Bioscience Evidence 2026, Vol.16, No.5, 497-517
http://bioscipublisher.com/index.php/be

Review and Outlook Open Access

Medicinal Plant Cultivation under Bamboo Forests: Intercropping Patterns, Ecological Effects, and Prospects

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Bioscience Evidence, 2026, Vol.16, No.5 doi: 10.5376/be.2026.16.0035
Received: 10 Sep., 2026
Accepted: 13 Oct., 2026
Published: 22 Oct., 2026

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Preferred citation for this article:
Xu G.M., and Wang Y.D., 2026, Medicinal plant cultivation under bamboo forests: intercropping patterns, ecological effects, and prospects, Bioscience Evidence, 16(5): 497-517 (doi: 10.5376/be.2026.16.0035)

Abstract Cultivating medicinal plants under bamboo forests is an important approach to improving the spatial utilization of existing bamboo stands and increasing the overall economic return per unit of forestland. This review focuses on medicinal plant cultivation under bamboo forests and systematically examines the ecological basis of bamboo-medicinal plant systems, including canopy light conditions, temperature and humidity, soil moisture, and competition between bamboo rhizomes and plant roots. Representative intercropping systems, including Moso bamboo (*Phyllostachys edulis*)-*Polygonatum cyrtonema*, Moso bamboo-*Bletilla striata*, Moso bamboo-*Paris polyphylla*, Moso bamboo-*Tetrastigma hemsleyanum*, Moso bamboo-*Cardiocrinum giganteum*, as well as bamboo-ginger and bamboo-turmeric systems, are compared. The effects of intercropping on soil nutrients, rhizosphere microorganisms, medicinal plant growth, medicinal organ yield, and bioactive constituents are also evaluated. The performance of bamboo-medicinal plant systems is jointly determined by bamboo stand density, understory light availability, belowground root competition, soil fertility, and medicinal plant species. Moderate shading and appropriate stand structure can promote the growth of some medicinal plants, whereas excessive bamboo density, nutrient imbalance, and long-term continuous cropping may lead to yield reduction, disease incidence, and fluctuations in medicinal quality. In practical production, bamboo species, stand structure, ecological requirements of medicinal plants, and site conditions should be precisely matched, while product quality, soil safety, labor inputs, and market returns should be considered simultaneously. Future research should strengthen region-specific parameter validation in major bamboo-producing areas of southern China, particularly Zhejiang, Fujian, and Jiangxi, and promote standardized management, digital record keeping, and coordination among family farms, processing enterprises, and marketing entities to improve the overall management efficiency and long-term stability of bamboo forests.

Keywords Understory cultivation; Medicinal plants; Bamboo-medicinal plant intercropping; Stand structure; Rhizosphere microorganisms; Medicinal plant quality; Understory economy

1 Introduction

Bamboo is characterized by rapid growth, strong regenerative capacity, wide ecological adaptability, and diverse uses, making it an important forest resource and agroforestry component in many regions of Asia, Africa, and Latin America (Allo et al., 2024; Ahmad et al., 2025). In China, bamboo resources are mainly distributed in the southern regions. In 2021, the national bamboo forest area reached 7.5627 million ha, of which Moso bamboo (*Phyllostachys edulis*) forests accounted for 5.2776 million ha, representing 69.78% of the total bamboo forest area. Fujian, Hunan, Jiangxi, and Zhejiang provinces together contained 4.2164 million ha of Moso bamboo forests, forming the most concentrated Moso bamboo production region in China (Feng and Li, 2023). For a long time, income from Moso bamboo forests has mainly depended on bamboo culms and shoots. However, in some traditional bamboo-producing areas, problems such as dependence on a limited range of products, rising labor inputs, and insufficient utilization of understory space have gradually become apparent. For established Moso bamboo forests, further expansion of bamboo area is not the only way to increase returns. A more practical issue is how to make better use of understory space and increase overall output per unit of forestland while maintaining the basic productive and ecological functions of bamboo forests.

Cultivating medicinal plants in the understory adds an additional productive layer to existing bamboo forests. *Polygonatum cyrtonema*, *Bletilla striata*, *Paris polyphylla*, *Tetrastigma hemsleyanum*, and some medicinal and edible plants of the Zingiberaceae exhibit varying degrees of shade tolerance. Some of these species are naturally

adapted to forest edges, forest understories, or diffuse-light environments and therefore show a certain degree of ecological compatibility with the light, temperature, and moisture conditions beneath bamboo canopies. However, shade tolerance does not mean that a species is suitable for all bamboo stands. Canopy-induced changes in light, temperature, humidity, and soil conditions, together with competition for water, nutrients, and rooting space between overstory bamboo and medicinal plants, can influence plant growth, yield, and bioactive constituents. Under different forest types and management regimes, yield and quality responses may even occur in opposite directions (Wen et al., 2025). Moso bamboo also develops extensive rhizomes and shallow root systems. Consequently, medicinal plants grown under bamboo may benefit from shading, moisture conservation, and litter inputs, but may also be constrained by insufficient light, rhizome competition, and depletion of soil nutrients. In practical production, the key questions are therefore which bamboo stands are suitable for understory cultivation, which medicinal plant species are best matched to particular stand conditions, and how these components should be configured to achieve stable long-term production.

Research on bamboo-medicinal plant systems has gradually expanded from early assessments of the feasibility of understory cultivation to studies of bamboo stand density, spatial configuration, soil nutrients, rhizosphere microorganisms, medicinal organ yield, and bioactive constituents. A range of representative systems has now been investigated, including Moso bamboo-*Polygonatum cyrtonema*, Moso bamboo-*Bletilla striata*, Moso bamboo-*Paris polyphylla*, Moso bamboo-*Tetrastigma hemsleyanum*, Moso bamboo-*Cardiocrinum giganteum*, as well as bamboo-ginger and bamboo-turmeric systems. However, substantial differences exist among studies in bamboo species, stand density, slope position, soil conditions, and medicinal plant species, making it difficult to directly transfer suitable parameters obtained in one region to other bamboo-producing areas. In addition, some studies have focused mainly on short-term changes in soil properties and microbial communities, whereas long-term data on medicinal plant yield, major bioactive constituents, marketable quality, and actual returns to family farms remain relatively limited.

Based on these considerations, this review focuses on the intercropping of medicinal plants under bamboo forests. It first summarizes the ecological basis for cultivation, including bamboo canopy conditions, temperature and humidity, and interactions between bamboo rhizomes and plant roots. It then compares the major bamboo-medicinal plant intercropping systems and their configuration characteristics, evaluates changes in soil nutrients, rhizosphere microorganisms, medicinal plant growth, yield, and quality after intercropping, and further discusses ecological and economic benefits, long-term production constraints, and conditions for regional application. Considering the management characteristics of bamboo-producing areas in Zhejiang and the southern margin of the Yangtze River Delta, as well as Fujian, Jiangxi, and other parts of southern China, this review proposes future directions including the precise matching of "bamboo species-stand structure-medicinal plant-site conditions," standardized and digital management, and closer coordination between family farms and downstream processing and marketing sectors. These perspectives are intended to provide a reference for the rational arrangement of understory medicinal plants and the long-term integrated management of existing bamboo forests.

2 Ecological Basis for Cultivating Medicinal Plants under Bamboo Forests

2.1 Bamboo canopy and understory light environment

Bamboo culm density, leaf area, canopy closure, and the spatial distribution of bamboo foliage jointly determine the amount of direct and diffuse light reaching the understory. A removal experiment in stands dominated by bamboo and lianas showed that after bamboo and lianas were removed, solar radiation reaching the understory increased by approximately 100%, while the proportion of transmitted solar radiation at 0.7 m above the ground increased from 0.1 to 0.2, indicating that bamboo canopies can substantially alter near-ground light conditions (Campanello et al., 2007). Surveys of Moso bamboo forests in the eastern subtropical region further showed that canopy closure is an important factor affecting understory plant communities, and changes in stand closure alter the amount of light space available to understory vegetation (Ge et al., 2025). *Atractylodes lancea* also responds markedly to different relative light intensities: moderate shading promotes plant growth and the accumulation of sesquiterpenoids, whereas extremely low light restricts biomass formation (Guo et al., 2022).

Before establishing medicinal plants in a bamboo forest, the first question should not simply be whether the site is shaded, but rather how strongly it is shaded. Bamboo stands that have not been thinned for many years, have strongly overlapping foliage, and remain very dark even at midday in summer are unsuitable for direct high-density cultivation of medicinal plants, even when soil conditions are favorable. In contrast, forest edges, canopy gaps, and areas with diffuse light created by moderate bamboo thinning are generally easier to manage. Shade-tolerant medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla* can make use of relatively continuous diffuse light, whereas species with higher light requirements are better placed along forest margins or in more open strips. In practical production, it is unnecessary to pursue a fixed canopy closure value at the outset. Instead, the need for further thinning should be judged from actual understory light conditions in spring and summer, together with leaf color and leaf expansion of medicinal plants, so that the bamboo canopy can buffer excessive solar radiation without chronically restricting photosynthesis.

2.2 Temperature, humidity, soil moisture, and medicinal plant suitability

In addition to modifying light conditions, the bamboo canopy can markedly buffer fluctuations in understory temperature and humidity. Monitoring of different bamboo communities in Hangzhou showed that during summer daytime, air temperature within bamboo stands was approximately 1.5℃-2.6℃ lower than in unshaded areas, relative humidity was 3.0%-7.6% higher, and light intensity was reduced by 95.4%-99.9%; in winter, only a slight warming effect was observed (Wu et al., 2023). Such summer cooling and humidifying effects can be beneficial to certain rhizomatous medicinal plants that prefer moist conditions and are sensitive to strong radiation. However, bamboo canopies also redistribute rainfall. Precipitation reaches the forest floor through canopy interception, throughfall, and culm stemflow, and as bamboo stand density increases, canopy interception generally increases while the proportion of throughfall reaching the ground decreases (Shen et al., 2025a).

In practical cultivation across southern bamboo-producing regions, water management must prevent both excessive moisture and water shortage. Low-lying sites and poorly drained areas are prone to prolonged waterlogging during the plum-rain season and after continuous rainfall, which is unfavorable for the underground medicinal organs of species such as *Bletilla striata* and *Polygonatum cyrtonema*. By contrast, ridge-top sites, shallow soils, and dense bamboo stands may appear cool and shaded but can still experience surface-soil drought in summer because of bamboo root water uptake and limited soil depth. Therefore, gently sloping sites with good drainage and relatively deep soils are more suitable for establishment, while existing bamboo litter should be retained where possible to reduce evaporation.

2.3 Bamboo rhizome-root systems and belowground resource competition

Moso bamboo is a typical clonal plant whose rhizomes can extend over long distances underground while continuously producing new absorbing roots and shoots. Ground-penetrating radar combined with soil coring has shown that the rhizome-root system of Moso bamboo is concentrated mainly within the upper 0-30 cm soil layer, and its distribution is closely related to soil moisture, alkali-hydrolyzable nitrogen, and available phosphorus (Xiao et al., 2021). New Moso bamboo shoots can also maintain rapid elongation under low-light conditions, with much of the water and nutrients required during early growth supplied through the underground rhizome network connected to mature bamboo culms (Wang et al., 2016). This means that medicinal plants grown beneath bamboo may face resource competition from the entire rhizome network rather than only from nearby culms. Species such as *Polygonatum cyrtonema*, *Bletilla striata*, *Paris polyphylla*, and *Paeonia lactiflora*, whose marketable organs are rhizomes, tubers, pseudobulbs, or fleshy roots, also rely heavily on shallow to intermediate soil layers, making belowground spatial overlap particularly important.

Rather than attempting to solve competition by simply increasing fertilizer inputs after medicinal plants have been established, it is more effective to manage bamboo rhizomes in advance. Trial excavation can be used to assess rhizome density, and planting strips should preferably be placed in inter-row spaces or canopy gaps where bamboo rhizomes are relatively sparse. For medicinal plants whose commercial organs are concentrated near the soil surface, local rhizome cutting, root barriers, or raised beds can be used to reduce rhizome encroachment into planting beds. For perennial medicinal plants, such measures should not be limited to the establishment year,

because bamboo rhizomes can continue expanding toward areas with loose soil, fertilizer inputs, and favorable moisture conditions. In production, rhizome invasion should therefore be checked during winter or harvest periods each year, and planting strips or local barriers should be adjusted according to rhizome distribution. This approach is more direct than relying solely on additional water and fertilizer inputs.

2.4 Matching bamboo stand density and canopy closure with the light requirements of medicinal plants

There is no single bamboo culm density suitable for medicinal plant cultivation across all regions, because the number of bamboo culms does not correspond exactly to the actual understory environment. Experiments conducted in Moso bamboo stands across eight provinces in southern China showed that canopy density is influenced not only by stand structure but also by slope, elevation, and soil conditions (Zhou et al., 2024). Consequently, even at a similar density of approximately 2 000 culms ha^{-1}, bamboo stands on fertile gentle slopes and those on steep slopes with shallow soils may differ substantially in canopy structure, rhizome abundance, and understory light availability. Production trials in Moso bamboo further illustrate this point. Among stand densities of 1 200, 1 800, 2 400, and 3 000 culms ha^{-1}, approximately 2 400 culms ha^{-1} produced relatively high bamboo shoot yields and favorable integrated root and soil performance under a specific bamboo shoot production regime (He et al., 2025).

For bamboo-medicinal plant production, a more practical approach than retaining a fixed number of bamboo culms is to first assess understory conditions and then adjust stand density accordingly. Before establishment, at minimum, it is necessary to determine whether the canopy is continuously closed, whether usable diffuse light reaches the understory, whether bamboo rhizomes are overly dense, and which soil layer is primarily exploited by the medicinal plant. Species with strong shade tolerance and reasonable competitive ability belowground can be grown under a relatively intact canopy, whereas species requiring more light or substantial expansion of underground organs require lower bamboo density and more canopy gaps or planting strips. Because Moso bamboo stands are continuously renewed, density management should not be completed only once at establishment, but should be adjusted over time through the removal of old culms, retention of new culms, and consideration of medicinal plant growth stages. In practical management, bamboo timber and shoot production should be evaluated together with medicinal plant performance.

2.5 Planting density and spatial configuration of medicinal plants

The objective of spatial configuration under bamboo forests is not to fill all available understory space with medicinal plants, but to place them where light, water, bamboo rhizome pressure, and field operations are relatively favorable. A strip-cutting study in Moso bamboo forests in Anji, Zhejiang Province, compared strip widths of 3, 5, and 8 m across slopes of 5-14°, 15-24°, and 25-34°. Strip treatments generally increased the number of understory herbaceous and shrub species, and under moderate slope conditions, 5-m strip cutting showed a relatively favorable balance among bamboo shoot emergence, culm recovery, and understory vegetation (Fu et al., 2026). These results indicate that stable understory utilization space can be created through strip-based adjustment of Moso bamboo stands without the need for large-scale removal of bamboo for medicinal plant cultivation.

From the perspective of family farms and grassroots management, concentrated strip, patch, or contour-based arrangements are more suitable than scattered planting throughout the entire forest. Planting strips should avoid areas with obviously thick bamboo rhizomes, and on sloping land they can be arranged along contour lines while leaving sufficient space for fertilization, weeding, harvesting, and access by small machinery. For perennial underground medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla*, adequate space should be reserved according to the expected size of mature plants and underground organs after 2-5 years rather than according to seedling size at establishment. Excessive planting density not only intensifies root competition among medicinal plants but also reduces ventilation and increases disease-management and harvesting difficulties. Spatial configuration under bamboo forests should therefore follow the principles of avoiding dense bamboo rhizomes, making use of bamboo shade, retaining working access, and facilitating harvest,

while maintaining sufficient planting area and operational space for subsequent bamboo thinning, fertilization, and medicinal plant harvesting.

The suitability of medicinal plants for cultivation under bamboo forests is not determined by light conditions alone, but by the combined effects of bamboo canopy structure, understory microclimate, bamboo rhizome-root competition, and the spatial arrangement of medicinal plants. Both excessively low and excessively high bamboo stand densities may negatively affect medicinal plant growth. Therefore, management measures such as bamboo thinning, canopy opening, root isolation, strip planting, and drainage management should be used to achieve an appropriate balance between aboveground light and thermal conditions and belowground resource competition. The major relationships through which bamboo stand structure regulates the understory environment and medicinal plant spatial configuration are illustrated in Figure 1.

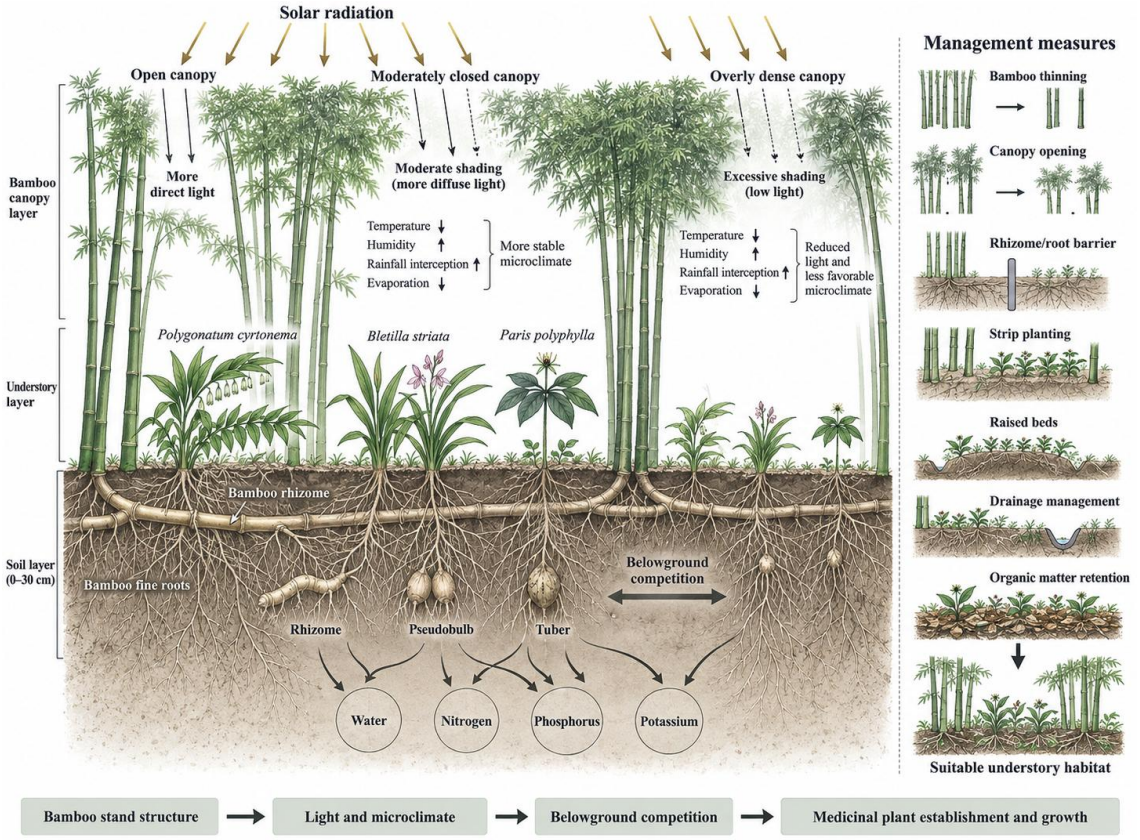


Figure 1 Conceptual framework of bamboo stand regulation on understory habitats and spatial configuration of medicinal plants

3 Major Bamboo-Medicinal Plant Intercropping Systems and Their Configuration Characteristics

3.1 Moso bamboo-*Polygonatum cyrtonema* system

The Moso bamboo-*Polygonatum cyrtonema* system is currently one of the better-supported bamboo-medicinal plant intercropping models in terms of field evidence. Research has gradually shifted from asking whether *P. cyrtonema* can grow under bamboo forests to determining how many bamboo culms should be retained. Xu et al. (2023) established four Moso bamboo stand densities in eastern Anhui Province, approximately 1 750, 2 000, 2 250, and 2 500 culms ha^{-1}, with a pure Moso bamboo stand of approximately 2 500 culms ha^{-1} as the control. One-year-old *P. cyrtonema* seedlings were planted beneath the bamboo at a spacing of 25 cm × 50 cm. Overall, bamboo-*P. cyrtonema* intercropping increased soil moisture, SOC, total nitrogen, nitrate nitrogen, ammonium nitrogen, microbial biomass carbon and nitrogen, and available phosphorus, although clear differences occurred among bamboo densities. The 1 750 culms ha^{-1} treatment had the highest soil quality index and the greatest rhizome yield, whereas rhizome yield gradually declined as bamboo density increased above 1 750 culms ha^{-1}. Structural equation modeling showed that bamboo stand density had a direct path coefficient of −0.83 on *P.*

cyrtonema rhizome yield, substantially greater than the effects of individual soil indicators such as SOC and nitrate nitrogen. This indicates that the system is primarily constrained by overstory stand structure rather than by simple nutrient deficiency.

Although *P. cyrtonema* is shade tolerant, it still requires sufficient light, soil moisture, and belowground growing space. As Moso bamboo density increases, the canopy becomes denser aboveground while bamboo rhizomes and fine roots become more abundant belowground, jointly restricting rhizome enlargement. In existing Moso bamboo forests in Zhejiang, Anhui, Fujian, and Jiangxi, it is therefore more appropriate to use established stands of moderate density or to thin overly dense bamboo before establishing *P. cyrtonema* planting strips, rather than directly intercropping medicinal plants in highly closed stands that have not been thinned for many years. A density of 1 750 culms ha^{-1} can serve as a reference point under similar site conditions, but slope position, soil depth, bamboo age, and soil fertility vary among regions. In practical production, bamboo density should therefore be adjusted dynamically according to understory light availability, bamboo rhizome distribution, and *P. cyrtonema* rhizome performance over 2-3 consecutive years.

3.2 Moso bamboo-*Bletilla striata* system

Research on the Moso bamboo-*Bletilla striata* system has moved beyond rhizosphere soil responses to directly evaluating pseudobulb yield and medicinal quality. Deng et al. (2023) compared *B. striata* monoculture, *B. striata*-*Cyclocarya paliurus*, and *B. striata*-Moso bamboo systems in Guangde, Anhui Province. In the Moso bamboo-*B. striata* treatment, *B. striata* was planted in strips at a density of approximately 160 000 plants ha^{-1}, while the bamboo stand was thinned into a strip-based configuration at approximately 3 000 culms ha^{-1}. After three consecutive years of cultivation, pseudobulb dry matter yield under Moso bamboo was significantly lower than under *B. striata* monoculture, while total polysaccharide content showed no significant change. In contrast, total flavonoid and total phenolic contents increased, reaching 6.55 and 5.07 mg g^{-1} DW, respectively. Pseudobulb dry matter was significantly positively correlated with solar radiation, SOC, total nitrogen, and nitrate nitrogen, whereas total flavonoids and total phenolics were negatively correlated with light availability, SOC, and total nitrogen.

Following Moso bamboo-*B. striata* intercropping, soil moisture and NO_3^--N were important factors explaining variation in bacterial communities, while predicted microbial functions shifted from stronger carbon-cycling characteristics toward enhanced nitrogen-cycling functions (Wang et al., 2023). Comparative studies of Moso bamboo intercropped with *B. striata*, *Paris polyphylla*, and *Tetrastigma hemsleyanum* further showed that SOC and available nitrogen increased after intercropping, whereas soil pH and available potassium declined; available phosphorus improved more clearly in the *B. striata* system (Zhang et al., 2020). Although *B. striata* can benefit from bamboo shade, this does not mean that denser bamboo and deeper shade are always advantageous. Both Moso bamboo and *B. striata* rely heavily on surface soil resources, and under overly dense bamboo stands, pseudobulb development is likely to be restricted first by light limitation and belowground competition. In practical establishment, overstory bamboo density should be controlled, soil should be kept moist but not waterlogged, and potassium and nitrogen should be supplemented according to soil testing. Unlike *P. cyrtonema*, an optimal Moso bamboo density range has not yet been clearly established for *B. striata*. At present, local configuration parameters should therefore be determined gradually through bamboo thinning, strip planting, and continuous monitoring of pseudobulb yield, polysaccharides, flavonoids, and related quality indicators.

3.3 Moso bamboo-*Paris polyphylla* and moso bamboo-*Tetrastigma hemsleyanum* systems

Direct production data for Moso bamboo-*Paris polyphylla* and Moso bamboo-*Tetrastigma hemsleyanum* systems remain more limited than those for *P. cyrtonema* and *B. striata*, and existing evidence mainly comes from comparative studies of multiple medicinal plants under Moso bamboo forests. Zhang et al. (2019, 2020) compared pure Moso bamboo stands with Moso bamboo intercropped with *P. polyphylla*, *T. hemsleyanum*, and *B. striata*. All three medicinal plant systems substantially altered soil nutrient status and bacterial communities. SOC and available nitrogen were generally higher in intercropped systems than in pure Moso bamboo stands, whereas soil pH and available potassium were lower; increases in available phosphorus were more pronounced in the *T.*

hemsleyanum and *B. striata* systems. The bacterial Shannon index was higher in all three bamboo-medicinal plant systems than in pure bamboo stands, although the bacterial groups enriched by different medicinal plants varied. These results indicate that both *P. polyphylla* and *T. hemsleyanum* can become established under Moso bamboo, but they differ in how they utilize soil nutrients and rhizosphere conditions.

Cross-forest comparisons of *P. polyphylla* further indicate that Moso bamboo is only one possible overstory type and is not necessarily the most suitable forest type for this species. Zhang et al. (2026) compared simulated wild cultivation of *P. polyphylla* under Moso bamboo forests, Chinese fir forests, and mixed bamboo-Chinese fir forests. SOC was 33.7 g kg^{-1} under Chinese fir but 26.5 g kg^{-1} under Moso bamboo; microbial biomass carbon reached 361.2 mg kg^{-1} under Chinese fir compared with 207.9 mg kg^{-1} under Moso bamboo, while water-soluble organic carbon was 176.6 and 98.6 mg kg^{-1}, respectively. The values under Chinese fir were 27.2%, 73.7%, and 79.1% higher than those under Moso bamboo for these respective indicators. *P. polyphylla* has a long growth cycle and relatively high requirements for humus and soil carbon conditions. Therefore, a Moso bamboo stand with long-term litter removal, low soil organic matter, or extremely dense rhizomes may not be suitable even when shading is appropriate. Moso bamboo-*P. polyphylla* systems are thus better established on sites with deeper soils, higher organic matter, and moderate bamboo density, whereas Moso bamboo-*T. hemsleyanum* systems still require additional data on tuberous root yield and bioactive constituents.

3.4 Moso bamboo-*Cardiocrinum giganteum* and other emerging medicinal plant systems

Cardiocrinum giganteum represents a relatively new and informative model in recent bamboo-understory medicinal plant research because studies have simultaneously compared the effects of different overstory forest types on rhizosphere conditions and medicinal plant metabolism. Zhang et al. (2024a, 2024b) compared Moso bamboo-*C. giganteum*, Chinese fir-*C. giganteum*, mixed bamboo-Chinese fir-*C. giganteum*, and forest-gap conditions in karst areas. Under Moso bamboo, the rhizosphere of *C. giganteum* exhibited relatively high bacterial and fungal diversity and a more complex microbial interaction network, while SOC, total nitrogen, and available potassium were important factors explaining community differences. Distinct metabolite profiles also developed under different forest types. Moso bamboo promoted the accumulation of certain terpenoid-, alkaloid-, and steroid-related metabolites, whereas Chinese fir and mixed bamboo-Chinese fir forests produced different metabolic responses. From a production perspective, these findings indicate that the same medicinal plant may not only grow differently under different forest types but may also develop different medicinal quality. Future evaluation of systems involving *C. giganteum* should therefore place greater emphasis on bulb yield, major bioactive constituents, and harvest quality rather than focusing only on understory survival.

Experiments with *Paeonia lactiflora* more directly illustrate the importance of cultivation method and competition with bamboo roots. Wang and Yang (2026) established Moso bamboo densities of 0, 1,200, 1,800, and 2,400 culms ha^{-1} and compared bag cultivation with direct field planting using plant material from Xinwo Town, Pan'an County, Jinhua, Zhejiang Province. Under bag cultivation, the low-density treatment of 1,200 culms ha^{-1} promoted biomass accumulation in leaves, stems, and roots and favored root elongation and thickening. In contrast, under direct field planting, increasing bamboo density intensified both overstory shading and belowground root competition, resulting in clear growth suppression. For medicinal plants such as *P. lactiflora*, whose fleshy roots constitute the commercial organ and compete strongly with bamboo roots for surface-soil resources, reducing root competition may be more effective than simply increasing fertilizer inputs. Bag cultivation may not be suitable for large-scale production, but the results suggest that root isolation, raised beds, and measures to prevent bamboo rhizomes from entering medicinal plant strips deserve further evaluation.

3.5 International bamboo-ginger, bamboo-turmeric, and related systems

Studies of bamboo-ginger and bamboo-turmeric systems in India provide relatively specific production parameters for configuring rhizomatous medicinal crops beneath bamboo. In a seven-year-old *Dendrocalamus strictus* plantation in Kerala, India, five bamboo spacings of 4 × 4, 6 × 6, 8 × 8, 10 × 10, and 12 × 12 m were compared. At 4 × 4 m spacing, the bamboo leaf area index reached 6.77 and understory photosynthetically active radiation (PAR) was only approximately 107 μmol m^{-2} s^{-1}, while turmeric rhizome yield was only 8 Mg ha^{-1}.

When bamboo spacing increased to 12 × 12 m, rhizome yield increased to 19.32 Mg ha^{-1}, approximately 58% higher than under the densest bamboo treatment. A ^{32}P tracer experiment further showed that phosphorus uptake by turmeric under the 4 × 4 m bamboo spacing was approximately 89% lower than under the no-bamboo control, indicating that root competition and shading occurred simultaneously. The study suggested that a light transmittance of approximately 66%-86% was more suitable for turmeric and that bamboo spacing should exceed 8 × 8 m (Kittur et al., 2016).

Ginger showed a different response. Garima et al. (2021) cultivated ginger beneath *D. asper* and *D. hamiltonii*. Although the bamboo canopy reduced PAR by approximately 60%, ginger rhizome yield increased by 10.5%-15.6% compared with open-field cultivation, and soil moisture was higher beneath *D. asper*. When *D. asper* was combined with farmyard manure and plant growth-promoting microorganisms, ginger yield reached 4 028 kg ha^{-1} and annual income reached USD 3 595.67 ha^{-1}. In another bamboo-ginger study involving *D. asper* and *Bambusa balcooa*, intercropping increased ginger yield by 10.5%-15.6% and oleoresin content by 14.45%-28.61%, while green-leaf mulching further improved soil moisture conservation and weed suppression (Sharma et al., 2022).

Even among rhizomatous crops, responses to bamboo canopy conditions can differ markedly. Ginger can benefit from a relatively moist, semi-shaded environment, whereas turmeric is clearly constrained by limited light and bamboo root competition under dense bamboo stands. Sinha et al. (2025) compared ginger, turmeric, taro, and finger millet beneath an eight-year-old *D. asper* stand. Although the individual yields of understory crops were affected by bamboo competition, the land equivalent ratio reached 1.57 for bamboo-ginger and 1.39 for bamboo-turmeric, while the benefit-cost ratio of the bamboo-ginger system reached 1.79. Economic analysis indicated that both ginger- and turmeric-based systems provided certain overall advantages compared with their corresponding monocultures. Therefore, evaluation should consider not only rhizome yield of understory medicinal crops, but also bamboo spacing, belowground competition, quality traits, and the combined economic return of bamboo and medicinal plants.

No single optimal configuration applies to all bamboo-medicinal plant combinations. *Polygonatum cyrtonema* currently has a relatively clear response to bamboo stand density, while *Bletilla striata* shows a distinct yield-quality trade-off. Long-term evidence on yield and quality remains insufficient for *Paris polyphylla* and *Tetrastigma hemsleyanum*, whereas *Cardiocrinum giganteum*, *Paeonia lactiflora*, bamboo-ginger, and bamboo-turmeric systems show clearly different responses to stand structure and belowground competition. Bamboo-medicinal plant intercropping should therefore be configured according to bamboo species, stand structure, and the ecological characteristics of individual medicinal plants. Representative bamboo-medicinal plant systems and their major production responses are summarized in Figure 2.

4 Effects of Bamboo-Medicinal Plant Intercropping on Soil and Rhizosphere Microorganisms

4.1 Changes in soil organic carbon and organic matter

Bamboo-medicinal plant intercropping does not necessarily increase soil organic matter, and in the short term medicinal plants may even rapidly consume soil nutrients and organic matter. Li et al. (2026a) established two stand densities, 8 400 and 11 200 culms ha^{-1}, under *Neosinocalamus affinis* and intercropped four medicinal plants, namely *Bletilla striata*, *Polygonatum cyrtonema*, *P. sibiricum*, and *P. kingianum*, in a one-year agroforestry experiment. After the four medicinal plants were introduced into the bamboo stands, soil bulk density decreased. However, in the higher-yielding stand at 8,400 culms ha^{-1}, soil organic matter and nitrogen contents declined. Among the four medicinal plants, the *B. striata* and *P. cyrtonema* treatments generally showed better soil nutrient status and enzyme activity than the *P. sibiricum* and *P. kingianum* treatments. In short-term bamboo-medicinal plant systems, rapid root expansion and the formation of underground medicinal organs can substantially increase nutrient demand, and carbon inputs from newly formed roots and plant residues may not immediately offset losses caused by plant uptake and organic matter decomposition.

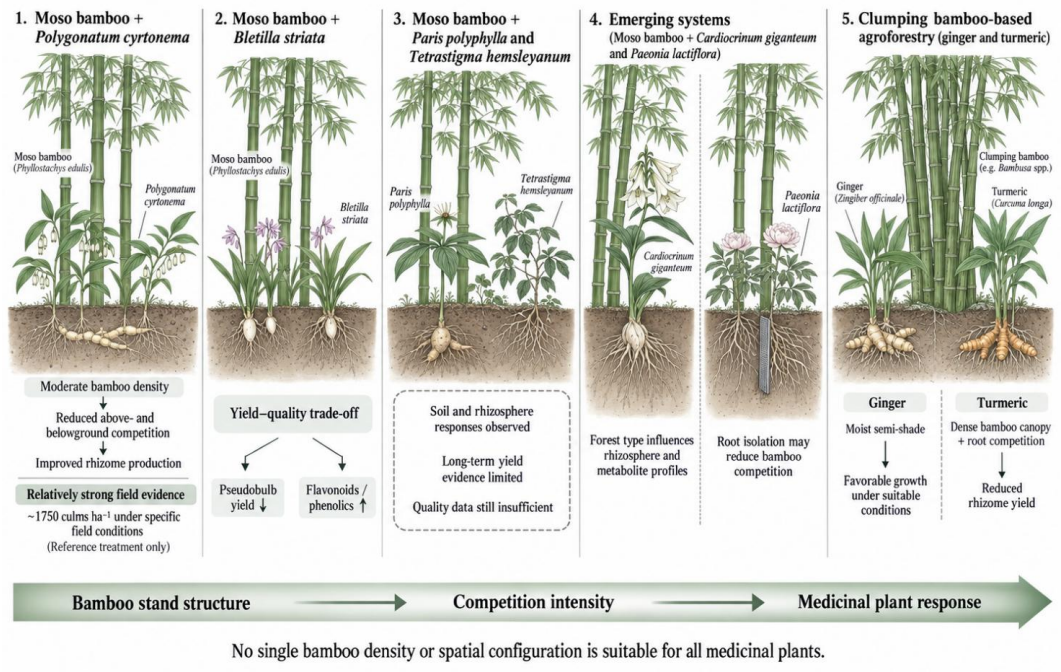


Figure 2 Representative bamboo-medicinal plant intercropping systems and their major production responses

The way organic materials are replenished directly affects whether soil carbon can be retained over the long term. In a Moso bamboo forest, Huang et al. (2025) applied bamboo-derived organic fertilizer at 0, 7.5, 15, and 30 t ha^{-1} and found that the 15 and 30 t ha^{-1} treatments significantly increased microbial necromass carbon, particularly fungal necromass carbon and its contribution to SOC. SOC in the 0-20 cm soil layer was an important predictor of total microbial necromass carbon and fungal necromass carbon, whereas available potassium was more closely associated with bacterial necromass carbon. For bamboo-medicinal plant production, if all aboveground medicinal plant residues are removed after harvest and bamboo litter is also continuously cleared, soil organic carbon inputs will gradually decline. A more appropriate strategy is to retain healthy bamboo litter and part of the non-marketable medicinal plant residues, together with the application of well-composted organic fertilizer as an additional carbon source. In bamboo stands with shallow soils or repeated harvesting of underground medicinal organs, soil organic matter should therefore be treated as a long-term monitoring indicator.

4.2 Responses of soil nitrogen, phosphorus, and potassium

After understory crops are introduced into bamboo forests, changes in soil nitrogen, phosphorus, and potassium depend largely on the identity of the intercrop. Soman and Chavan (2024) compared soil changes in soybean intercropped with *Bambusa balcooa*, *Dendrocalamus stocksii*, *D. asper*, and *Bambusa vulgaris*. Compared with soybean monoculture, the bamboo-soybean systems generally had higher SOC, available nitrogen, available phosphorus, and available potassium, but lower pH. In a *Dendrocalamus brandisii*-based agroforestry experiment, nutrient responses also differed among intercrops. Following black gram cultivation, the response index of soil available nitrogen reached approximately 0.25-0.42 across different treatments and soil depths of 0-30 cm, while Ca, Mg, and S also increased and SOC declined only slightly. In contrast, okra produced different responses in some soil physical and chemical properties (Manasa et al., 2024). These findings indicate that nutrient changes following understory planting cannot simply be summarized as “intercropping improves soil fertility,” because root type, nutrient uptake capacity, and residue return all influence the outcome.

For bamboo-medicinal plant systems, nutrient balance is more important than the increase in any single nutrient. Zhang et al. (2023) compared unmanaged, conventionally managed, and intensively managed Moso bamboo forests in Anji, Zhejiang Province. Relative to unmanaged stands, both management regimes showed lower TOC, TN, TP, and available nitrogen, whereas available phosphorus increased under intensive management. Activities of carbon- and nitrogen-acquiring enzymes declined, while acid phosphatase activity increased. These results indicate that high-input bamboo management alters microbial demand for C, N, and P rather than increasing all

nutrients simultaneously. In bamboo-medicinal plant systems, underground organs of *Polygonatum cyrtonema*, *Bletilla striata*, *Paris polyphylla*, and other medicinal plants continuously remove substantial quantities of nutrients from surface soils. If fertilization follows only the conventional nitrogen-oriented practice used in bamboo shoot forests, nitrogen may remain sufficient while phosphorus, potassium, or organic matter gradually becomes imbalanced. For practical management, available nitrogen, phosphorus, and potassium should be tested before planting and after each harvest cycle, and fertilizer inputs should then be adjusted according to the growth stage of the medicinal crop.

4.3 Changes in soil pH, bulk density, and moisture

Soil pH in bamboo forests already varies considerably among regions and management regimes; therefore, neither acidification nor an increase in pH after bamboo-medicinal plant intercropping should be interpreted as a universal response. Wu et al. (2024) synthesized 81 studies comprising 2 037 paired observations and found that after Moso bamboo expansion, soil pH increased on average by 6.99% in the 0-20 cm layer and by 4.49% in the 20-40 cm layer. At the same time, total nitrogen declined, NH_4^+-N increased by 30.39%, and NO_3^--N decreased by 21.12% in pure Moso bamboo stands. Considerable differences were also observed among forest types and stages of bamboo expansion. Changes in pH are therefore related to rhizosphere processes of Moso bamboo, transformations among nitrogen forms, the original forest type, and management duration. In red-soil bamboo regions of southern China, where readily available nitrogen fertilizers may be applied for many years and underground medicinal organs are repeatedly harvested without sufficient replenishment of organic matter or base cations, the use of lime, plant ash, or other soil amendments should be determined by soil testing rather than by fixed empirical practice.

Soil moisture and structure should likewise be evaluated in relation to the original bamboo stand conditions. Abayneh et al. (2026) compared natural forest, bamboo plantation, agroforestry land, and cereal cropland in the Ethiopian highlands using 72 soil samples collected from three layers within 0-60 cm. Mean soil moisture in bamboo forests reached 28.2%, almost identical to the 28.3% recorded in natural forests, whereas cereal cropland contained only 14.4%. SOC stocks in the 0-60 cm layer were 235.9 Mg ha^{-1} in natural forest, 230.0 Mg ha^{-1} in bamboo forest, and 155.6 Mg ha^{-1} in cropland. Bamboo forests also exhibited lower bulk density and a greater proportion of macroaggregates. These findings indicate that stable bamboo forests can provide favorable soil water retention and structural protection. However, this does not mean that medicinal plants in bamboo-medicinal plant systems are free from water limitation. Species such as *Polygonatum cyrtonema* and *Bletilla striata*, together with bamboo rhizomes, rely heavily on surface soil resources. Under excessive bamboo density or prolonged drought, root competition may still cause medicinal plants to experience water shortage before the bamboo itself is visibly affected.

4.4 Responses of rhizosphere bacterial and fungal communities

An important issue in bamboo soil microbiology is that rhizosphere soil and ordinary bulk forest soil should not be interpreted together as if they were equivalent. Guo et al. (2025) selected six major Moso bamboo-growing regions in China-Changning, Xinyang, Anji, Taojiang, Conghua, and Longmen-and established 24 plots, from which 144 rhizosphere soil samples and 48 bulk soil samples were collected. Site, soil type, and rhizosphere versus bulk soil position all significantly affected bacterial and fungal community structure. Moso bamboo rhizosphere soils were relatively enriched in Chloroflexi, Planctomycetota, Gemmatimonadota, and some Acidobacteriota groups, whereas bulk soils were enriched in some Pseudomonadota, Mucoromycota, and Basidiomycota groups. More importantly, soil multifunctionality in the rhizosphere was more strongly associated with fungal diversity and community composition, whereas bacterial diversity played a more prominent role in bulk soil. For bamboo-medicinal plant experiments, mixing soil adjacent to bamboo roots, soil adjacent to medicinal plant roots, and inter-row soil into a single composite sample can easily dilute or obscure true rhizosphere effects.

Planting configuration itself can also alter rhizosphere bacterial communities in bamboo forests. Bian et al. (2023) compared Moso bamboo monoculture with Moso bamboo-*Sedum* intercropping in heavy-metal-contaminated

bamboo forests and obtained 325 259 high-quality sequences and 21 591 OTUs. Proteobacteria, Acidobacteria, Planctomycetes, Gemmatimonadetes, and Actinobacteria were the dominant bacterial groups, together accounting for approximately 78.7% of 16S rRNA sequences. After intercropping, SOM, DOM, and bacterial composition changed in both rhizosphere and bulk soils. *Sphingomonas* became an important differential taxon in rhizosphere soil, whereas MND1 and *Nitrospira* were more abundant in bulk soil. Although DOM represented only 1.7%-2.5% of SOM, changes in DOM were closely associated with bacterial community reorganization. Because this study focused on phytoremediation rather than medicinal plant production, its main value for bamboo-medicinal plant research is methodological. Future studies of *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla* should separately sample bamboo rhizosphere soil, medicinal plant rhizosphere soil, and inter-row soil, while simultaneously recording pH, available nutrients, and organic carbon.

4.5 Soil-microbe-bamboo-medicinal plant interaction mechanisms

Bamboo-medicinal plant systems are better understood as dynamic rhizosphere resource-exchange systems rather than as simple cases in which the addition of medicinal plants increases microbial abundance and thereby improves the soil. Wang et al. (2025) summarized research on bamboo-associated microorganisms and showed that bamboo species, spatial position, season, management practices, and coexistence with other plants can all alter the composition of rhizosphere and endophytic microbial communities. These microorganisms, in turn, participate in organic matter decomposition, nitrogen transformation, phosphorus solubilization, phytohormone production, and stress resistance. In bamboo-medicinal plant systems, the overstory bamboo first modifies soil moisture and nutrient availability through shading, litter inputs, and nutrient uptake by rhizomes. After medicinal plants are introduced, their fine roots, root exudates, and plant residues further reshape the local rhizosphere. Bacteria and fungi then respond to these resource changes and influence subsequent nutrient supply through mineralization, immobilization, and enzyme-mediated processes.

Microbial management should likewise not be interpreted as a case of "the more microbial inoculant, the better." Li et al. (2026b) compared *Bacillus subtilis* ACP81, *Terribacillus goriness* CS3, and a mixed ACP81 + CS3 treatment in Moso bamboo forests. When ACP81 and CS3 were applied individually, SOC decreased by 14.01% and 12.76%, respectively, while microbial necromass carbon declined by 15.81% and 23.22%. In contrast, the combined ACP81 + CS3 treatment increased SOC by 14.38% and microbial necromass carbon by 7.91%, and also resulted in higher soil quality and ecological multifunctionality than the single-strain treatments. Thus, even when putatively beneficial microorganisms are identified, single-strain inoculation does not necessarily improve soil conditions. Interactions among microbial strains, the original soil nutrient status, and organic matter availability can all influence the final outcome. At the current stage, management of bamboo-medicinal plant systems should therefore prioritize soil organic matter, pH, available N, P, and K, and soil moisture, while microbial inoculants should be used as complementary measures rather than as substitutes for sound stand and soil management.

5 Effects of the Bamboo Forest Environment on Medicinal Plant Growth, Yield, and Quality

5.1 Medicinal plant growth and biomass accumulation

The growth of medicinal plants under bamboo forests reflects their combined responses to light availability, soil moisture, and belowground competition. In central India, ginger (*Zingiber officinale*) grown beneath *Dendrocalamus strictus* produced a fresh rhizome yield of 18.46 q ha^{-1}, lower than the 22.12 q ha^{-1} obtained under open-field conditions. However, clear differences were observed among planting spacings, and the more suitable spacing treatment still achieved 22.44 q ha^{-1}, indicating that adjustment of medicinal plant density can partly alleviate growth limitations caused by bamboo shading and competition (Lal and Naugraiya, 2022). In nutrient-management experiments with ginger grown under bamboo, the combined application of nitrogen, appropriate amounts of phosphorus and potassium, and *Azospirillum*, *Azotobacter*, and phosphate-solubilizing bacteria improved plant height, leaf number, rhizome length and width, and both fresh and dry weights (Tiwari et al., 2022).

The suitability of a bamboo forest for medicinal plant cultivation should not be judged simply by whether the plants survive. Instead, leaf area, tiller or shoot number, and enlargement of underground organs should be

monitored continuously. In overly dense bamboo stands, medicinal plants often first show reductions in leaf area and underground organ growth, whereas in relatively open stands with insufficient soil fertility, plants may grow well during the early stage but show inadequate rhizome enlargement later. After perennial medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla* are established, survival rate, plant height, aboveground biomass, and increases in underground organ biomass should be recorded at least annually, and bamboo thinning, fertilization, and planting density should be adjusted according to actual plant performance.

5.2 Yield and marketability of medicinal organs

Whether a bamboo-medicinal plant system can generate production benefits ultimately depends on the yield of marketable organs such as rhizomes, tubers, tuberous roots, or bulbs. Kumar and Naugraiya (2020) compared two turmeric (*Curcuma longa*) cultivars under bamboo and found that the average fresh turmeric yield beneath bamboo was 161.46 q ha^{-1}, approximately 28.5% lower than that under open-field conditions. The cultivar Ranga consistently outperformed Roma, with yields under bamboo of approximately 167.75 and 155.18 q ha^{-1}, respectively. In bamboo-turmeric systems, different mulching and nutrient-management practices also significantly affected the weights of mother rhizomes and primary and secondary finger rhizomes, with the better-performing treatment reaching a yield of 12.48 t ha^{-1} (Bhardwaj et al., 2017).

For medicinal plants such as *Polygonatum cyrtonema*, *Paris polyphylla*, and *Bletilla striata*, which require several years before harvest, evaluation based only on fresh weight can easily overlook problems such as uneven underground organ size, increased decay, or insufficient dry matter accumulation. Medicinal plants grown under bamboo forests are therefore better evaluated using a combination of yield per unit area, individual medicinal organ size, dry matter content, and marketable proportion. In sites with dense bamboo roots, even when total fresh weight changes little, individual underground organs may become smaller, harvesting may become more difficult, and mechanical damage may increase. All of these factors can directly reduce the final marketable yield available to family farms.

5.3 Changes in polysaccharides, flavonoids, saponins, and other bioactive constituents

Yield and quality do not necessarily change in parallel after medicinal plants are introduced into bamboo forests. Dhale et al. (2024) compared turmeric grown beneath eight bamboo species and found that the highest yield occurred under open-field conditions, reaching 235.18 q ha^{-1}. Among the bamboo treatments, *Bambusa tulda* and *B. balcooa* performed relatively well, with yields of 230.93 and 220.00 q ha^{-1}, respectively. In contrast to yield, curcumin content was generally higher under bamboo shade. The values reached 3.99% under *Dendrocalamus stocksii*, 3.94% under *D. longipathus*, and 3.92% under *Bambusa cacherensis*, compared with only 3.37% in the open field. These results show that bamboo environments may reduce the yield of some medicinal plants while increasing particular quality-related constituents; therefore, the performance of bamboo-medicinal plant systems cannot be judged solely on the basis of fresh yield.

After eight years of growth under natural forest conditions, *Paris polyphylla* showed marked differences from greenhouse-grown plants in the accumulation of steroidal saponins, flavonoids, and several other secondary metabolites in the rhizomes, indicating that understory environments can substantially alter medicinal plant metabolic profiles (Yan et al., 2024). In practical production, it is therefore inappropriate to make a general claim that “medicinal plants grown under forests have better quality”. Instead, one to three key indicators that truly determine commercial grade should be identified for each medicinal plant. For example, *Polygonatum* should be evaluated primarily for polysaccharides and extractives, *Bletilla striata* for polysaccharides and other characteristic constituents, *Paris polyphylla* for specified saponins, and turmeric for both curcuminoid content and rhizome yield.

5.4 Regulation of medicinal plant secondary metabolism by rhizosphere microorganisms

Rhizosphere microorganisms are associated with medicinal plant quality, but the key issue is whether changes in microbial communities are actually linked to changes in bioactive constituents. Li et al. (2024) compared *Bletilla striata* from different production regions in China and found that the accumulation of metabolites such as militarine and polysaccharides was significantly associated with rhizosphere microbial composition, while SOC

was also an important environmental factor influencing metabolite accumulation. Rhizosphere microorganisms may therefore participate indirectly in the formation of medicinal quality through nutrient transformation, phytohormone regulation, and plant stress responses.

Recent studies on medicinal plants have also proposed the concept of stress-induced quality enhancement, whereby moderate environmental stress can stimulate the accumulation of secondary metabolites such as phenolics, terpenoids, and alkaloids, with rhizosphere microorganisms contributing through nutrient supply, antioxidant responses, and metabolic regulation (Zhang et al., 2025). For medicinal plants cultivated under bamboo forests, this suggests that moderate shading or nutrient competition may enhance certain bioactive constituents, whereas excessive stress may directly reduce yield or even increase disease incidence. At present, a more practical strategy is to first maintain stable soil organic matter, moisture, and nutrient conditions, and then screen candidate microbial groups from the rhizosphere of high-quality medicinal plants.

5.5 Integrated evaluation of medicinal plant yield, quality, and safety

For yield evaluation, medicinal organ yield per unit area, individual plant or organ weight, and marketable proportion should be recorded. For quality evaluation, polysaccharides, saponins, flavonoids, curcuminoids, volatile oils, or other specified indicators should be determined according to the medicinal plant species. Safety evaluation should not be based solely on whether plants appear healthy, but should also include potentially harmful elements such as Cd, Pb, As, and Hg in soils and plant products, together with pesticide residues. Heavy metals can accumulate in medicinal plant tissues and may also interfere with rhizosphere microorganisms and the formation of bioactive constituents, ultimately affecting both product safety and commercial value (Bao et al., 2025). Pesticide use and residues have likewise become important components of quality control in the production of traditional Chinese medicinal materials and medicinal and food homologous plants (Zhang et al., 2024c).

For family farms and grassroots production units, these key indicators should be incorporated into site establishment and production management rather than being assessed only after harvest. Soil heavy metals and basic fertility should be tested before planting; bamboo stand density, fertilization, and pesticide use should be recorded during cultivation; and marketable yield and major bioactive constituents should be assessed at harvest. For species used as both food and medicine, risk control should follow the stricter requirements applicable to either use. In particular, bamboo forests that have previously been used for pollution remediation, have received long-term high-input fertilization, or have an uncertain land-use history should not be directly converted to food or medicinal plant production simply because understory space is available.

Bamboo-medicinal plant systems can be summarized as a continuous chain of effects. Bamboo stand density, canopy openness, and rhizome-root structure first alter understory light, temperature and humidity, soil moisture, and nutrient competition. These changes subsequently influence medicinal plant biomass, underground medicinal organ formation, and secondary metabolism through soil nutrient cycling and rhizosphere microbial processes. Final production performance should therefore not be evaluated on yield alone, but should simultaneously consider bioactive constituents, marketability, and safety, while balancing ecological benefits and economic returns. The integrated pathways through which bamboo stand structure affects medicinal plant yield, quality, and safety are illustrated in Figure 3.

6 Ecological and Economic Benefits and Production Constraints of Bamboo-Medicinal Plant Systems

6.1 Forestland utilization and ecosystem services

The most direct value of bamboo-medicinal plant integrated management is the addition of a continuously usable understory production layer within existing bamboo forests, allowing the same forestland to simultaneously produce bamboo timber, bamboo shoots, and medicinal plant products. Compared with pure bamboo stands, appropriately configured understory crops can improve overall land-use efficiency while maintaining the basic productive functions of the bamboo forest. In intercropping experiments involving different bamboo species and indigo (*Indigofera tinctoria*), indigo monoculture produced 3.43 Mg ha^{-1}, whereas yields under intercropping with *Bambusa balcooa* and *B. tulda* reached 3.21 and 3.02 Mg ha^{-1}, respectively, indicating that understory crops can

still maintain relatively high production levels under suitable bamboo configurations (Pramod Kumar et al., 2025). In addition to providing bamboo timber, shoots, and understory products, bamboo-based agroforestry systems can improve land-use efficiency through vertical stratification and complementary rooting patterns, while also contributing to soil conservation, water regulation, and biomass accumulation (Chanu et al., 2026).

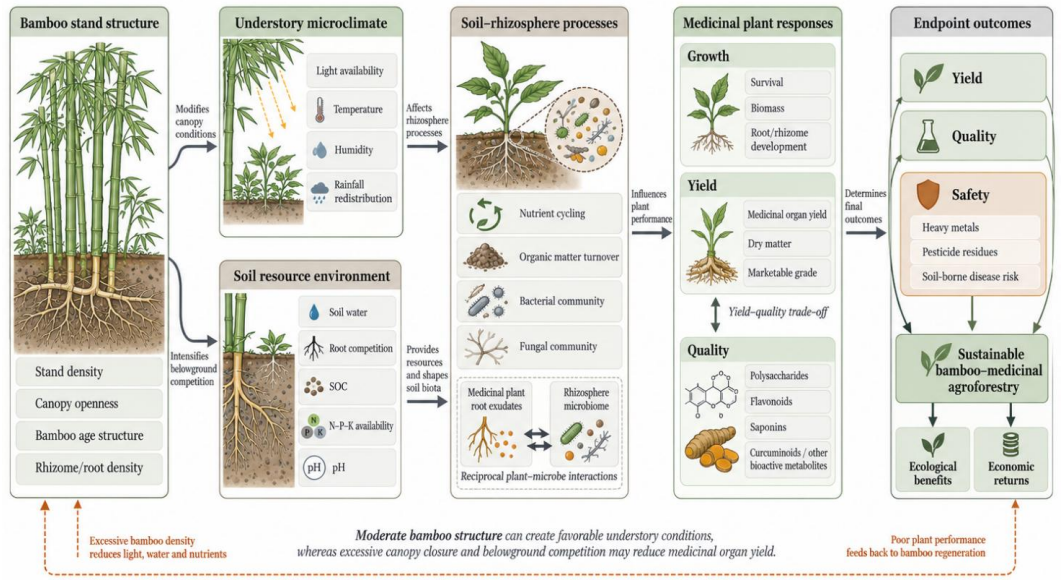


Figure 3 Integrated pathways linking bamboo stand structure with medicinal plant yield, quality, and safety

For existing bamboo forests in southern China, especially Moso bamboo stands where bamboo timber prices are relatively low and understory space has remained unused for long periods, the introduction of medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, or other suitable species can transform a single-output system based mainly on shoots or timber into a two-layer production system. However, such integrated use should not significantly damage the original bamboo stand. Large-scale bamboo removal, repeated deep tillage, or complete removal of litter merely to expand the medicinal planting area should be avoided. In grassroots production, a more meaningful comparison is how much bamboo product and medicinal plant yield can be obtained from the same hectare each year and how much additional labor is required.

6.2 Soil and water conservation, carbon cycling, and biodiversity

Long-term surface cover and underground rhizome networks in bamboo forests provide an important basis for soil conservation, water retention, and carbon accumulation on sloping land, although these ecological benefits require time to develop. Research on bamboo forest restoration in karst regions of southwestern China showed that soil bulk density generally decreased with increasing restoration age, while soil porosity and water-holding capacity gradually improved. Total and labile soil organic carbon in 20-year-old restored bamboo forests were significantly higher than those in 5- and 10-year-old stands and gradually approached the levels found in natural bamboo forests (Pang et al., 2025). These findings have direct implications for bamboo-medicinal plant management. Medicinal plants established under stable bamboo forests can make use of the soil structure and ground cover that have already developed, whereas frequent deep tillage, litter removal, or large-scale trenching for medicinal plant cultivation may offset the original advantages of bamboo forests in soil protection and carbon accumulation. On sloping land, strip planting, small patches, and contour-based layouts are therefore particularly important for minimizing exposed soil.

However, the ecological benefits of bamboo forests do not necessarily increase with bamboo abundance. Li et al. (2025) used ecosystem-service simulations under different bamboo expansion scenarios and showed that bamboo expansion can increase carbon storage and reduce sediment and nutrient losses, but may simultaneously reduce water supply and habitat quality, with substantial regional variation. A more appropriate ecological objective for bamboo-medicinal plant systems is therefore to improve stand structure within existing bamboo forests rather than promote further bamboo expansion. In practical management, moderate thinning, retention of vegetation along

forest margins, reduced whole-stand weeding, and maintenance of litter cover can help preserve understory biodiversity and soil protection while generating medicinal plant income. If a bamboo forest is cleared to the point where only bamboo and a single medicinal plant species remain for the sake of neatness and uniformity, many of its ecological advantages may be substantially weakened.

6.3 Family farm management and overall economic returns

For family farms, whether a bamboo-medicinal plant system is worthwhile ultimately depends on total returns over multiple years rather than on the market price of medicinal plants in a single season. Lakra et al. (2025) compared *Bambusa nutans* intercropped with medicinal plants including *Andrographis paniculata*, *Withania somnifera*, and *Catharanthus roseus*. Net returns from bamboo-*Catharanthus*, bamboo-*Withania*, and bamboo-*Andrographis* systems reached INR 40 557.60, 35 791.20, and 34 144.18 ha^{-1}, respectively, all higher than the INR 26 459.00 ha^{-1} obtained from pure bamboo stands. However, benefit-cost ratios were not always higher than those of medicinal plant monocultures. The bamboo-*Catharanthus* system had a benefit-cost ratio of 1.66, whereas both bamboo-*Withania* and bamboo-*Andrographis* had ratios of 1.32. This indicates that intercropping may increase total net income per unit land area, but does not necessarily mean that each unit of investment generates a higher return than medicinal plant monoculture.

This consideration is particularly important for perennial medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla*. High-value medicinal plants can be profitable, but final economic returns are strongly influenced by capital availability, distance to markets, technical capacity, and management experience. In a survey of 150 smallholder farmers, medicinal plant cultivation generated an average net return of ZAR 19 091.72, with a return on investment of 0.77 per production cycle, while 30% of farmers identified insufficient capital as their main constraint (Mbelebele et al., 2024). For family farms, a more cautious approach is to begin with small experimental plots on better-quality sites and continuously account for the costs of planting material, bamboo thinning, fertilization, weeding, harvesting, and transport. Expansion should occur only when the additional income from medicinal plant harvesting is sufficient to cover these costs and when bamboo shoot or timber production is not substantially reduced.

6.4 Soil degradation, root competition, and disease and safety risks

The greatest long-term risks in bamboo-medicinal plant systems may not appear during the first year of cultivation, but gradually emerge after several consecutive years of management. Most medicinal plants harvested for underground organs have long growth cycles, and their roots and medicinal organs remain concentrated within the same soil layers for extended periods. This can lead to nutrient depletion, accumulation of root exudates, and increases in soil-borne pathogens. Studies of continuous cropping in medicinal plants have shown that long-term monoculture can disrupt rhizosphere microbial balance, promote the accumulation of autotoxic compounds, reduce beneficial microorganisms, and increase pathogenic microorganisms, ultimately resulting in reduced growth, root rot, and deterioration in medicinal quality (Ul Haq et al., 2025). Bamboo forests themselves are perennial clonal systems. Therefore, when *Polygonatum cyrtonema*, *Bletilla striata*, *Paris polyphylla*, and similar medicinal plants are repeatedly cultivated within the same bamboo stand, they face both the continuous-cropping risks associated with the medicinal crop itself and persistent belowground competition caused by bamboo rhizomes entering the planting strips. In production, particular attention should be paid to root rot, plant mortality, reductions in underground organ size, and soil compaction. These risks can be reduced through rotation of planting strips, partial fallowing, organic matter inputs, and timely removal of diseased plants.

Another important concern is soil environmental safety. Medicinal plants can absorb elements such as Cd, Pb, and As from contaminated soils, and apparently normal aboveground growth does not necessarily indicate that underground medicinal organs are safe. An assessment of 12 commonly used medicinal plants found that Cr and Cd concentrations in some samples exceeded permissible levels, demonstrating that medicinal plant safety is directly associated with the contamination history of the cultivation site (Sulaiman et al., 2024). For grassroots production, areas near mining sites, industrial facilities, historically sludge-amended land, and fields with long-term high-input management should not be converted to food-medicinal plant production based on

experience alone. Before establishing bamboo-medicinal plant systems, soils should at least be screened for potentially hazardous elements such as Cd, Pb, As, and Hg. Bamboo forests with a known history of contamination should preferably be used for ecological restoration, bamboo timber production, or other non-food purposes rather than being converted into commercial medicinal plant production sites simply because understory space is available.

7 Regional Applications and Future Prospects

7.1 Application potential in zhejiang and the southern yangtze river delta

Zhejiang and the southern Yangtze River Delta have a long history of Moso bamboo management, with large existing bamboo forest areas and relatively well-developed road networks and forest management infrastructure. Therefore, the future development of bamboo-medicinal plant systems should focus less on expanding the area of Moso bamboo and more on improving existing bamboo stands and increasing the value of understory space. Scenario simulations conducted in Anji, Zhejiang Province, showed that simply expanding Moso bamboo forests could increase product supply but might also be accompanied by declines in carbon storage, soil conservation, nitrogen and phosphorus retention, and habitat quality. In contrast, the introduction of a suitable understory production layer within bamboo forests increased simulated income by 66.89% and improved multiple ecosystem services, including flood regulation, carbon sequestration, soil conservation, and nutrient retention (Ma et al., 2022). Therefore, increasing the overall value per unit area of existing bamboo forests should be given higher priority than further expansion of bamboo into surrounding forestland.

In Zhejiang, it is more appropriate to first classify bamboo forests according to stand and site conditions and then determine which medicinal plants should be cultivated. Highly closed stands with dense rhizome networks and long periods without thinning should first undergo bamboo thinning and planting-strip preparation, whereas stands with relatively open canopies, good road access, and favorable drainage can be prioritized for understory medicinal plant trials. In northern Zhejiang and areas such as Anji and Lin'an, demonstration systems can focus on structural adjustment of Moso bamboo stands. In hilly bamboo-producing areas such as Jinhua and Quzhou, greater attention should be paid to slope position, soil depth, and summer water availability. Medicinal plants such as *Polygonatum cyrtonema*, for which a certain production base already exists, can first undergo region-specific parameter validation. *Bletilla striata*, *Paris polyphylla*, and *Tetrastigma hemsleyanum* are better suited to small-scale, multi-site trials, with survival rate, disease incidence, underground organ development, and product quality monitored continuously for 2-3 years before larger-scale expansion.

7.2 Regional adaptation in Fujian, Jiangxi, and other southern bamboo-producing areas

Although Fujian, Jiangxi, and other bamboo-producing areas in southern China all possess substantial bamboo resources, bamboo-medicinal plant systems should not simply replicate the Zhejiang model. Bamboo forests in Fujian are often managed by dispersed smallholders, and their willingness to make sustained investments depends not only on cultivation technology. A survey of 1 090 bamboo farmers in Sanming, Fujian Province, by Huang and Wen (2025) showed that farmers' subjective perceptions of forest tenure security promoted production investment and long-term harvesting arrangements, while positive expectations regarding the market value of bamboo forest certification also strengthened their willingness to continue management. For bamboo-medicinal plant systems, which require early investments in seedlings, bamboo thinning, and continuous management but often do not generate medicinal plant harvests for several years, stable expectations regarding forestland tenure, technical services, and product marketing are as important as cultivation techniques themselves. Therefore, project selection in Fujian should consider bamboo forest operators, tenure duration, labor availability, and purchasing channels together rather than relying only on bamboo forest area.

Jiangxi and other warm and humid bamboo-growing regions in southern China require even greater emphasis on site-specific parameters. Red-soil hills, karst mountains, low-elevation humid valleys, and high-elevation bamboo areas differ greatly in soil depth, acidity, rainfall, and drainage. After the same medicinal plant is transferred to a different site, the main limiting factor may shift from light to water availability or from soil fertility to soil-borne disease. At present, it is more appropriate to establish small long-term monitoring plots in major Moso

bamboo-producing counties and consistently record bamboo culm density, understory light availability, soil pH, organic matter, available potassium, drainage conditions, and medicinal plant yield and quality. Regional technical guidelines should also allow management parameters to be adjusted according to slope position and stand conditions rather than applying a single fixed standard.

7.3 Establishing a precise "bamboo species-stand structure-medicinal plant-site" matching system

Future configuration of bamboo-medicinal plant systems should simultaneously consider at least four components: bamboo species, stand structure, medicinal plant characteristics, and site conditions. For bamboo species, running and clumping bamboo types should be distinguished. Stand-level factors should include culm density, bamboo age structure, canopy closure, and rhizome distribution. Medicinal plant characteristics should include light requirements, rooting depth, type of marketable organ, growth duration, and water demand. Site conditions should include slope, aspect, soil depth, pH, organic matter, and drainage. Reviews of bamboo biomass models have likewise shown that the accuracy of a single model declines when it is directly transferred across bamboo species and regions, indicating that bamboo management parameters require greater regional and species-specific calibration (Tesema et al., 2025).

Digital technologies can improve the efficiency of this matching process, but grassroots applications do not need to begin with highly complex equipment. UAS-LiDAR can already identify understory bamboo layers in complex forests and estimate structural indicators such as bamboo height, basal diameter, and aboveground biomass with relatively high accuracy, with model R^2 values reaching 0.84-0.91 (Shen et al., 2025b). For bamboo-medicinal plant production, a more practical approach is to first classify bamboo forests into several site and stand types using drone imagery, handheld light meters, GPS, and conventional soil testing, and then assign suitable medicinal plants and management practices to each type. In the future, regional databases could gradually be developed around the framework of "bamboo forest conditions-recommended medicinal plants-risk alerts-management parameters," enabling family farms to determine before planting whether a particular bamboo stand is more suitable for *Polygonatum cyrtonema*, *Bletilla striata*, or is temporarily unsuitable for cultivation of underground medicinal crops.

7.4 Promoting standardized, digital, and ecological management

The standardization needed for bamboo-medicinal plant systems is not a single fixed bamboo density or medicinal plant spacing, but rather the standardization of key management procedures. Grassroots technical guidelines can be organized around the sequence of site assessment-bamboo stand adjustment-medicinal plant establishment-water and nutrient management-soil and disease monitoring-quality testing-harvest recording. Before establishment, at least bamboo stand density, canopy closure, rhizome distribution, soil pH, organic matter, available nitrogen, phosphorus and potassium, and soil safety indicators should be recorded. After planting, survival rate, disease incidence, fertilization, bamboo thinning, underground organ development, and harvest yield should be continuously documented. Annual records are particularly important for perennial medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla*. Otherwise, when yield decline or disease occurs after 3-5 years of cultivation, it becomes difficult to determine whether the cause is increased bamboo density, soil degradation, planting material, or management practices.

The first objective of digitalization should be to ensure that production information is recorded, comparable, and traceable. Bamboo resource management studies have proposed frameworks using environmental sensors, GPS, cloud databases, and visualization platforms to record bamboo forest conditions and production information (Maramag et al., 2026), although these approaches currently remain mainly at the stage of system design and demonstration. For family farms, establishing electronic production records for stand density, light availability, soil moisture, fertilization, disease occurrence, and medicinal plant batches is more practical than immediately investing in LiDAR systems or intelligent robots. As production expands, automatic temperature and humidity monitoring, drone-based mapping, and product traceability can gradually be incorporated. The purpose of digitalization should be to reduce inappropriate bamboo thinning, repeated fertilization, missed disease detection, and inconsistency among product batches, while preserving comparable records for subsequent production cycles.

7.5 Building coordinated models linking family farms with the value chain

Smallholder medicinal plant production commonly faces problems such as unstable seedling quality, insufficient technical services, limited investment capital, and uncertain marketing channels. Stable contract production, purchase agreements, or buy-back arrangements can reduce the market risks faced by farmers entering the production of perennial medicinal plants (Nwafor et al., 2021). Research on agricultural value chains has also shown that smallholder participation in cooperative arrangements is not limited to product marketing, but can also provide access to inputs, technical services, processing capacity, and more stable market channels (Mishra et al., 2024). Therefore, before planting medicinal plants such as *Polygonatum cyrtonema*, *Bletilla striata*, and *Paris polyphylla*, growers should, as far as possible, determine cultivar or planting material specifications, quality requirements, purchasing entities, and primary processing pathways.

From the perspective of practical organization, a three-tier structure can be developed consisting of family farms or cooperatives + technical service providers + processing and purchasing enterprises. Family farms would be responsible for bamboo stand preparation, medicinal plant production, and field records; cooperatives or regional service providers would coordinate planting materials, soil testing, pest and disease guidance, and quality testing; and pharmaceutical companies, food enterprises, or specialized purchasers would undertake grading, processing, and marketing. Small-scale farmers do not all need to pursue the same high-value medicinal crop, but can select species with different harvest cycles according to bamboo forest conditions and available capital, thereby reducing the risk associated with concentrated harvesting and marketing. In bamboo-producing regions such as Zhejiang, Fujian, and Jiangxi, future evaluation should place greater emphasis on the combined net returns from bamboo timber, bamboo shoots, and medicinal plants per unit area, product compliance rates, duration of continuous management, and the establishment of stable purchasing channels.

Acknowledgements

The authors were responsible for the conceptualization of the review, literature screening and organization, evidence synthesis, interpretation of the findings, and preparation and revision of the manuscript. The authors reviewed and approved the final version of the manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Reference

Abayneh D., Lemma B., and Yimer F., 2026, Effect of bamboo plantation and adjacent land uses on soil organic carbon stock in Sidama Highlands, Ethiopia, Applied and Environmental Soil Science, 2026(1): 8062908.
https://doi.org/10.1155/aess/8062908

Ahmad Z., Kumari R., Mir B., Saeed T., Firdaus F., Vijayakanth V., Keerthana K., Ramakrishnan M., and Wei Q., 2025, Bamboo for the future: From traditional use to Industry 5.0 applications, Plants, 14(19): 3019.
https://doi.org/10.3390/plants14193019

Allo M. K., Loppies J. E., Rosniati, and Ramlah S., 2024, Agroforestry of bamboo in Tana Toraja, Indonesia (a way combining plants inherited from ancestors), IOP Conference Series: Earth and Environmental Science, 1315(1): 012016.
https://doi.org/10.1088/1755-1315/1315/1/012016

Bao H., Wang Y., Bao H., Wang F., Jiang Q., He X., Li H., Ding Y., and Zhu C., 2025, Ecotoxicological impacts of heavy metals on medicinal plant quality and rhizosphere microbial communities, Plants, 14(20): 3214.
https://doi.org/10.3390/plants14203214

Bhardwaj D. R., Kikon G., Thakur C. L., and Kumar N., 2017, Effect of bamboo species and mulch materials on turmeric crop production and curcumin contents, Indian Journal of Agroforestry, 19(2): 13-22.

Bian F., Zhang X., Li Q., Huang Z., and Zhong Z., 2023, Enhancement of phytoremediation of heavy metal pollution using an intercropping system in Moso bamboo forests: Characteristics of soil organic matter and bacterial communities, Forests, 14(9): 1895.
https://doi.org/10.3390/f14091895

Campanello P. I., Gatti M. G., Ares A., Montti L., and Goldstein G., 2007, Tree regeneration and microclimate in a liana and bamboo-dominated semideciduous Atlantic Forest, Forest Ecology and Management, 252(1-3): 108-117.
https://doi.org/10.1016/j.foreco.2007.06.032

Chanu T. B., Chand H. B., John A., Sharma V., Mahajan A., Nirala D., Apshahana K., and Chanu T. A., 2026, Bamboo-based agroforestry systems: A nature-based solution for degraded land restoration, Frontiers in Ecology and Evolution, 14: 1904908.
https://doi.org/10.3389/fevo.2026.1904908

Deng P., Yin R., Wang H., Chen L., Cao X., and Xu X., 2023, Comparative analyses of functional traits based on metabolome and economic traits variation of Bletilla striata: Contribution of intercropping, Frontiers in Plant Science, 14: 1147076.
https://doi.org/10.3389/fpls.2023.1147076

Dhale R. B., Raut P. D., Katkar R. N., Illorkar V. M., Dangore S. T., Dolaskar U. B., Nagdeve S. S., and Shahare N. J., 2024, Impact of bamboo based agroforestry system on yield and quality of turmeric (Curcuma longa) grown in entisols, International Journal of Advanced Biochemistry Research, 8(8): 1327-1331.
https://doi.org/10.33545/26174693.2024.v8.i8q.1983

Feng P. F., and Li Y. M., 2023, China's bamboo resources in 2021, World Bamboo and Rattan, 21(2): 100-103.
https://doi.org/10.55899/09734449/jbr021302

Fu D., Guan F., Li Z., Li M., Lu Y., Zhou X., and Zhang X., 2026, Effects of slope and strip-cutting width on bamboo shoot emergence, culm formation, and understory vegetation diversity in Moso bamboo forests in China, Plants, 15(2): 258.
https://doi.org/10.3390/plants15020258

Garima, Bhardwaj D. R., Thakur C. L., Kaushal R., Sharma P., Kumar D., and Kumari Y., 2021, Bamboo-based agroforestry system effects on soil fertility: Ginger performance in the bamboo subcanopy in the Himalayas (India), Agronomy Journal, 113(3): 2832-2845.
https://doi.org/10.1002/agj2.20684

Ge Z., Yu T., Tian X., Chen X., Yao Y., and Mao L., 2025, Analysis of understory plant community assembly differences in Moso bamboo forests in the subtropical evergreen broad-leaved forest region of eastern China, Forests, 16(3): 478.
https://doi.org/10.3390/f16030478

Guo W., Li M. H., and Qi L., 2025, The contrasting roles of fungal and bacterial diversity and composition in shaping the multifunctionality of rhizosphere and bulk soils across large-scale bamboo forests, BMC Microbiology, 25: 252.
https://doi.org/10.1186/s12866-025-03962-0

Guo X., Li Q., Yan B., Wang Y., Wang S., Xiong F., Zhang C., Zhang Y., and Guo L., 2022, Mild shading promotes sesquiterpenoid synthesis and accumulation in Atractylodes lancea by regulating photosynthesis and phytohormones, Scientific Reports, 12: 21648.
https://doi.org/10.1038/s41598-022-25494-7

He T. Y., Cai X., Zhang J., Cai Z., Chen Q., Li S., Ye J., Chen L., Rong J., Chen L., and Zheng Y., 2025, Effects of Moso bamboo (*Phyllostachys edulis*) forest stand density on root growth and soil quality for shoot production under a long-term bamboo-stocking retention model, Biology, 14(9): 1179.
https://doi.org/10.3390/biology14091179

Huang Y., and Wen Y., 2025, Perception over possession: How farmers' subjective tenure security and forest certification drive sustainable bamboo management, Land, 14(10): 1979.
https://doi.org/10.3390/land14101979

Huang Z., Li Q., Bian F., Zhong Z., and Zhang X., 2025, Effects of bamboo-sourced organic fertilizer on the soil microbial necromass carbon and its contribution to soil organic carbon in Moso bamboo (*Phyllostachys edulis*) forest, Forests, 16(3): 553.
https://doi.org/10.3390/f16030553

Kittur B. H., Sudhakara K., Mohan Kumar B., Kunhamu T. K., and Sureshkumar P., 2016, Bamboo based agroforestry systems in Kerala, India: Performance of turmeric (Curcuma longa L.) in the subcanopy of differentially spaced seven year-old bamboo stand, Agroforestry Systems, 90(2): 237-250.
https://doi.org/10.1007/s10457-015-9849-z

Kumar R., and Naugraiya M. N., 2020, Performance of turmeric (Curcuma longa) under bamboo (Dendrocalamus strictus) based agroforestry system in Chhattisgarh, International Journal of Current Microbiology and Applied Sciences, 9(6): 4080-4084.
https://doi.org/10.20546/ijcmas.2020.906.477

Lakra S., Oraon P. R., and Singh B. K., 2025, Performance of medicinal plants and soil fertility under Bambusa nutans-based agroforestry system, Indian Journal of Agroforestry, 27(1).

Lal J., and Naugraiya M. N., 2022, Yield of Zingiber officinale under Dendrocalamus strictus based agroforestry system in plains of Chhattisgarh, International Journal of Current Microbiology and Applied Sciences, 11(1): 184-193.
https://doi.org/10.20546/ijcmas.2022.1101.021

Li C. E., Wang S. H., Wu S. P., Chen W. H., and Yuan M. H., 2025, Beyond carbon: Navigating ecosystem service synergies and trade-offs in bamboo expansion, Advances in Bamboo Science, 13: 100209.
https://doi.org/10.1016/j.bamboo.2025.100209

Li Q., Huang Z., Bian F., Zhong Z., and Zhang X., 2026b, Bamboo-sourced liquid microbial fertilizer improves soil quality and ecological multifunctionality via regulating microbial necromass carbon, Applied Soil Ecology, 219: 106774.
https://doi.org/10.1016/j.apsoil.2025.106774

Li S., Li X., Ye Y., Chen M., Chen H., Yang D., Li M., Jiang F., Zhang X., and Zhang C., 2024, The rhizosphere microbiome and its influence on the accumulation of metabolites in Bletilla striata (Thunb.) Reichb. f., BMC Plant Biology, 24: 409.
https://doi.org/10.1186/s12870-024-05134-0

Li Z., Zheng Y., Tang H., Li X., Luo Z., and Jiang M., 2026a, Short-term agroforestry with four medicinal herbs under Neosinocalamus affinis plantation: Growth performance and impacts on soil properties, Journal of Sichuan Forestry Science and Technology, 47(1): 52-60.

Ma S., Wang H. Y., Zhang X., Wang L. J., and Jiang J., 2022, A nature-based solution in forest management to improve ecosystem services and mitigate their trade-offs, Journal of Cleaner Production, 351: 131557.
https://doi.org/10.1016/j.jclepro.2022.131557

Manasa P. A. C., Hegde R., Salimath S. K., and Maheswarappa V., 2024, Intercropping performance and its influence on soil nutrient status in bamboo-based agroforestry practice, Agroforestry Systems, 98(6): 1803-1816.
https://doi.org/10.1007/s10457-024-00992-x

Maramag C. L., Ayuyang D. M., and Ayuyang R. R., 2026, Design and architecture of an IoT-enabled bamboo resource management system: Data-driven approach for sustainable agriculture, International Journal of Biosciences, 28(4): 107-115.
https://doi.org/10.12692/ijb/28.4.107-115

Mbelebele Z., Mdoda L., and Ntlanga S. S., 2024, Growing wealth from nature: Analyzing the profitability and determinants of high-value medicinal plants in smallholder production systems, Cogent Economics & Finance, 12(1): 2426536.
https://doi.org/10.1080/23322039.2024.2426536

Mishra V., Ishdorj A., Tabares Villarreal E., and Norton R., 2024, Collaboration in agricultural value chains: A scoping review of the evidence from developing countries, Journal of Agribusiness in Developing and Emerging Economies, 15(6): 1168-1192.
https://doi.org/10.1108/JADEE-12-2023-0311

Nwafor I., Nwafor C., and Manduna I., 2021, Constraints to cultivation of medicinal plants by smallholder farmers in South Africa, Horticulturae, 7(12): 531.
https://doi.org/10.3390/horticulturae7120531

Pang L., Tian C., Yuan Q., and Deng W., 2025, Effects of different restoration years on soil carbon sequestration and water retention capacity in bamboo forest: A case study in Southwest China Karst, Ecological Engineering, 210: 107434.
https://doi.org/10.1016/j.ecoleng.2024.107434

Pramod Kumar P., Hegde R., Maheswarappa V., Clara Manasa P. A., and Kencharaddi R. N., 2025, Performance of different bamboo species and Indigofera tinctoria in agroforestry situation in the tropical humid region of Karnataka, Indian Journal of Agroforestry, 27(3): 31-38.

Sharma U., Bhardwaj D. R., Sharma S., Sankhyan N., Thakur C. L., Rana N., and Sharma S., 2022, Assessment of the efficacy of various mulch materials on improving the growth and yield of ginger (Zingiber officinale) under bamboo-based agroforestry system in NW-Himalaya, Agroforestry Systems, 96(5-6): 925-940.
https://doi.org/10.1007/s10457-022-00753-8

Shen J., Zeng X., Fan S., and Liu G., 2025a, Impacts of intensive management practices on the long-term sustainability of soil and water conservation functions in bamboo forests: A mechanistic review from silvicultural perspectives, Forests, 16(5): 787.
https://doi.org/10.3390/f16050787

Shen X., Cao L., Ma Y., Coops N. C., Muise E. R., Wang G., and Cao F., 2025b, Estimating structure of understory bamboo for giant panda habitat by developing an advanced vertical vegetation classification approach using UAS-LiDAR data, International Journal of Applied Earth Observation and Geoinformation, 136: 104304.
https://doi.org/10.1016/j.jag.2024.104304

Sinha A., Malakar A., and Gorain S., 2025, Efficacy of edible bamboo (Dendrocalamus asper) based agroforestry to aid socio-economic status in red and lateritic belt of eastern India, Indian Journal of Economics and Development, 21(1): 69-76.
https://doi.org/10.35716/IJED-23576

Soman D., and Chavan R. L., 2024, Influence of bamboo-soybean agroforestry system on soil chemical characteristics in northern transitional zone of Karnataka, Journal of Farm Sciences, 37(1): 83-85.
https://doi.org/10.61475/JFS.2024.v37i1.19

Sulaiman M. B., Adamu A. M., Ali S. B., Ezenobi U. V., Gimba A. M., Akinlotan O. O., and Abubakar A., 2024, Heavy metal contamination in medicinal plants: Assessing carcinogenic and non-carcinogenic health risks, Discover Environment, 2: 11.
https://doi.org/10.1007/s44274-024-00035-3

Tesema H. A., Durai J., and Alamerew A. N., 2025, Bamboo biomass estimation for sustainable forest management and climate mitigation: A comprehensive review of allometric models and emerging technologies, Discover Sustainability, 6: 1315.
https://doi.org/10.1007/s43621-025-02001-2

Tiwari M., Toppo P., Sahu M., Toppo S., and Singh L., 2022, Effect of nutrients on growth and yield of ginger under bamboo-based agroforestry system, The Pharma Innovation Journal, 11(9S): 2924-2926.

Ul Haq M. Z., Bai Z., Gu G., Liu Y., Yang D., Yang H., Yu J., and Wu Y., 2025, Continuous cropping obstacles in medicinal plants: Driven by soil microbial communities and root exudates. A review, Plant Science, 359: 112686.
https://doi.org/10.1016/j.plantsci.2025.112686

Wang B., and Yang Z., 2026, Effects of different cultivation patterns and bamboo stand densities on growth and physiological traits of Paeonia lactiflora intercropped under *Phyllostachys edulis* forests, Forests, 17(8): 862.
https://doi.org/10.3390/f17080862

Wang H., Cao X., Fan W., Deng P., and Xu X., 2023, Effects of intercropping systems of *Phyllostachys edulis* and Bletilla striata on soil bacterial community composition and function, Agroforestry Systems, 97(4): 617-630.
https://doi.org/10.1007/s10457-023-00814-6

Wang Y., Bai S., Binkley D., Zhou G., and Fang F., 2016, The independence of clonal shoot's growth from light availability supports Moso bamboo invasion of closed-canopy forest, Forest Ecology and Management, 368: 105-110.
https://doi.org/10.1016/j.foreco.2016.02.037

Wang Y., Ren H., Zhong Y., Song R., Jiang S., Lai M., Shen Y., Liu S., Shi W., and Qi G., 2025, Microbial diversity and function in bamboo ecosystems, Frontiers in Microbiology, 16: 1533061.
https://doi.org/10.3389/fmicb.2025.1533061

Wen D. M., Zhang H. B., Qin F. Y., Xu C. Q., Li D. D., and Guo B. L., 2025, Effects of understory environmental factors on understory planting of medicinal plants, China Journal of Chinese Materia Medica, 50(5): 1164-1171.

Wu R., Wu N., Nan X., Yan H., Wang K., Ma T., She J., and Bao Z., 2023, Effects of the bamboo communities on microclimate and thermal comfort in subtropical climates, Forests, 14(6): 1231.
https://doi.org/10.3390/f14061231

Wu Y., Guo J., Tang Z., Wang T., Li W., Wang X., Cui H., Hu X., and Qi L., 2024, Moso bamboo (*Phyllostachys edulis*) expansion enhances soil pH and alters soil nutrients and microbial communities, Science of the Total Environment, 912: 169346.
https://doi.org/10.1016/j.scitotenv.2023.169346

Xiao L., Li C., Cai Y., Zhou T., Zhou M. H., Gao X., Shi Y., Du H., Zhou G., and Zhou Y., 2021, Interactions between soil properties and the rhizome-root distribution in a 12-year Moso bamboo reforested region: Combining ground-penetrating radar and soil coring in the field, Science of the Total Environment, 800: 149467.
https://doi.org/10.1016/j.scitotenv.2021.149467

Xu H., Wang F., Hu Z., Du Z., Cheng L., and Xu X., 2023, Moso Bamboo-Polygonatum cyrtonema agroforestry systems: Evaluation of soil quality and Polygonatum yield, Forests, 14(7): 1426.
https://doi.org/10.3390/f14071426

Yan X., Wang D., Zhang A., Xia J., Jiao J., Ghanim M., Ou X., He X., and Shi R., 2024, Understory growth of Paris polyphylla accumulates a reservoir of secondary metabolites of plants, Frontiers in Microbiology, 15: 1400616.
https://doi.org/10.3389/fmicb.2024.1400616

Zhang C. C., Cheng M., Li X. Y., Tian K., Zheng B. W., Chen M., and Yang G., 2024c, Review and prospects of pesticide use and residues in cultivation of medicinal and food homologous substances, China Journal of Chinese Materia Medica, 49(17): 4553-4561.

Zhang H., Liu S., Zhang S., and Bai Y., 2026, Positive microbial-enzyme feedbacks on soil organic carbon enhance understory cultivation of Paris polyphylla across forest types, Land Degradation & Development, 37(9): 4189-4204.
https://doi.org/10.1002/ldr.70367

Zhang J., Ning Y., Wu H., Gao G., Wu Z., Peng Y., Huang Z., and Zhang X., 2024a, Intercropping shapes the metabolome and microbiome of medicinal giant lily (*Cardiocrinum giganteum*) in bamboo, Chinese fir, and mixed forests, Forests, 15(12): 2201.
https://doi.org/10.3390/f15122201

Zhang J., Wu H., Gao G., Peng Y., Ning Y., Huang Z., Chen Z., Xu X., and Wu Z., 2024b, Karst ecosystem: Moso bamboo intercropping enhances soil fertility and microbial diversity in the rhizosphere of giant lily (*Cardiocrinum giganteum*), Forests, 15(11): 2004.
https://doi.org/10.3390/f15112004

Zhang X., Gao G., Wu Z., Wen X., Zhong H., Zhong Z., Bian F., and Gai X., 2019, Agroforestry alters the rhizosphere soil bacterial and fungal communities of Moso bamboo plantations in subtropical China, Applied Soil Ecology, 143: 192-200.
https://doi.org/10.1016/j.apsoil.2019.07.019

Zhang X., Gao G., Wu Z., Wen X., Zhong H., Zhong Z., Yang C., Bian F., and Gai X., 2020, Responses of soil nutrients and microbial communities to intercropping medicinal plants in Moso bamboo plantations in subtropical China, Environmental Science and Pollution Research, 27(2): 2301-2310.
https://doi.org/10.1007/s11356-019-06750-2

Zhang X., Li Q., Zhong Z., Huang Z., Wen X., Bian F., and Yang C., 2023, Determining changes in microbial nutrient limitations in bamboo soils under different management practices via enzyme stoichiometry, Catena, 223: 106939.
https://doi.org/10.1016/j.catena.2023.106939

Zhang X., Ran Q., Han Y., Gan L., Zou X., and Dong C., 2025, The rhizosphere microecological mechanisms of stress-induced quality enhancement in medicinal plants, Plant Stress, 17: 100965.
https://doi.org/10.1016/j.stress.2025.100965

Zhou X., Zhang X., Sharma R. P., and Guan F., 2024, Response of bamboo canopy density to terrain, soil and stand factors, Trees, 38(6): 1353-1366.
https://doi.org/10.1007/s00468-024-02552-3

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