alternaria alternata</i> , <i>Phytophthora drechsleri</i> f.sp. <i>cajani</i> and <i>Sclerotium rolfsii</i>	Pigeon pea	<i>T. harzianum</i> <i>T. asperellum</i> <i>T. virens</i>	55.53 (against <i>A. alternata</i>) 50.87 (against <i>S. rolfsii</i>) 55.88 (<i>Phytophthora drechsleri</i> f.sp. <i>cajani</i>)	(68)
8	Blight	<i>Alternaria brassicicola</i>	Cabbage	<i>T. harzianum</i> <i>T. asperellum</i>	88.88 87.03	(69)
9	Stem canker	<i>Neoscytalidium dimidiatum</i>	Dragon fruit	<i>T. virens</i>	63.34	(70)
10	Wilt	<i>Fusarium oxysporum</i>	Cherry tomato	<i>T. harzianum</i>	48.33	(71)
11	Stem rot	<i>Sclerotium rolfsii</i>	Sunflower	<i>T. asperellum</i> , <i>T. harzianum</i>	52.77	(72)
12	Leaf blight	<i>Alternaria</i> spp.	Cabbage	<i>Trichoderma</i> sp. <i>Bacillus subtilis</i>	69.44 31.11	(73)
13	-	<i>S. rolfsii</i> , <i>R. solani</i> , <i>F. oxysporum</i> f.sp. <i>lycopersici</i>	-	<i>Paraburkholderia insulsa</i>	30.30	(74)
14	-	<i>S. rolfsii</i> , <i>R. solani</i> , <i>Fusarium oxysporum</i> f.sp. <i>lycopersici</i>	-	<i>Trichoderma afroharzianum</i>	57.00 63.00 56.67	(75)
15	Anthrachnose	<i>Colletotrichum</i> sp.	Chilli	<i>Trichoderma</i> sp.	62.48	(76)
16	Early blight	<i>Alternaria solani</i>	Tomato	<i>Trichoderma harzianum</i>	57.13	(77)
17	Collar rot	<i>Sclerotium rolfsii</i>	French bean	<i>Pseudomonas fluorescens</i> and <i>Trichoderma asperellum</i>	87.55 85.77	(78)
18	Panama wilt	<i>F. oxysporum</i>	Banana	<i>T. asperellum</i> (endophytic)	61.90	(79)
19	Wilt	<i>Fusarium oxysporum</i>	Groundnut	<i>Trichoderma asperellum</i>	71.73	(80)
20	Wilt	<i>Fusarium oxysporum</i>	King chilli	<i>Trichoderma harzianum</i>	74.24	(81)
21	-	<i>Sclerotium rolfsii</i> , <i>Fusarium oxysporum</i> f.sp. <i>lycopersici</i> , <i>Alternaria solani</i>	-	<i>Acremonium cellulolyticus</i>	73.30	(82)
22	Soft rot	<i>Pythium aphanidermatum</i>	Ginger	<i>Trichoderma asperellum</i> <i>T. afroharzianum</i>	71.85	(83)
23	Stem rot	<i>Sclerotium rolfsii</i>	Ground nut	<i>T. asperellum</i>	72.96	(84)
24	Anthrachnose	<i>Colletotrichum capsici</i>	King chilli	<i>T. harzianum</i> <i>T. viride</i> <i>T. asperellum</i> <i>T. ovalisporum</i>	75.98	(85)

Table 3. Effectiveness of botanicals for the management of plant pathogens under Nagaland condition

Sl. No.	Disease	Pathogen	Crop	Most effective botanical	% effectiveness <i>in vitro</i>	Reference
1	Sheath rot	<i>Sarocladium oryzae</i>	Rice	Tulsi (<i>Ocimum sanctum</i>) (20 % aqueous extract)	72.48 (<i>in vivo</i>)	(86)
2	Leaf spot and flower blight	<i>Alternaria tagetica</i>	Marigold	Garlic clove, (20 % aqueous extract)	78.25	(64)
3	Early blight of tomato	<i>Alternaria solani</i>	Tomato	CTC tea extract + neem + eucalyptus leaf extract	75.28	(87)
4	-	<i>Sclerotium rolfsii</i>	-	Garlic bulb extract (5 and 10 %)	100.00	(67)
5	Blight	<i>Alternaria brassicicola</i>	Cabbage	Garlic bulb extract (30 %) Neem (30 %)	100.00 78.02	(69)
6	Stem canker	<i>Neoscytalidium dimidiatum</i>	Dragon fruit	Garlic bulb extract (15 %)	55.63	(70)
7	Wilt	<i>Fusarium oxysporum</i>	Cherry tomato	Garlic bulb extract (15 %) (<i>in vitro</i>) (BCA + garlic 15 %) <i>in vivo</i>	70.37 Minimum PDI 25.00	(71)
8	Anthrachnose	<i>Colletotrichum</i> sp.	Chilli	Neem oil (0.2 %)	Minimum PDI 19.49	(88)
9	Anthrachnose	<i>Colletotrichum</i> sp.	Chilli	<i>Polyalthia longifolia</i> (15 %)	73.56	(76)
10	Early blight	<i>Alternaria solani</i>	Tomato	<i>Datura stramonium</i> (20 %) Neem (20 %)	67.09 64.92	(77)
11	Wilt	<i>Fusarium oxysporum</i>	Ground nut	Neem (10 %)	66.23	(80)

and supports sustainable agriculture, while contributing to climate adaptation, agroecological preservation and food security in Nagaland's farming communities.

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Authors' contributions

NTA carried out conceptualisation. NTA and SB carried out the literature collection and writing of manuscript. All authors read and approved the final manuscript.

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