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Natural greenhouse: a biologically engineered, low-cost and climate-resilient protected cultivation system

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Abstract

Protected cultivation has emerged as an important approach for enhancing crop productivity, quality, and income in Indian agriculture. However, the widespread adoption of conventional polyhouse technology remains limited due to its high capital cost, dependence on synthetic materials, recurring energy requirements, vulnerability to extreme weather events, and short functional lifespan. Therefore, a farmer-led, field-validated and biologically-engineered natural greenhouse has been developed and demonstrated to farmers at Maa Danteshwari Herbal Farms, Kondagaon, Bastar, Chhattisgarh, India. The natural greenhouse is based on a multi-tier living architecture integrating a fast-growing nitrogen-fixing tree species, locally known as Australian teak (*Acacia* spp.), with a high-yielding black pepper variety (MDBP-16). The system functions as a self-regulating protected cultivation unit, creating a favourable microclimate through canopy-mediated light diffusion, temperature moderation, moisture conservation, and continuous organic nutrient cycling. Unlike conventional polyhouses, it operates without plastic structures, artificial climate control, or external energy inputs.It cost, approximately ₹ 1.0–1.5 lakh per acre, compared to nearly ₹ 40 lakh per acre for a standard polyhouse. The natural greenhouse remains productive for 25–30 years. Independent scientific validation by senior scientists of the ICAR–Indian Institute of Spices Research (IISR), Kozhikode, Kerala, and its regional centre at Madikeri, Karnataka, confirmed black pepper yields of 8–10 kg dry berries per vine, far exceeding the national average of 1.5–2.0 kg. In addition to annual crop income, the system generates long-term timber value, enhances soil health, and contributes to carbon sequestration. The study establishes the natural greenhouse as a scientifically credible, economically viable, and ecologically regenerative alternative to conventional protected cultivation, with significant potential for replication in suitable agroclimatic regions globally

Key words: Natural greenhouse, Protected cultivation, Australian teak, Black pepper, Climate-resilient agriculture, Indigenous innovation

Protected cultivation has emerged as an important technological intervention for enhancing crop productivity, quality, and resource-use efficiency under diverse agroclimatic conditions. By modifying crop microenvironment—particularly temperature, humidity, light, and carbon dioxide concentration—greenhouse and polyhouse systems enable year-round production and protection from adverse climatic factors such as heavy rainfall, strong winds, and temperature extremes, and pest incidence. These systems therefore play crucial role in stabilizing production and ensuring consistent supply of high-value horticulture crops, especially in regions where open field cultivation is constrained by environmental variability (Mhada 2024) Despite these advantages the whispered widespread adoption of conventional greenhouse technologies remain limited, particularly by small and marginal farmers. (Jhadav and Rosentrators, 2017). To overcome these constraints, considerable research has been directed towards the development of low-cost protected cultivation system using logically available materials and passive environmental control. For instant successful production of capsicum (*Capsicum annuum* L.) under such system has enhanced yield, extended harvesting duration, and improve quality attributes under mild winter conditions (Kumar and Verma 2009).Similarly optimisation of agro-techniques under low-cost polyhouse conditions has resulted in improved growth, flowering, and yield of chrysanthemum (*Chrysanthemun Ap.*), indicating the effectiveness of partial micro climate regulation in such systems (Janakarin *et al.,* 2006). Further evidence suggest that even simple greenhouse modifications can significantly enhance yield of tomato (*Lycopersicum esculentum* L.). (Ganesan, 2003). Likewise, studies on ornamental crops such as gerbera (Gerbera sp.) have demonstrated that optimized fertigation and nutrient management under protected conditions significantly enhanced plant growth and flower yield, emphasizing the importance of controlled environment in improving crop performance (Sujatha *et al.,* 2002). However despite, these advancements, existing protected cultivation system both conventional and low-cost still face several limitations. These include inadequate regulation of extreme environmental conditions, dependence on external inputs for nutrient and water management, and variability in performance across different agro-climatic regions.

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Moreover, most systems relay on static structural designs that do not dynamically respond to environmental fluctuations, thereby limiting their efficiency and resilience under changing climatic scenarios (Bonachela *et al.,* 2024). In this context, there is an increasing need to explore alternative approaches that integrate ecological principles with production systems to achieve sustainable intensification. Nature-based and biologically-driven systems offer the potential to regulate microclimate, enhance nutrient cycling, improve soil health, and support biodiversity, thereby reducing dependence on external inputs while maintaining productivity. Such approaches align with emerging paradigms of climate-resilient and resource-efficient agriculture (Jhadav and Rosentrater, 2017).

The concept of a natural greenhouse represents one such innovative approach, wherein living plant architecture is utilized to create a self-regulating microenvironment in place of synthetic structures. By integrating fast-growing tree spices with climbing crops, this system aims to provide functional benefits similar to conventional protected cultivation-like as light diffusion, temperature moderation, and moisture conservation. Unlike conventional polyhouses, this biologically engineered system relies on natural processes r,ather than atificial inputs offering a long-term and climate-resilient alternative for sustainable production.

MATERIALS AND METHODS

The natural greenhouse is established through systematic plantation of fast-growing Australian teak (*Acacia* spp.) at designed spacing. These trees serve multiple functions: they act as permanent life supports for black pepper vines create a vertically stratified canopy, and regulate the farm microclimate. Black pepper vines are trained vertically on these trees enabling true vertical farming extending up to 20 feet in early years and progressively higher with tree growth.

The tree canopy provides approximately 60–70 per cent diffused shading, comparable to the light filtration achieved in polyhouses. Unlike static plastic films, the shade dynamically shifts with solar movement, extending the effective photosynthetic period and reducing photoinhibition. Field observations show that the internal temperature within the Natural Greenhouse remains 3–4°C lower than ambient temperatures during summer and relatively warmer during winter.

RESULTS AND DISCUSSION

A defining feature of natural greenhouse system is the integration of biological processes for nutrient supply and ecosystem regulation. The use of *Acacia* spp. as a structural component enables biological nitrogen fixation through symbiotic associations with Rhizobium, providing a continuous and natural source of nitrogen. This process reduces or eliminates the need for synthetic fertilizers, aligning with findings from protected cultivation systems where optimized nutrient management significantly enhances plant growth and productivity (Sujatha *et al.,* 2002). In addition, seasonal leaf litter contributes to *in-situ* organic matter accumulation, improving soil organic carbon, enhancing microbial activity, and increasing soil moisture retention-factors known to support sustained crop performance under low-input systems.

The multi-tier vegetation structure further contributes to ecological intensification by creating a functional agroecosystem. The canopy-mediated microclimate moderates temperature and light, similar to microenvironmental regulation observed in low-cost polyhouse systems, which significantly influence crop growth and yield (Janakiran *et al.,* 2006). Furthermore, the system promotes biodiversity, particularly avian populations, which play a role in natural pest regulation. Bird activity also contributes to nutrient recycling through droppings, thereby supplementing soil fertility. The dense canopy cover, combined with organic mulching from litter fall, reduces evapotranspiration losses and improves water-use efficiency. Such microclimatic buffering and resource conservation are consistent with observations in protected cultivation systems, where controlled environments enhance crop performance and reduce abiotic stress (Mhade *et al.,* 2024).

The performance of black pepper under the natural greenhouse system has been independently validated by scientists from ICAR–Indian Institute of Spices Research (IISR), Kozhikode, Kalicut, Kerala, and its regional centre at Madikeri. Their findings, (Spice India, April 2023), provide empirical support for productivity and quality advantages of this system .The yields, of 8–10 kg dry berries/vine under organic management is substantially higher than the national average of 1.5–2.0 kg/vine. Such enhanced productivity can be attributed to favourable microclimatic conditions, improved nutrient availability, and reduced physiological stress. These observations are in agreement with studies on protected cultivation, where modification of environmental parameters significantly improves crop yield and quality. For instance, greenhouse-based studies on vegetable crops have demonstrated improved biochemical attributes and productivity due to better regulation of temperature, humidity, and light (Jadhav and Rosentrater, 2017).

In addition to higher yields, the system produces berries of superior quality with strong vine vigour and better market acceptance. The produce meets exports quality standards, indicating its commercial viability. Importantly, the system has demonstrated adaptability to non-traditional pepper-growing regions such as Bastar, suggesting that microclimate modification through biological structures can expand the geographical scope of crop cultivation (Ganesan, 2002).

The greenhouse system offers significant economic advantages over conventional protected cultivation structures. With an establishment cost of approximately ₹1.0–1.5 lakh per acre, it is substantially more affordable than conventional polyhouses, whose high capital requirements are a major barrier to adoption (Jadhav and Rosentrater, 2017). The system generates annual gross returns of up to ₹5 lakh per acre from black pepper alone, indicating strong economic viability. In addition to annual income, the inclusion of *Acacia* trees provides long-term capital gains through timber production, comparable to high-value species such as teak and mahogany. This dual-income model—combining annual crop yield with long-term timber value—enhances financial stability and resilience for farmers. Unlike conventional polyhouses, which have a limited lifespan and generate plastic and metal waste, the natural greenhouse remains productive for 25-30 years. This extended lifespan significantly improves cost-benefit ratio and reduces environmental burden, aligning with the need for sustainable and low-input agricultural systems.

The such adaptability is comparable to low-cost protected cultivation systems, which have been successfully implemented across varied environments to improve crop performance and livelihood outcomes (Mahde *et al.,* 2024). However, Natural Greenhouse extends this concept further by replacing synthetic structures with biological components, thereby reducing dependence on external inputs and enhancing ecological sustainability.

Conclusion

The natural greenhouse represents a scientifically validated, farmer-led innovation that advances the concept of protected cultivation through a biologically engineered approach. By integrating *Acacia* (Australian teak) with high-performing black pepper within a living structural framework, the system effectively regulates microclimate, enhances nutrient cycling, and supports sustained crop productivity without reliance on synthetic inputs.

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