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Quality Differences Between Log-Cultivated and Substrate-Cultivated *Ganoderma lucidum*

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Abstract Log cultivation and substrate cultivation of *Ganoderma lucidum* differ markedly in substrate source, nutrient supply, growth cycle, environmental regulation, and production management, and these differences may influence fruiting body appearance, marketability, and the accumulation of bioactive compounds. This study compares the two cultivation systems in terms of production characteristics, fruiting body morphology and color, drying performance, yield and marketable yield, as well as polysaccharides, triterpenoids, proteins, and mineral elements, and further analyzes the effects of strain, cultivation materials, temperature and humidity, light conditions, harvest stage, drying, and storage. Log cultivation shows certain advantages in traditional market perception and some quality indicators, whereas substrate cultivation offers greater flexibility in substrate formulation, standardization, and large-scale production. However, quality differences between the two systems are not consistent across all indicators. The quality of *G. lucidum* should therefore be evaluated comprehensively by integrating biochemical quality, commercial quality, production performance, economic performance, and safety, rather than being judged solely on the basis of cultivation method or a single component. This study provides a reference for cultivation system selection, product grading, and quality control of *G. lucidum*.
Keywords *Ganoderma lucidum*; Log cultivation; Substrate cultivation; Quality differences; Bioactive compounds; Commercial quality; Cultivation selection

1 Introduction

Ganoderma lucidum is an important medicinal mushroom whose artificial production and product development have gradually expanded from traditional medicinal use to functional foods, dietary supplements, and related health products. Its fruiting bodies contain a wide range of constituents, including polysaccharides, triterpenoids, sterols, proteins, and phenolic compounds, among which polysaccharides and triterpenoids are currently regarded as important indicators for evaluating functional quality. External traits, such as cap size, thickness, integrity, color, and drying performance, also directly affect the commercial value of whole dried fruiting bodies and sliced products. Therefore, obtaining fruiting bodies with desirable appearance and stable chemical composition under consistent production conditions remains an important concern in *G. lucidum* cultivation (Ahmad et al., 2021; Ekiz et al., 2023).

At present, artificial production of *G. lucidum* mainly involves two representative cultivation systems: log cultivation and substrate cultivation. In log cultivation, intact wood serves as the substrate for mycelial colonization and fruiting body formation. The woody structure remains relatively stable, nutrients are gradually released as the wood is degraded, and the overall growth cycle is generally longer. In contrast, substrate cultivation mainly uses sawdust and other lignocellulosic materials supplemented with nutrient sources such as wheat bran and rice bran, and production is commonly conducted in bags or bottles. Substrate composition, moisture content, and cultivation conditions can be adjusted more readily, making this system more suitable for facility-based and batch production (Berovic et al., 2022). However, substrate formulations may differ considerably in C/N ratio, lignocellulosic composition, pore structure, and nutrient level, meaning that substrate cultivation itself also encompasses substantial production variability (Amiri-Sadeghan et al., 2022).

Cultivation method may influence fruiting body development and metabolite accumulation through substrate nutrition, physical structure, growth duration, and environmental factors such as temperature, humidity, light, and ventilation. Different cultivation substrates and harvest stages can alter the contents of triterpenoids, ganoderic acids, polysaccharides, and phenolic compounds in *G. lucidum* (Bidegain et al., 2019), while changes in environmental conditions may simultaneously affect fruiting body morphology and internal chemical composition (Sudheer et al., 2018). Direct comparisons between wood-based and bag-based cultivation have further shown that fruiting bodies produced under the two systems may differ in nutritional composition, trace elements, and functional components, although the direction of change is not consistent across all indicators (Song et al., 2020). Therefore, product quality cannot yet be adequately judged solely on the basis of cultivation method, and further comparison is needed to determine whether commercial appearance, major bioactive components, and production performance show consistent patterns of variation.

Accordingly, this study focuses on fruiting bodies of *G. lucidum* produced by log cultivation and substrate cultivation and compares the two systems in terms of fruiting body morphology and commercial quality, major nutritional and bioactive components, and production performance. Possible causes of the observed differences are further analyzed in relation to substrate characteristics, growth environment, and production management. The study aims to clarify the major quality differences between the two cultivation systems and their practical significance for production, thereby providing a reference for cultivation system selection, product quality evaluation, and commercial grading of *G. lucidum*.

2 Production Characteristics of Log and Substrate Cultivation

2.1 Log cultivation

Log cultivation uses intact woody tissue as the nutritional basis for the long-term growth of *Ganoderma lucidum*, and its key requirement is the selection of suitable wood capable of supporting mycelial colonization and fruiting body formation. As traditional long-log cultivation gradually developed into short-log cultivation, producers generally selected suitable broad-leaved tree species, cut the wood into shorter sections, inoculated the logs, and allowed mycelial colonization before transferring them to soil-covering or buried-log fruiting systems. Early studies on short-log production showed that log size, moisture status, inoculation method, and subsequent soil-covering management can all influence mycelial colonization and fruiting performance, indicating that intact wood itself is the most fundamental production basis of the log cultivation system. Unlike formulated substrates produced by grinding and recombining raw materials, logs retain the natural cell-wall structure, density, and chemical composition of wood, and their nutrients are gradually utilized by the mycelium as lignin, cellulose, and hemicellulose are decomposed.

Another important characteristic of intact wood is its relatively slow and prolonged decomposition process. Experiments using oak logs for *G. lucidum* cultivation have shown that the structures of lignin, cellulose, and hemicellulose continue to change as cultivation duration increases, and the extent of degradation differs among cultivation years (Zhang et al., 2022). Logs therefore do not function as substrates that release nutrients all at once, but rather as continuously changing nutritional environments shaped by mycelial penetration and wood decay. Such slow and sustained lignocellulosic degradation may support a prolonged period of mycelial growth and fruiting body maturation, but it also results in a longer production cycle and extended occupation of cultivation space. Whether a longer growth period necessarily leads to greater accumulation of triterpenoids, polysaccharides, or other bioactive compounds cannot be determined solely from cultivation duration and should instead be evaluated together with strain, wood species, and compound-specific analytical results.

2.2 Substrate cultivation

The main feature of substrate cultivation is that the cultivation medium can be artificially formulated. In production, lignocellulosic materials such as sawdust, straw, and corn cobs are commonly used as major carbon sources, while wheat bran, rice bran, corn flour, and other nutrient supplements are added, and materials such as gypsum or calcium carbonate are used to adjust substrate properties. Different combinations of raw materials can create markedly different nutritional environments. Jandaik et al. (2013) compared various forestry by-products,

agricultural straws, and supplements such as wheat bran, rice bran, and corn flour, and found that different combinations of basal materials and supplements produced different effects on mycelial growth, primordium formation, and yield. Therefore, "substrate cultivation" should not be regarded as a single fixed production system. Formulations such as sawdust + wheat bran, straw + bran, and mixtures of multiple agricultural by-products actually represent different nutritional systems. Accordingly, variations in the quality of substrate-cultivated *G. lucidum* reported among studies are not necessarily contradictory, but may first arise from differences in substrate formulation.

This flexibility in formulation is also one of the most obvious characteristics distinguishing substrate cultivation from log cultivation. Rashad et al. (2019) used agricultural residues such as cotton stalks, corn straw, rice straw, and sugarcane bagasse, supplemented with wheat bran or corn gluten, for *G. lucidum* production and found that different raw materials and their combinations significantly altered mycelial growth, production cycle, and fruiting body yield. Substrate systems can therefore be adjusted according to locally available resources by modifying the proportions of carbon sources, nitrogen sources, and supplementary materials, allowing a balance among raw material cost, mycelial growth rate, and fruiting body yield. However, this also means that substrate-cultivated *G. lucidum* produced in different regions, by different enterprises, or even in different production batches may not share an identical nutritional background.

2.3 Differences in growth environment

The most explanatory differences between log and substrate cultivation arise first from nutrient-release patterns and substrate structure. Intact logs have a dense structure in which woody tissues remain relatively complete, requiring the mycelium to penetrate progressively inward through lignocellulosic degradation. In contrast, formulated substrates are produced through grinding, mixing, and repacking, creating new pore structures among substrate particles, while moisture content, nutrient level, and packing density can be artificially adjusted. Dynamic studies of substrate cultivation have shown that as *G. lucidum* progresses from the mycelial stage to primordium formation, elongation, and maturity, substrate moisture, total nitrogen, total phosphorus, total potassium, and pH all change significantly. This indicates that the cultivation substrate is not a static nutritional carrier but undergoes continuous nutrient consumption and microenvironmental change during fungal growth (Zhang et al., 2018). In standardized bag cultivation, substrate moisture can even be preset to approximately 65%, while bag structure and ventilation design can be optimized to improve conditions for mycelial colonization (Ye et al., 2018). Compared with natural logs, substrate cultivation therefore provides greater scope for artificial regulation of moisture, nutrient availability, and aeration (Figure 1).

Temperature, humidity, light, and air exchange represent another layer of difference between the two systems. Log cultivation, particularly under soil-covered, forest-understory, or simple-shed conditions, is more strongly influenced by seasonal temperature, air humidity, soil moisture, and natural ventilation, resulting in greater temporal and spatial variability in the microenvironment. In contrast, bag-based substrate cultivation is more readily conducted under facility-controlled conditions, allowing temperature, humidity, light, and ventilation to be adjusted separately during mycelial growth and fruiting body development. Artificial cultivation studies have shown that different *Ganoderma* strains do not respond identically to cultivation temperature, air humidity, and substrate conditions. Even when similar sawdust-based substrates are used, suitable fruiting conditions still need to be adjusted according to the strain (Wannasawang et al., 2023). The complete growth cycle of log cultivation is also generally much longer than that of rapid artificial cultivation systems (Oke et al., 2022). The quality differences between log- and substrate-cultivated *G. lucidum* can therefore be understood as the cumulative result of two contrasting growth backgrounds: slow wood degradation and prolonged maturation on the one hand, and adjustable nutrition, relatively controlled environmental conditions, and a shorter production cycle in artificial substrates on the other. However, a longer growth period should only be regarded as a possible explanatory factor for quality differences and cannot be used to directly infer that any specific bioactive compound must necessarily be present at a higher level.

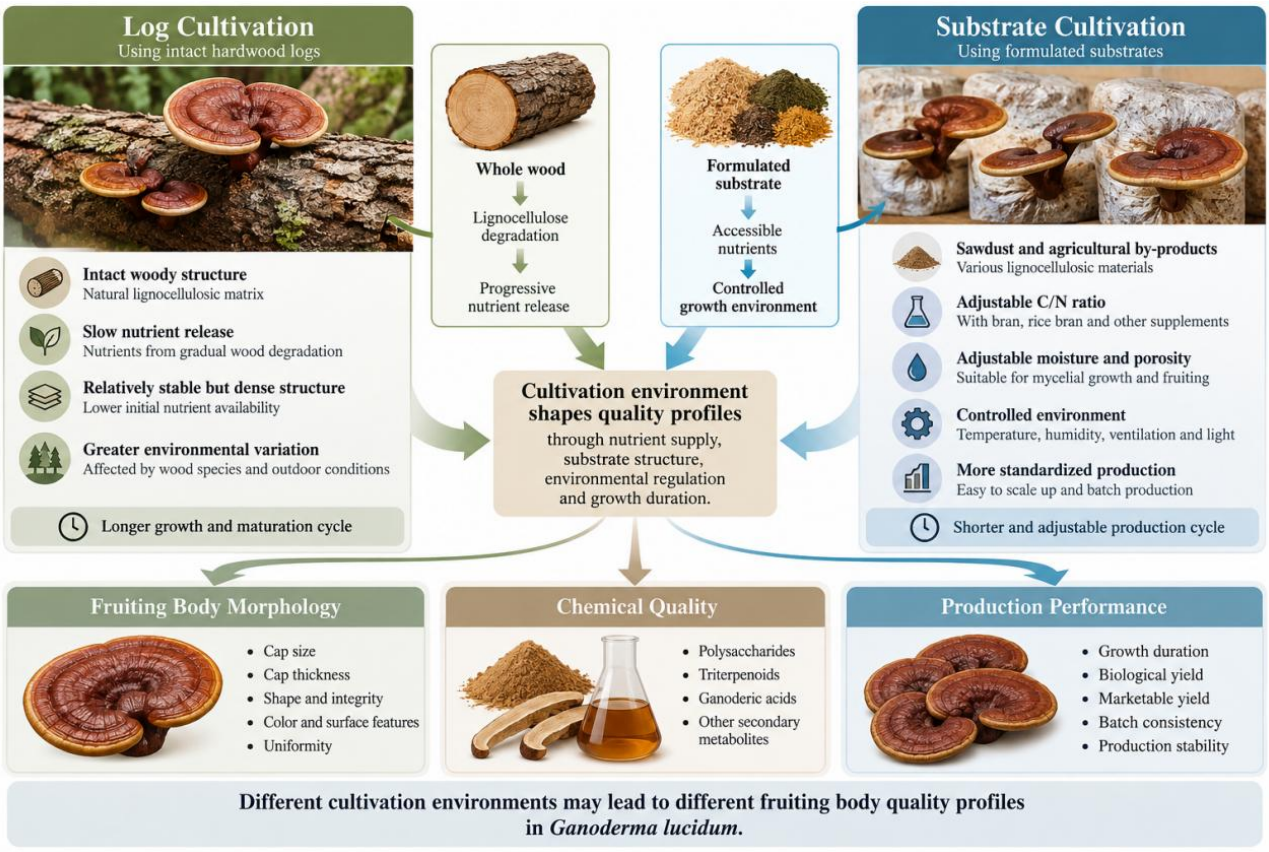


Figure 1 Contrasting cultivation environments of log- and substrate-cultivated *Ganoderma lucidum* and their potential effects on quality formation

2.4 Differences in production management

The most meaningful management difference between the two cultivation systems is not simply the amount of labor involved, but rather the controllability and degree of standardization of the production process. Log cultivation is first influenced by natural variation in wood species, log diameter, moisture content, and wood maturity. After mycelial colonization, it may also involve soil covering, log burial, and prolonged fruiting management, making it difficult to maintain completely uniform production progress among individual logs. Although substrate bag cultivation involves multiple standardized procedures, including grinding, formulation, bag filling, sterilization, and inoculation, once stable operating parameters have been established, bag weight, substrate moisture, formulation ratio, and cultivation conditions can be reproduced across production batches. In their review of medicinal mushroom production technologies, Nikšić et al. (2023) also regarded log, bag, and bottle cultivation as systems with distinct production-organization characteristics, noting that artificial substrate systems are more readily integrated into large-scale and batch production.

However, a higher degree of standardization does not mean that substrate cultivation is easier to manage. The source of basal materials, particle size, proportion of nutrient supplements, initial moisture content, and sterilization quality can all affect subsequent mycelial colonization, and changes in raw materials may require existing formulations to be readjusted. Kurd-Anjaraki et al. (2022) compared mixed and unmixed agroforestry waste substrates and found that substrate selection and combination significantly influenced both vegetative and reproductive growth of *G. lucidum*, indicating that "formulation controllability" also places greater demands on formulation management. Log cultivation involves fewer adjustable technical parameters, but greater uncertainty associated with wood supply, cultivation site, production cycle, and natural environmental conditions. Overall, the major sources of variation in log cultivation arise from natural wood materials and prolonged exposure to the growth environment, whereas those in substrate cultivation arise mainly from artificial formulations and production parameters. This distinction also explains why subsequent differences in appearance, nutritional

composition, and bioactive compounds should not be attributed simply to the labels “log cultivation” and “substrate cultivation,” but should instead be interpreted in relation to specific wood species, substrate formulations, strains, and environmental conditions.

3 Differences in Appearance and Commercial Quality Between Log- and Substrate-Cultivated *Ganoderma lucidum*

3.1 Fruiting body morphology

Fruiting body morphology is the most direct basis for evaluating the commercial appearance of *Ganoderma lucidum*. Cap diameter, cap thickness, individual fruiting body weight, overall shape, and stipe characteristics can all be used for comparison. However, from the perspective of whole-fruiting-body sales and production grading, cap thickness, fruiting body integrity, and individual weight are generally of greater practical importance than stipe length alone. Studies on substrate cultivation have shown that substrate type can markedly influence fruiting body size. Under cultivation with different agricultural and forestry by-products, cap size varied significantly, with the maximum cap diameter reaching 78.0 mm on sawdust substrate, compared with approximately 55.0 mm on rice straw and 52.3 mm on coco peat. Yield and biological efficiency also varied with substrate type (Sethi and Chinara, 2025). One notable feature of substrate cultivation is therefore that visible traits such as cap size can be more directly adjusted through substrate formulation and production conditions.

This degree of controllability becomes even more evident in formulation trials. Soriano et al. (2022) compared different combinations of sawdust, rice straw, and rice bran and found that substrate composition affected not only yield but also cap size. A formulation containing 20% rice bran produced an average cap diameter of 69.41 mm together with relatively high fruiting body yield. Substrate cultivation is therefore more amenable to formulation and management optimization aimed at producing larger caps, suitable thickness, and relatively uniform individual fruiting body weight. In contrast, fruiting body performance under log cultivation is also influenced by log dimensions, degree of wood decay, soil-covering conditions, fruiting position, and the microenvironment within the cultivation shed, making complete elimination of individual variation more difficult. When comparing the morphological marketability of the two systems, emphasis should therefore be placed on batch-level size uniformity and the proportion of intact fruiting bodies rather than on a small number of exceptionally large specimens.

3.2 Color and surface appearance

In addition to size and thickness, cap color, lacquer-like gloss, color uniformity, and surface integrity are readily recognizable commercial traits in whole-fruiting-body sales. Mature *G. lucidum* generally develops reddish-brown to dark-brown caps with varying degrees of lacquer-like gloss, although these traits themselves exhibit substantial biological variation. Morphological observations of cultivated Chinese *Ganoderma* materials have shown that caps may range from reniform to nearly circular and from convex to depressed, while cap thickness, stipe attachment position, and pore-surface color also vary markedly. Considerable variation in external morphology may therefore occur even among cultivated materials (Wang et al., 2012). Consequently, darker color, a more rounded cap, or stronger gloss should not be taken as direct evidence that a particular cultivation method or internal quality is necessarily superior.

Similar external appearance also does not imply complete similarity in taxonomic origin or chemical composition. Hennicke et al. (2016), in comparing commercially cultivated *Ganoderma* materials from Europe and East Asia, found differences in fruiting body morphology, pore-surface color, and triterpenic acid profiles. These findings indicate that cap color, lacquer-like gloss, or overall morphology alone cannot reliably predict internal chemical composition. For commercial grading, uniform color, absence of obvious surface damage or abnormal spots, and normal maturity remain important visual quality traits. However, these characteristics are more appropriately regarded as indicators of “commercial appearance quality” rather than “medicinal or biochemical quality.” This distinction is particularly important when comparing log- and substrate-cultivated products, because differences in visual grade do not necessarily imply corresponding differences in bioactive compound levels.

3.3 Texture and drying characteristics

Fresh *G. lucidum* fruiting bodies ultimately enter the market mainly as whole dried products, slices, or raw materials for further processing. Therefore, fresh moisture content, dry matter proportion, drying shrinkage, and the ability to retain shape after drying are important links between cultivation quality and commercial quality. Akçay et al. (2025) compared different lignocellulosic substrates and found significant variation in the dry matter content of *G. lucidum* fruiting bodies. In some formulations containing 91% basal material and 9% wheat bran, dry matter content ranged from 22.6% to 28.2%, whereas a specific mixed substrate produced a dry matter content as high as 32.09%. Dry matter content is therefore a trait of practical importance in the dried-product market. For producers, fruiting bodies with similar fresh weights may generate substantially different dried yields if their dry matter proportions differ, meaning that comparisons based solely on fresh weight may overestimate the actual commercial output of high-moisture fruiting bodies.

Direct comparisons of hardness, drying shrinkage, and post-drying shape retention between log- and substrate-cultivated *G. lucidum* under standardized conditions remain limited, representing a current gap in appearance-quality evaluation. Earlier substrate studies incorporated fruiting body moisture content, dried product recovery, and cap and stipe characteristics into the same assessment framework, indicating that "how large the fresh fruiting body grows" and "how much stable dried product is ultimately obtained" should be treated as two distinct levels of evaluation (Veena and Pandey, 2011). High-quality whole dried fruiting bodies should therefore not only have large caps at harvest, but should also retain acceptable morphology after drying without excessive curling, obvious cracking, tissue breakage, or severe shrinkage.

3.4 Biological yield and marketable yield

When comparing log and substrate cultivation, it is first necessary to distinguish between "how much fruiting body is produced" and "how much of the harvested product can actually be sold." The former represents biological yield and is usually expressed as fresh weight, dry weight, or biological efficiency per cultivation bag, per kilogram of substrate, or per unit of cultivation material. The latter is closer to marketable yield and should exclude malformed, damaged, incompletely developed, or visually low-grade fruiting bodies. Yield in substrate cultivation is highly sensitive to raw material composition. Atila (2022), using different agricultural and forestry by-products for *G. lucidum* cultivation, reported total fresh yields of 71.39-110.10 g/kg substrate and biological efficiencies of 21.0%-31.46%. In another study using sawdust from six hardwood species, yields ranged from 31.45 g/kg to 308.76 g/kg depending on the substrate (Adongbede and Atoyebi, 2021). These findings demonstrate that substrate cultivation has substantial potential for yield optimization, but the use of artificial substrate itself does not guarantee high productivity; the suitability of raw material properties and formulation remains critical to commercial output.

For log cultivation, marketable yield is also closely related to whether complete and normally developed fruiting bodies can be formed. Tong et al. (2020) reported that the accumulation of antagonistic fungi in soils under continuous *G. lucidum* cultivation could prevent normal fruiting on logs, whereas waterlogging treatment improved the soil microbial environment and restored production. Thus, part of the "low yield" observed in log cultivation may actually result from failure of logs to fruit normally or from a reduced proportion of marketable fruiting bodies, rather than simply from lower individual fruiting body weight. Unfortunately, most cultivation studies still focus primarily on total yield and biological efficiency, while rarely reporting the proportion of first-grade whole fruiting bodies, deformation rate, damage rate, or actual saleable proportion. Future comparisons between the two cultivation systems should therefore treat "marketable yield" as an independent indicator, defined as the proportion of fruiting bodies that are morphologically complete, normally mature, acceptable in color, and suitable for commercial sale. This indicator may better reflect the actual economic value of a cultivation system than yield per bag alone.

3.5 Appearance quality and market acceptance

The first product characteristics encountered by consumers or buyers are still fruiting body size, thickness, shape, color, and integrity. *Ganoderma lucidum* is currently produced both through large-scale cultivation on artificial

substrates such as sawdust and through traditional log-based systems, while marketed products include whole dried fruiting bodies and various further-processed forms (Thakur et al., 2024). Industry-related information from India has reported market prices of approximately ₹4 000-5 000/kg for dried *G. lucidum* fruiting bodies, indirectly demonstrating that dried whole fruiting bodies themselves possess independent commercial value (Kaushik et al., 2025). In production systems targeting whole-fruiting-body or sliced products, fruiting bodies with intact caps, suitable thickness, minimal surface damage, uniform coloration, and good shape retention after drying are more favorable for grading and display. In some markets, log cultivation carries a product image associated with traditional and more natural production, whereas the advantages of substrate cultivation are more closely linked to production standardization, size uniformity, and stable large-volume supply. The commercial value of the two systems is therefore not determined solely by yield per unit of cultivation material.

However, commercial appearance and internal quality must be clearly distinguished, that is, commercial quality ≠ biochemical quality. Ghafoor et al. (2024) compared wild and cultivated *G. lucidum* and found relatively small differences in most essential and trace mineral elements between the two groups, indicating that differences in cultivation origin or external phenotype do not necessarily translate into marked differences in all internal quality indicators. The same principle applies to log- and substrate-cultivated products: thicker caps, darker coloration, and a more pronounced lacquer-like gloss may improve the visual presentation of whole fruiting bodies, but they do not directly demonstrate higher levels of polysaccharides, triterpenoids, or other bioactive compounds. Therefore, from the perspective of primary production and commercial evaluation, appearance quality should be treated as an independent dimension. Log cultivation should focus on improving the proportion of intact fruiting bodies and batch stability, whereas substrate cultivation should avoid emphasizing high yield and size uniformity at the expense of cap thickness, structural integrity, and drying performance. Ultimately, comprehensive quality assessment should be combined with the evaluation of chemical composition and bioactive components discussed in the following sections.

4 Differences in Major Quality Components Between Log- and Substrate-Cultivated *Ganoderma lucidum*

4.1 Polysaccharides

Polysaccharides are among the most commonly used core indicators for evaluating the quality of *Ganoderma lucidum* fruiting bodies and represent an important link between cultivation practices and final product quality. Current quality-control systems have already incorporated polysaccharides into the evaluation of *G. lucidum*. The Chinese Pharmacopoeia determines *G. lucidum* polysaccharides using procedures such as aqueous extraction followed by ethanol precipitation, with content expressed as anhydrous glucose equivalents; a minimum level of 0.90% has become one of the important criteria for evaluating the quality of *G. lucidum* medicinal material (Wu et al., 2024). From a compositional perspective, *G. lucidum* polysaccharides are not a single substance but comprise β-glucans, α-glucans, and heteropolysaccharides with different branching structures. Among these, β-glucans are involved in fungal cell-wall formation and are also widely used as important components in the evaluation of functional *G. lucidum* products. Therefore, comparisons between log- and substrate-cultivated *G. lucidum* should consider not only total polysaccharide content but also specific fractions such as β-glucans.

There are clear interaction effects between strain and cultivation material. Skalicka-Woźniak et al. (2012) compared 36 cultivation combinations involving four *G. lucidum* strains grown on sawdust from birch, maple, and alder, each supplemented with 10%, 20%, or 30% wheat bran. Polysaccharide contents ranged from 18.45 to 112.82 mg/g dw, representing more than a sixfold difference. Importantly, the strain with generally high polysaccharide accumulation was not necessarily the one producing the highest value under every treatment. The maximum value of 112.82 mg/g dw was obtained from strain GL04 cultivated on maple sawdust supplemented with 30% wheat bran. These results demonstrate that even within substrate or sawdust-based cultivation systems, differences in wood species, supplementation level, and strain are sufficient to generate substantial variation in polysaccharide content.

Cortina-Escribano et al. (2020) cultivated different *G. lucidum* strains on sawdust or wood chips from birch, aspen, spruce, pine, and larch and found that the combination producing the highest fruiting body yield was not the same as that producing the highest β-glucan content. Strain MUS192 showed relatively high yields on birch and aspen substrates, whereas the highest β-glucan level occurred in strain MUS75 cultivated on aspen. Hayati et al. (2021) also compared wild and cultivated samples from different origins and reported that water-soluble polysaccharides in cultivated *G. lucidum* ranged from 21.65 to 29.86 mg/g dw, with obvious differences among cultivation locations alone. From a production perspective, polysaccharide content is therefore better understood as a quality trait jointly shaped by strain, cultivation material, cultivation environment, and maturity stage, rather than one that can be predicted simply from the labels "log cultivation" or "substrate cultivation."

4.2 Triterpenoids and ganoderic acids

Compared with polysaccharides, triterpenoids currently provide relatively clearer direct evidence for differences between log and substrate cultivation. *G. lucidum* triterpenoids mainly consist of highly oxidized lanostane-type compounds, with more than 300 structures reported, including ganoderic acids, ganoderenic acids, lucidenic acids, ganoderols, and related aldehydes, alcohols, and lactones (Ren et al., 2025). Quality control of *G. lucidum* fruiting bodies in the United States Pharmacopeia likewise does not rely on ganoderic acid A alone. Instead, the combined contents of 10 triterpenoid acids, including ganoderic acids A, B, C2, D, F, G, and H and ganoderenic acids B, C, and D, are required to reach at least 0.3% on a dry-weight basis. This further indicates that triterpenoid quality evaluation is inherently a multi-component assessment.

Luo et al. (2024) provided direct evidence comparing wood-log-cultivated *G. lucidum* (WGL) with substitute-cultivated *G. lucidum* (SGL). The study showed that log-cultivated samples had significantly higher total triterpenoid content, DPPH radical-scavenging activity, and total antioxidant activity. However, UHPLC-Q-Orbitrap-MS analysis of the detailed triterpenoid profile showed that the result was not simply that "all triterpenoids were higher in log-cultivated samples." A total of 96 triterpenoids were tentatively identified, of which 17 differed significantly between the two groups. Six compounds, including ganosporelactone B, ganoderol A, ganoderic acid A, and ganoderic acid α, were more abundant in substrate-cultivated samples, whereas 11 compounds, including lucidenic acids A, D1, F, G, and J and ganoderic acids E and O, were more abundant in log-cultivated samples. This distinction is important because "higher total triterpenoids in log-cultivated samples" and "higher levels of every individual ganoderic acid" are fundamentally different conclusions.

Harvest stage and fruiting body part can further alter the outcome of triterpenoid comparisons. Gao et al. (2024), using metabolomic and proteomic analyses across different developmental stages, found that triterpenoids, sterols, and polyphenols were generally more abundant during the bud stage, whereas many triterpenoids gradually declined as development progressed, while polysaccharides, flavonoids, and purine-related compounds increased during later maturation. Ren et al. (2020) further reported that total ganoderic acids were higher in the pileus than in the stipe and that individual ganoderic acids accumulated at different times: ganoderic acids A and D were relatively higher at maturity, whereas ganoderic acids B, C2, and G were higher during the bud-elongation stage. Accordingly, comparisons of triterpenoids between log- and substrate-cultivated *G. lucidum* should report strain, sampling position, and maturity stage. From a production perspective, comparisons made using the same strain, similar maturity, and identical analytical methods are more meaningful than comparisons among products of different origins.

4.3 Proteins, amino acids, and basic nutritional components

Compared with polysaccharides and triterpenoids, relatively few studies have conducted strictly paired comparisons of proteins, amino acids, and crude fat between log- and substrate-cultivated *G. lucidum*. These components are therefore more appropriately used as supplementary indicators of internal quality rather than as primary criteria for judging the relative superiority of the two cultivation systems. Analyses of *G. lucidum* fruiting bodies from different sources have shown considerable variation in basic nutritional composition. Gharib et al. (2022) reported that dried *G. lucidum* powder contained 8.54% crude protein, 1.91% crude fat, 2.03% ash, 50.19% crude fiber, and 37.33% carbohydrates, showing an overall low-fat and high-fiber profile. In contrast, wild *G.*

lucidum samples have been reported to contain 16.79% crude protein, 1.52% crude fat, 7.77% crude fiber, and 63.27% carbohydrates, demonstrating that substantial differences in basic nutritional composition can occur even among *G. lucidum* fruiting bodies from different sources (Ogbe and Obeka, 2013).

Such variability cannot be attributed simply to a particular cultivation method. Protein contents of approximately 7% to more than 20% have been reported for *G. lucidum* samples from different countries and production regions, while even greater variation has been observed in dietary fiber and carbohydrate contents. Possible causes include strain, maturity stage, pileus-to-stipe ratio, drying degree, and differences in analytical methods used for protein, carbohydrate, and dietary fiber determination. From a production perspective, it is therefore inappropriate to use a single crude protein or crude fat value to demonstrate that log-cultivated *G. lucidum* has higher nutritional value than substrate-cultivated material, or vice versa.

Environmental effects on basic metabolism should also be considered. Ji et al. (2024), in a two-year continuous cultivation experiment conducted on the same field, identified 64 significantly different metabolites between fruiting bodies produced in the first and second years, of which 39 were relatively higher in the first year and 25 were relatively lower. These differences were significantly associated with factors such as topsoil pH, organic matter, available phosphorus, and alkaline phosphatase activity. Thus, even when the cultivation method remains unchanged, changes in the production environment and duration of continuous cultivation may alter amino acids, nitrogen-containing metabolites, and other nutritional components.

4.4 Mineral elements and safety

Ganoderma lucidum fruiting bodies can accumulate a range of mineral elements, including K, Ca, Mg, Fe, Zn, Cu, Mn, and Se. Although some of these elements are nutritionally valuable, this accumulation capacity also means that mineral composition is sensitive to cultivation materials and environmental conditions. Nutritional analyses of fruiting bodies have shown that dried *G. lucidum* powder contains K, Ca, Mg, Fe, and Zn, as well as trace elements such as Se. Gharib et al. (2022) reported approximately 654.16 mg/100 g K, 125.76 mg/100 g Ca, 76.45 mg/100 g Mg, 15.87 mg/100 g Fe, 3.05 mg/100 g Zn, and 0.94 mg/100 g Se. Although mineral composition therefore has nutritional value for quality assessment, simply having “higher mineral content” does not necessarily indicate higher overall quality.

Mineral composition can change substantially with cultivation substrate. Rzymski et al. (2016) supplemented cultivation media with Se, Cu, and Zn and found that *G. lucidum* fruiting bodies showed clear accumulation of these elements. When Se was added to the substrate, organic Se in fruiting bodies exceeded 44 mg/kg under the highest enrichment conditions, while Zn and Cu also increased with increasing substrate supplementation. Therefore, tree species used in log cultivation, soil background, and substrate components such as sawdust, cottonseed hulls, wheat bran, corn cobs, and other agricultural by-products can all influence the final mineral profile.

Safety must be incorporated into mineral evaluation. Early cultivation experiments demonstrated that *G. lucidum* can absorb Zn from sawdust-based substrates, while elements such as Cd, Hg, and Pb may also be detected in fruiting bodies; Zn transfer efficiency can exceed 60% under Zn-enriched substrate conditions. Hazardous elements such as Pb, Cd, As, and Hg may also enter fruiting bodies through cultivation materials. From a production perspective, increasing the content of a particular mineral should not be treated as an isolated quality-improvement objective. Raw-material origin, contamination background, and heavy-metal control should be evaluated together with nutritional mineral composition. This is particularly important when agricultural and forestry wastes are used as substrate materials, for which raw-material testing should form part of routine quality control.

4.5 Sterols, phenolics, nucleosides, and other bioactive components

In addition to polysaccharides and triterpenoids, *G. lucidum* contains sterols, phenolics, flavonoids, nucleosides, protein-derived peptides, and numerous other secondary metabolites. More than 240 secondary metabolites have been reported in *G. lucidum* alone, while an even larger number has been reported across the genus *Ganoderma*

(Ahmad et al., 2024). Although most of these compounds have not yet been incorporated into stable industrial threshold standards comparable to those used for polysaccharides and total triterpenoids, they have considerable value as chemical fingerprints for distinguishing raw materials, production environments, and product types.

The interpretive value of any single extended indicator is often limited. Yeung et al. (2021) selected 13 compounds to establish an HPLC-DAD-based quality evaluation system, including multiple ganoderic acids, ganoderenic acids, ganoderol A, and ergosterol. Eleven ganoderic acids were considered more suitable as quality markers for *G. lucidum* products, whereas ergosterol showed insufficient specificity. Chemical fingerprint differences among samples harvested in different years were also greater than those among different batches harvested within the same year.

Phenolics and sterols likewise show pronounced variation with source and developmental stage. Kolniak-Ostek et al. (2022) identified 13 triterpenoids and 28 polyphenols in methanolic extracts of wild *G. lucidum*, including phenolic acids, flavonols, flavones, flavan-3-ols, and resveratrol-related compounds, with substantial differences in the contents of individual compounds. When considered together with studies across different growth stages, these findings indicate that sterols, triterpenoids, and polyphenols do not accumulate synchronously. Some compounds are more abundant during the bud stage, whereas certain polysaccharides, flavonoids, or purine-related compounds increase during later maturation. Therefore, when comparing log- and substrate-cultivated products, sterols, phenolics, and nucleosides are more appropriately treated as supplementary quality indicators and chemical fingerprint markers.

4.6 Integrated comparison of internal quality

Log cultivation and substrate cultivation can indeed produce different internal chemical profiles, but current evidence does not support a uniform ranking in which all quality indicators are consistently “higher in log cultivation and lower in substrate cultivation,” or vice versa. Direct comparisons have shown that log-cultivated samples may contain higher total triterpenoid levels and exhibit stronger antioxidant activity for some indicators, while certain specific triterpenoids, including ganoderic acid A and ganoderol A, may instead be more abundant in substrate-cultivated samples. Polysaccharide studies further demonstrate that even within artificial cultivation systems, changes in strain, sawdust species, and wheat bran supplementation can generate several-fold differences. Cultivation method is therefore only one of several major determinants of final product quality rather than the sole controlling factor (Figure 2).

From a practical production perspective, quality evaluation should distinguish at least three levels. The first comprises core bioactive indicators, including total polysaccharides, β-glucans, total triterpenoids, and representative ganoderic acids. The second comprises basic composition and extended bioactive indicators, including proteins, amino acids, mineral elements, sterols, phenolics, and nucleosides. The third comprises quality stability and safety indicators, including batch-to-batch compositional consistency and risks associated with heavy metals and other contaminants. Only by considering these three levels together can product quality be evaluated more realistically.

A scientifically meaningful comparison between log- and substrate-cultivated *G. lucidum* should therefore be based on identical or clearly defined strains, comparable maturity stages, clearly characterized cultivation materials, and standardized analytical methods. The focus of evaluation should shift from asking “which cultivation method is absolutely better” to determining what type of quality profile is produced by each cultivation system. For log-cultivated *G. lucidum*, particular attention should be given to whether advantages in total triterpenoids, characteristic ganoderic acids, and premium commercial quality are stable and reproducible. For substrate-cultivated *G. lucidum*, emphasis should be placed on whether strain selection and formulation optimization can consistently produce stable polysaccharide levels, specific triterpenoids, and uniform batch quality. Such a multi-indicator evaluation approach can avoid equating traditional market perception directly with chemical quality and is more consistent with the practical needs of modern standardized production and graded utilization of *G. lucidum*.

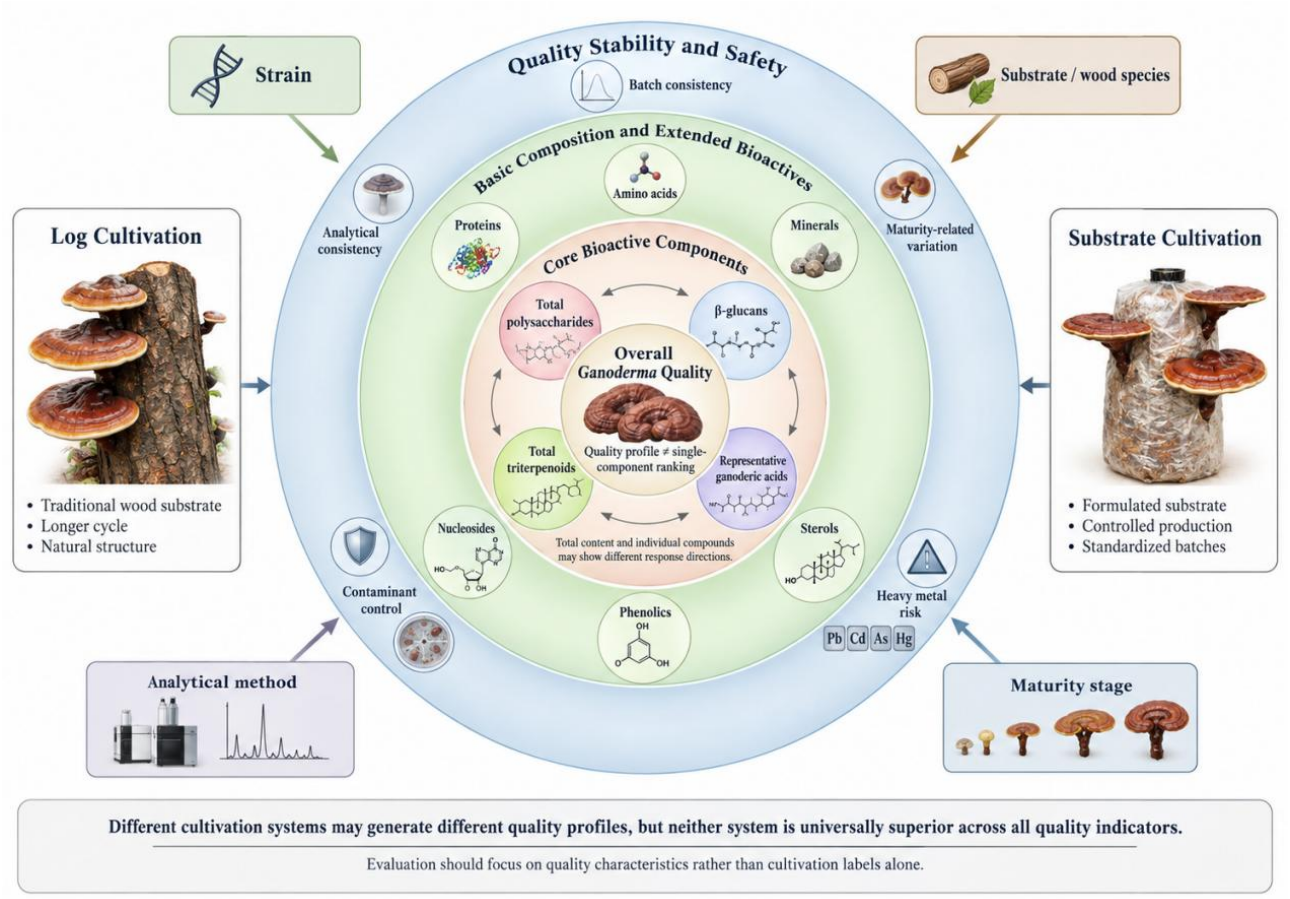


Figure 2 Multi-dimensional quality profiles and integrated evaluation framework for log- and substrate-cultivated *Ganoderma lucidum*

5 Major Factors Contributing to Quality Differences Between Log- and Substrate-Cultivated *Ganoderma lucidum*

5.1 Cultivation materials

Cultivation material is the most fundamental production factor underlying quality differences between log- and substrate-cultivated *Ganoderma lucidum*. As a typical wood-decaying fungus, *G. lucidum* relies on extracellular enzyme systems to decompose lignin, cellulose, and hemicellulose and thereby obtain carbon sources and other nutrients. Log cultivation uses intact wood sections as the cultivation material. Because tree species differ in lignin, cellulose, hemicellulose, mineral composition, and C/N ratio, different wood species may produce different rates of mycelial growth and different fruiting body quality even within the same category of "log cultivation." Substrate cultivation further expands this source of variation because sawdust, bran, corn cobs, cottonseed hulls, and other agricultural and forestry by-products can be mixed in different proportions, thereby altering C/N ratio, porosity, water-holding capacity, and nutrient-release rate. Atila (2020), in comparing several lignocellulosic wastes, reported total yields of 28.6-86.1 g/kg and biological efficiencies of 8.9%-24.7% across substrates. Yield showed a strong negative relationship with substrate nitrogen content but positive relationships with C/N ratio, cellulose, and lignin content, with coefficients of determination of 0.915 for C/N ratio and 0.879 for lignin content.

In practical production, even sawdust from different sources may perform very differently. Thiribhuvanamala and Krishnamoorthy (2021) cultivated *G. lucidum* using mixed sawdust, coconut wood sawdust, coconut petiole, coco peat, and areca wood sawdust, each supplemented with 20% wheat bran. Coconut wood sawdust required only 46.5 d for complete mycelial colonization, produced primordia on day 54, and allowed the first harvest by day 70.5. Each bag produced an average of 5.75 fruiting bodies with a mean individual weight of 13.5 g, and 175 g of substrate yielded 77.5 g of fruiting bodies, corresponding to a biological efficiency of 44.3%, whereas the coco

peat treatment achieved only 25.6%. Thus, "sawdust-based substrate" itself should not be treated as a uniform cultivation treatment, because wood species and physical structure alone can substantially alter the entire production cycle and final yield. The same principle applies to log cultivation, in which different hardwood species should not be regarded as identical cultivation materials.

The incorporation of agricultural by-products may also directly alter the nutritional composition of fruiting bodies. İnce et al. (2024) evaluated nine formulations composed of sawdust, chickpea straw, pea straw, poppy straw, corn cobs, and bran. Biological efficiency ranged from 7.84% to 17.92%, whereas protein content ranged from 31.51% to 51.40%. Addition of 40% corn cobs increased N, K, Ca, Mg, and Fe in the fruiting bodies, whereas a formulation containing 20% chickpea straw favored Zn accumulation. However, the highest yield, 88.38 g per 1.5 kg cultivation bag, occurred in a different formulation rather than in the one with the highest mineral concentrations. In other words, high yield, high protein, high mineral content, and rapid harvest do not necessarily occur in the same formulation. Therefore, from a practical production perspective, the more appropriate comparison should focus on wood species + substrate formulation, rather than simply log versus substrate.

5.2 Strain

Strain is one of the most easily overlooked confounding factors when interpreting quality differences between log- and substrate-cultivated *G. lucidum*. Different strains of the same species can vary substantially in mycelial extension rate, primordium formation, maturation time, fruiting body morphology, and yield. Poyeri and Ohimain (2024) compared one commercial strain, W1, with two wild strains, W2 and W3, isolated from tree stumps under the same cultivation system. All three strains required approximately 6-11 d for primordium formation, but fruiting body maturation differed markedly: W1 required only 10-11 d, W2 required 18-22 d, and W3 approximately 30 d, while biological efficiency ranged from 0.7% to 2.4%.

Strain differences are reflected not only in yield but also directly in the accumulation of bioactive components. Shi et al. (2023) compared seven "Hunong" *G. lucidum* cultivars under identical cultivation conditions and found that total polysaccharide content in fruiting bodies ranged from 1.15% to 5.11%. "Hunong No. 7" contained 5.11%, "Hunong No. 8" 2.36%, and "Hunong No. 4" 2.07%, and the molecular-weight distributions of crude polysaccharides also differed markedly among cultivars. Liu et al. (2017) generated multiple hybrid combinations by mating monokaryotic strains derived from basidiospores of two commercial cultivars. Among 16 hybrids capable of normal fruiting, polysaccharide contents ranged from 6.79 to 18.21 mg/g dw and triterpenoid contents from 5.90 to 10.87 mg/g dw. Hybrid H-23 simultaneously contained 16.63 mg/g polysaccharides and 10.50 mg/g triterpenoids while maintaining a biological efficiency of 19.41%. These findings demonstrate that strain alone can generate several-fold differences in chemical composition even when cultivation materials and environmental conditions are essentially similar. If strain A is used in a log-cultivation experiment and strain B in a substrate-cultivation experiment, observed differences in polysaccharides or triterpenoids cannot be attributed directly to cultivation method. Strain effects must be separated from cultivation-method effects, and this should be regarded as a basic prerequisite for meaningful log-versus-substrate comparisons.

5.3 Temperature, humidity, and ventilation

Temperature primarily affects mycelial growth rate and the transition from vegetative to reproductive growth, but no single fixed temperature is optimal for all *G. lucidum* strains and all developmental stages. Nguyen et al. (2019) studied strain GA3 and found that its mycelium grew well at 25-30°C and tolerated a broad pH range of 4-12. During fruiting, the formulation containing 87% sawdust + 4% corn flour + 8% rice bran + 1% $CaCO_3$ performed best, producing a fresh fruiting body weight of 17.16 g and a biological efficiency of 2.56%. Thus, the effect of temperature does not act independently, but interacts with strain and cultivation material to determine nutrient utilization and fruiting performance. In practical production, log cultivation is more strongly affected by seasonal and ambient temperatures, whereas facility-based substrate cultivation can maintain temperatures within a more stable range. Consequently, the two systems may differ in production cycle and batch consistency.

Log cultivation is particularly sensitive to environmental temperature variation. Bijalwan et al. (2021) cultivated *G. lucidum* on poplar logs under farmer conditions at Sherpur and Manjgaun in the Garhwal Himalaya, India,

which differ in altitude and climate. The total production cycle was 132-136 d at the warmer Sherpur site but 141-145 d at the cooler Manjgaun site, a difference of approximately 9 d. The first flush was harvested after 64-66 d at Sherpur but required 69-71 d at Manjgaun. The difference was mainly attributed to lower temperatures delaying primordium formation and fruiting body development. From a practical production perspective, even the same wood material and fungal strain can show markedly different production cycles when cultivated in different regions. Therefore, when comparing log-cultivated *G. lucidum* from different locations with facility-grown substrate products, failure to consider the temperature background may lead to regional environmental effects being mistakenly interpreted as cultivation-method effects.

Humidity and ventilation are directly related to fruiting body morphology. Fruiting requires relatively high air humidity to maintain cap expansion, but high humidity must be accompanied by sufficient air exchange; otherwise, CO_2 accumulation can redirect fruiting body development. Sudheer et al. (2018) showed that when CO_2 accumulated to approximately 2%-5% under restricted ventilation, typical antler-type fruiting bodies were induced. Their phenolics, flavonoids, water-soluble polysaccharides, and ganoderic acids were reported to reach approximately twice the levels observed in normal kidney-shaped fruiting bodies. This does not imply that high CO_2 should be generally adopted in production, but rather demonstrates that ventilation conditions can alter both commercial morphology and internal chemical composition. If log-cultivated fruiting bodies develop normal caps in an open environment while substrate-cultivated fruiting bodies in poorly ventilated facilities develop elongated stipes, antler-like structures, or incompletely expanded caps, the apparent "quality difference" may primarily reflect CO_2 concentration and ventilation management rather than cultivation material itself.

5.4 Light conditions

Light is an important environmental signal regulating the transition of *G. lucidum* from vegetative mycelial growth to primordium formation and final fruiting body development. Its effects depend not only on the presence or absence of light but also on light quality, intensity, and whether illumination is continuous or intermittent. Liu et al. (2024) applied continuous white, red, green, and blue light, together with corresponding intermittent-light treatments, in a controlled mushroom-growing room at a uniform intensity of 15 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Both continuous and intermittent red light inhibited fruiting body differentiation. Intermittent green light increased stipe length by 71.3% and cap diameter by 3.2% relative to the white-light control, while continuous green light increased individual fruiting body weight by 21.4%. Intermittent blue light increased cap thickness and the number of caps by 31.2% and 37.5%, respectively. Continuous green light increased crude protein and total triterpenoids in the pileus by 14.9% and 28.1%, respectively, whereas intermittent green light increased crude polysaccharides by 35.7%. Thus, light is not merely an auxiliary condition required for normal cap formation, but can also participate directly in the formation of major quality components.

Different *G. lucidum* strains do not respond identically to light. Seo et al. (1995) compared 17 strains and found that 13 formed atypical fruiting structures under different light wavelengths, with responses varying among blue, green, yellow, and red light. Some structures were induced at light intensities as low as 0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$. For producers, the more practical approach is therefore not to prescribe one specific light color mechanically, but to maintain a stable, uniform, and reproducible light environment during fruiting and adjust management according to cap expansion, coloration, and lacquer-like gloss. Log cultivation in open fields or simple sheds is more strongly influenced by the natural photoperiod, whereas facility-based substrate cultivation allows more standardized control. This difference in environmental stability may ultimately be reflected in product appearance and batch consistency.

5.5 Cultivation cycle and harvest stage

Polysaccharides and triterpenoids in *G. lucidum* fruiting bodies change continuously during development. Therefore, when comparing log- and substrate-cultivated products, whether samples are collected at the same maturity stage is as important as which cultivation method is used. Nakagawa et al. (2018) quantified 18 triterpenoids, total triterpenoids, and total polysaccharides at different growth stages. Ganoderic acids A, C2, I, and LM2 and ganoderenic acids C and D were more abundant at earlier developmental stages, whereas ganoderic

acids K, TN, and T-Q were higher at maturity. Total triterpenoids and total polysaccharides both reached relatively high levels before full maturity, during stipe elongation or the early stage of cap formation. No single harvest time therefore guarantees that all individual triterpenoids simultaneously reach their maximum levels, and the assumption that "fully mature *G. lucidum* always has the highest quality" cannot be applied uniformly to every chemical indicator.

Ma et al. (2023) used "Hunong *G. lucidum* No. 1" and divided harvest from the second to the seventh month after inoculation into six stages, P1-P6. Ganoderic acids B, A, S, and T and total triterpenoids in fruiting bodies were highest at P1; ganoderic acids C2 and G were relatively high at P1 and P2; and ganoderenic acid B and ganoderic acids D, F, and DM reached their highest levels at P2. Water-soluble polysaccharide content and yield in both fruiting bodies and the fungal base were also highest at P1. However, when both compound concentration and total yield per fruiting body were considered, the highest yields of some triterpenoids occurred at P2 or P3. Thus, the practical production objective is to identify an appropriate harvest window for the target product rather than simply harvesting as early or as late as possible.

5.6 Postharvest drying and storage

Harvesting does not represent the end of quality formation in *G. lucidum*. Fresh fruiting bodies contain high levels of moisture, and delayed drying can increase the risk of microbial contamination and color change while also amplifying compositional differences formed during cultivation. Inla et al. (2023) treated 3-mm-thick *G. lucidum* slices using hot-air-assisted microwave drying and compared air temperatures of 50, 60, and 70°C with microwave powers of 200, 400, and 600 W. Increasing temperature and microwave power significantly shortened drying time, with drying completed in approximately 25 min at 70°C and 600 W. However, higher drying intensity also increased overall color difference and reduced rehydration capacity, whereas treatment at 50°C and 200 W resulted in less color change and better rehydration performance. Therefore, "the fastest drying" does not necessarily mean "the best color retention," and production must balance processing efficiency with appearance quality.

Different drying principles can also lead to different levels of component retention. Naseri et al. (2023) compared hot-air convective drying at 40℃-60℃ with infrared drying at 500-1500 W. Infrared drying reached the target moisture level in as little as 25 min, whereas even the shortest hot-air drying treatment required approximately 270 min. Infrared drying offered advantages in drying time and energy consumption, but its overall color difference ranged from 8.14 to 28.85, compared with 8.21-19.66 for convective drying, indicating that higher drying efficiency may be accompanied by more pronounced color changes. Liu et al. (2021) compared sun drying, vacuum freeze-drying, vacuum drying, and hot-air drying and identified a total of 247 volatile compounds. Thermal treatments increased the proportions of aldehydes, esters, and alkenes while decreasing those of alcohols and ketones. Thus, altering the drying method alone can substantially change the final color, aroma, and chemical fingerprint of the same batch of fresh *G. lucidum*. If log-cultivated products are naturally sun-dried while substrate-cultivated products are dried using hot air or low-temperature mechanical systems, the resulting quality differences cannot be attributed entirely to cultivation system.

More recent metabolomic studies further support this interpretation. Xia et al. (2026) compared vacuum freeze-drying, microwave vacuum drying, hot-air drying, and natural drying and found that the metabolite profile after freeze-drying was most similar to that of fresh samples, helping preserve overall color and some heat-sensitive flavor compounds. Hot-air drying, in contrast, markedly altered volatile composition and produced relatively high levels of flavor-related 5′-nucleotides. Fresh *G. lucidum* remains metabolically active after harvest, meaning that moisture, oxygen, and temperature during storage also require consideration. Zhang et al. (2023) further showed that storage under different oxygen conditions can continue to regulate the accumulation of polysaccharides and ganoderic acids, indicating that postharvest fruiting bodies remain metabolically active before complete drying. Drying and storage should therefore be regarded as important confounding factors in comparisons between log- and substrate-cultivated *G. lucidum*. Only when the two product types are compared at

similar harvest maturity and under comparable drying temperature, final moisture content, and storage conditions can the observed chemical differences be more confidently attributed to cultivation method itself.

6 Production Efficiency, Economic Performance, and Cultivation System Selection

6.1 Advantages and limitations of log cultivation

The main production advantage of log cultivation lies in its ability to use natural woody substrates to produce relatively intact fruiting bodies while retaining clear characteristics of traditional cultivation. This system can therefore be attractive to producers whose primary products are whole dried fruiting bodies, specialty products, or products emphasizing geographical origin. Nguyen et al. (2026), in a log-cultivation experiment using a wild *Ganoderma lucidum* strain from Vietnam, found that log dimensions significantly affected fruiting body formation. Rubberwood logs with diameters of 12-15 cm produced relatively favorable fruiting body morphology, and clear relationships were observed among stipe characteristics, fruiting body size, and biomass. Log cultivation is therefore not simply a matter of "producing mushrooms on wood"; wood species, log diameter, and the nutritional support capacity of the wood directly influence the final quality of marketable fruiting bodies. Where suitable wood is legally available at stable and acceptable cost, and the target market values whole-fruiting-body appearance, traditional cultivation, or regional identity, log cultivation can serve as an important production system for differentiated products.

The main limitations of log cultivation involve raw materials, production cycle, and continuous use of cultivation land. Compared with substrate systems based on agricultural and forestry by-products, log cultivation first requires a stable supply of suitable wood, while wood purchasing, cutting, transport, and burial all increase initial investment. Fruiting is also more dependent on temperature, humidity, and soil conditions, making output per unit area and per unit time less readily adjustable than in bag-based production. Log cultivation also faces challenges related to wood cost and changes in soil and substrate conditions under continuous cultivation, whereas substrate cultivation can make use of a wider range of agricultural by-products and therefore offers greater flexibility in raw-material substitution and continuous production (Lu et al., 2026). Log cultivation is consequently more suitable for producers with access to wood resources, appropriate cultivation sites, and stable sales channels, rather than being expanded indiscriminately in all regions simply because it is considered "traditional."

6.2 Advantages and limitations of substrate cultivation

The greatest production advantage of substrate cultivation is the wide range of raw materials that can be used and the greater ease with which standardized production processes can be established. Sawdust, rice husks, rice straw, sugarcane bagasse, and other agricultural and forestry by-products can all serve as cultivation materials when appropriately formulated, allowing producers to select relatively low-cost and consistently available substrates according to local resource conditions. Geetha et al. (2012) compared natural logs with several cultivation systems based on agricultural wastes and found that artificially formulated substrates offered considerable scope for regulating mycelial growth rate, fruiting time, and yield. Some formulations based on rice husks and rubberwood sawdust performed better than natural logs in production terms. Therefore, the real advantage of substrate cultivation is not that one fixed formulation is inherently high-yielding, but that production cycle and output per unit cultivation material can be adjusted through raw-material combinations, bag-filling amount, and nutrient supplementation, making the system more suitable for large-scale and staggered continuous production.

However, substrate cultivation should not be regarded simply as a "low-cost and rapid production" system. Substrate preparation, moisture control, sterilization, inoculation, incubation, and fruiting management all require a high degree of consistency. Deviations at any stage may lead to contamination, discarded cultivation bags, or non-uniform fruiting body specifications. Karunarathna et al. (2025), in a review of *Ganoderma* cultivation, identified substrate selection, spawn production, and environmental parameter management as key requirements for achieving stable yield and specifically highlighted contamination control as one of the major technical challenges in artificial cultivation. Although substrate cultivation can more readily expand production volume, scaling up should be based on stable bag preparation and environmental control. For small- and medium-scale

producers, a more practical approach is to first establish a locally stable combination of basal materials and supplements before increasing batch size.

6.3 Production costs and economic returns

Economic comparison should not focus only on how much *G. lucidum* can be produced per bag or per log; production cost and marketable output should be evaluated within the same framework. Actual production costs include at least substrate or wood, spawn, supplements, plastic bags and other consumables, energy for sterilization, facility depreciation, labor, site occupation, and the time cost associated with the entire production cycle. Mehta et al. (2014), in low-cost substrate trials using different sawdusts and nutrient supplements, found that suitable substrate combinations could not only increase yield but also shorten the growth cycle, with mango sawdust supplemented with an appropriate amount of wheat bran achieving relatively high biological efficiency. Therefore, whether a raw material is truly "inexpensive" cannot be judged solely by its purchase price. If a cheaper material results in a longer cultivation period, reduced fruiting, or lower biological efficiency, the final cost per unit product may still be high.

More importantly, economic return should be evaluated beyond "total yield" and should incorporate "marketable yield." Saludares (2016), in an economic comparison of different spawn substrates for *G. lucidum*, found that raw materials influenced not only mycelial growth and fruiting body yield but also profit and return on investment, showing that production efficiency must ultimately be assessed in relation to inputs and actual saleable output. The long production cycle and relatively high processing costs associated with solid-state cultivation can also affect technical and economic feasibility, while production scale and equipment utilization can significantly alter unit production cost (Araque et al., 2020). A more practical production-side evaluation framework is therefore: raw material and spawn costs + labor + facilities and energy + production cycle → total yield → marketable yield and product grade → actual selling price → net return. Within this framework, marketable proportion is especially important. A high-yield batch containing a large proportion of malformed, damaged, or low-grade fruiting bodies may ultimately generate lower profit than a batch with lower total yield but a higher proportion of marketable products.

6.4 Selection of cultivation system

The choice between log and substrate cultivation should be based on product objectives and available resources. If a producer has access to forest-understory space, suitable wood, and the capacity to accommodate a longer production cycle, and if the target market values geographical origin, traditional cultivation, intact fruiting bodies, and product traceability, log cultivation may be considered for specialty-product production. Ha and Uong (2026), in an analysis of the *G. lucidum* value chain in the buffer zone of a national park in Vietnam, showed that understory cultivation, product certification, traceability systems, and integration with processing and marketing are important directions for increasing product value and strengthening farmer participation. The market advantage of log or understory cultivation therefore depends on the combined support of resource endowment, product certification, and sales channels.

If the production goal is stable large-volume supply, specification control, and faster turnover, substrate cultivation is generally easier to integrate into facility-based production systems. This is particularly relevant for markets supplying slices, powders, extracts, and other processing raw materials, where enterprises and cooperatives are often more concerned with batch consistency, raw-material traceability, and quality standards than with the traditional cultivation label of individual fruiting bodies. As the *G. lucidum* industry expands toward food, health-related products, and medicinal raw materials, raw-material standardization and whole-process quality control are becoming increasingly important foundations for industrial production (Wu et al., 2024). A relatively clear production correspondence can therefore be established: premium whole fruiting bodies and specialty markets may place greater emphasis on log cultivation; standardized raw materials and large-scale supply are more closely aligned with substrate cultivation; producers with well-developed facilities and continuous delivery requirements may prioritize substrate cultivation; and producers with forest resources and regional branding advantages may retain log cultivation to create product differentiation.

6.5 Layered production and combined management

For producers serving multiple sales channels, a layered product structure can be developed according to market demand. Substrate cultivation can provide relatively stable baseline production and processing raw materials, while log cultivation can be maintained at a smaller scale for whole fruiting bodies, specialty gift products, or products with distinctive regional identity. This approach is based on the fact that the two cultivation systems differ in their requirements for raw materials, production cycle, and management, and may therefore help distribute risks associated with dependence on a single raw material source or a single product market (Figure 3). Substrate production can also make use of regional agricultural wastes. Rashwan et al. (2025), using date palm residues for *G. lucidum* cultivation, found that appropriate wheat bran supplementation significantly increased fresh weight, dry weight, and biological efficiency. The study further suggested that local agricultural residues have potential for commercial production while reducing resource waste, indicating that the local utilization of by-products can be an important means of controlling substrate-production costs.

The more important value of combined management does not lie simply in operating two cultivation technologies simultaneously, but in assigning different production functions according to local resources and product grades. Regions with favorable forest resources may retain a certain proportion of log cultivation for specialty products, while using by-products such as corn cobs, sugarcane bagasse, and cassava stems to establish substrate-production lines that ensure baseline output and supply of processing raw materials. Trials conducted under eucalyptus plantations showed that cultivation substrates based on cassava stems combined with corn cobs or sugarcane bagasse could achieve yields per bag comparable to or higher than conventional substrates, while some formulations also generated markedly higher profit per hectare (Zhang et al., 2026). Production systems can therefore move beyond the simple question of "log or substrate?" toward the more practical question of which production method is most suitable for each product type. Long-term economic comparisons of producers simultaneously operating both log and substrate production lines remain limited, however, and such combined systems are therefore more appropriately regarded as production strategies proposed on the basis of current cultivation and economic evidence rather than as universally validated models.

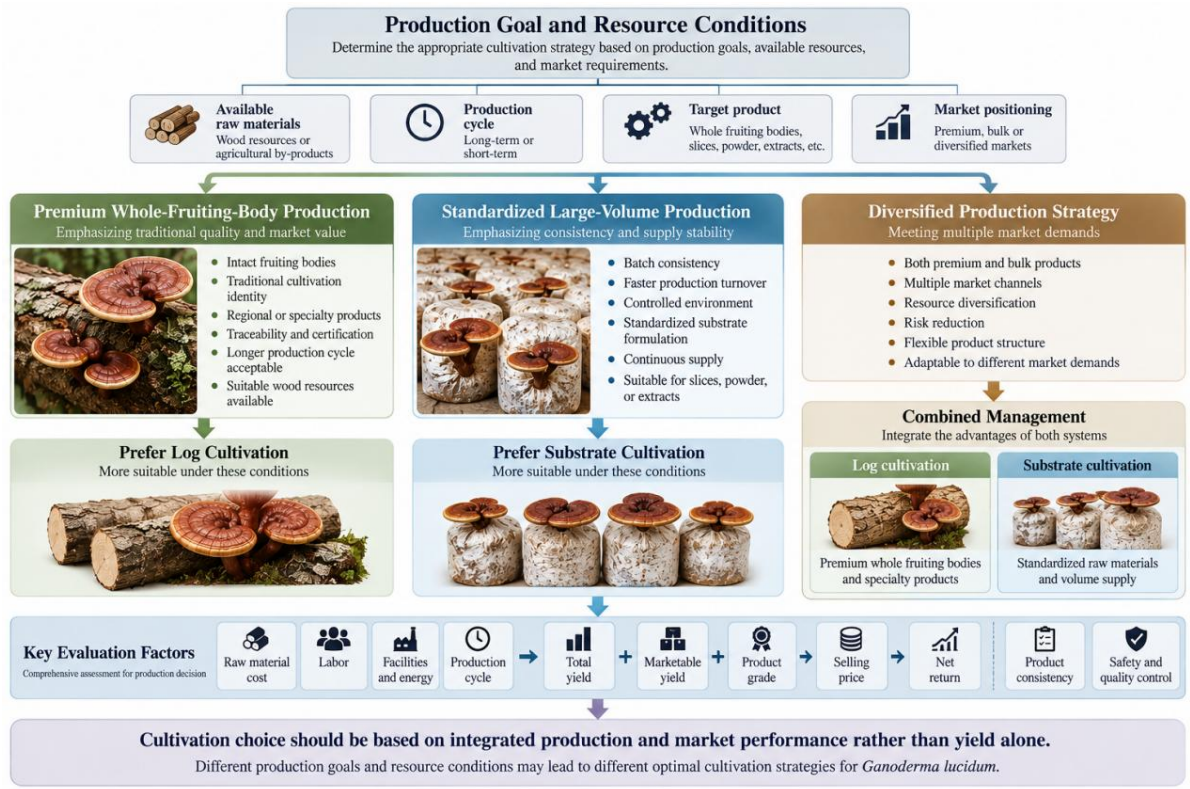


Figure 3 Decision framework for *Ganoderma lucidum* cultivation and combined management based on production goals and resource conditions

7 Current Issues and Future Directions

7.1 Insufficient standardization of quality evaluation and research comparability

A major challenge currently facing *Ganoderma lucidum* research and commercial evaluation is the insufficient standardization of material identity and quality indicators. Wu et al. (2017) analyzed 19 batches of *G. lucidum* dietary supplements collected from the United States market and found that only five batches, corresponding to 26.3%, showed detected constituents consistent with their product labels, indicating substantial quality inconsistency among commercial products. A more recent market survey conducted molecular identification of 84 commercial *Ganoderma* samples and detected 16 adulterated samples. Total polysaccharide contents ranged from 0.22% to 3.31%, while total triterpenoid contents ranged from 0.21% to 10.56%, demonstrating that even products marketed under the common name "*Ganoderma*" may differ considerably in species identity and major chemical indicators (Liu et al., 2025). Before comparing log- and substrate-cultivated products, strain and species identity should therefore first be confirmed; otherwise, differences attributed to cultivation method may be confounded by differences in genetic material.

In addition to material origin, harvest maturity, drying treatment, extraction conditions, and analytical methods are important factors affecting the comparability of research results. Polysaccharides, in particular, are structurally complex macromolecules, and different extraction, purification, and characterization procedures may produce different yields, molecular-weight distributions, and monosaccharide compositions. Consequently, direct comparison of "total polysaccharide content" reported across different studies does not always have exactly the same analytical meaning (Gong et al., 2020). *G. lucidum* fruiting bodies have now been incorporated into a dedicated ISO quality-standard system, and ISO 21315:2026, issued in February 2026, replaced the 2018 edition and specifies requirements and test methods for *Ganoderma lucidum* fruiting bodies. Future comparative studies of log and substrate cultivation should, at a minimum, standardize strain identity, maturity stage, sampling position, drying conditions, and analytical methods, while fully reporting cultivation substrate information, in order to improve comparability among studies.

7.2 Is log-cultivated *Ganoderma lucidum* always superior to substrate-cultivated material ?

The perception that "log-cultivated *G. lucidum* is of higher quality" is relatively common in production and consumer markets, but current scientific evidence more appropriately supports the conclusion that advantages may exist for certain indicators. Song et al. (2020), in a direct comparison between wood-cultured and bag-cultured *G. lucidum*, found differences in nutritional composition, trace elements, and functional components, while some extracts from wood-cultured samples showed stronger antioxidant and hypoglycemic activities. These findings confirm that cultivation substrate can influence final fruiting body quality. However, the results were obtained using a specific strain, oak logs, and a particular bag-substrate formulation and therefore cannot be directly generalized to conclude that all log-cultivation systems are superior to all substrate-cultivation systems.

The accumulation of bioactive substances in *G. lucidum* is influenced by many factors beyond cultivation method. Samples from different geographical origins can show different combinations of ganoderic acid A, ganoderic acid B, polysaccharides, and total triterpenoids, meaning that no single sample necessarily performs best across all quality indicators (Lu et al., 2012). Fruiting body developmental stage can also alter such comparisons: some ganoderic acids are more abundant at earlier stages, whereas others increase during maturation, while high levels of total triterpenoids and total polysaccharides may occur before full maturity (Zhou et al., 2018). A more meaningful scientific question is therefore which quality indicators show stable differences between the two production systems when the same strain, comparable maturity, and standardized analytical methods are used, and whether these differences are large enough to translate into practical commercial value.

7.3 Optimization of substrate resources and formulations

Future optimization of substrate cultivation should simultaneously consider raw-material cost, mycelial utilization efficiency, fruiting body yield, and final chemical quality. Agricultural and forestry by-products are highly diverse and differ substantially in lignin, cellulose, hemicellulose, protein, and mineral composition. Therefore, materials should not be assumed to have equivalent substitution value simply because they are classified as "agricultural

wastes." When phenolic-rich by-products such as grape pomace and green walnut husks are incorporated into cultivation substrates, different inclusion levels can simultaneously affect *G. lucidum* yield, antioxidant activity, and antimicrobial activity, demonstrating that substrate optimization is fundamentally a balance between production traits and quality traits (Atila et al., 2024).

Regional utilization of raw materials is particularly worthy of further investigation. Liu et al. (2023) used different *Miscanthus* materials to replace conventional sawdust in *Ganoderma* cultivation and found that suitable formulations maintained normal fruiting body production without reducing triterpenoid, sterol, or polysaccharide levels. This indicates considerable potential for resource substitution and formulation optimization in substrate cultivation. For primary producers, future research would be more valuable if it focused on locally and consistently available materials such as corn cobs, straw, branches, and sawdust and evaluated them comprehensively in terms of price, transport distance, C/N ratio, water-holding capacity, aeration, yield, marketable proportion, and major quality components. The ultimate goal should be to identify regional formulations that combine low cost, stable production, and acceptable product quality.

7.4 Low-cost standardized production

Standardization does not necessarily imply high investment or complete industrialization. For most producers, a more practical approach is to standardize the key production steps most likely to generate batch-to-batch variation, including strain source, cultivation bag weight, ratio of basal materials to supplements, initial moisture content, sterilization conditions, inoculation rate, and the ranges of temperature, humidity, light, and ventilation during fruiting. Developments in artificial *Ganoderma* production have shown that an important advantage of bag and bottle cultivation is that raw-material formulations and production parameters can be recorded and reproduced, thereby improving consistency across batches (Zhou et al., 2012). For primary producers, standardization should therefore begin with one mature formulation and one stable production process.

Standardization should also extend to harvesting and drying because fruiting body quality may continue to be affected by processing conditions after removal from the cultivation environment. Naseri et al. (2023) compared convective and infrared drying and found that different drying parameters significantly affected drying time, color, energy consumption, and several quality characteristics, indicating that postharvest handling itself can become a new source of variation among studies and production batches. Future low-cost production standards should therefore specify at least several key steps: maturity assessment → harvesting → drying → moisture control → appearance grading → packaging and batch recording. Ordinary producers do not necessarily require complex automated equipment, but products within the same grade should be harvested and processed under comparable conditions.

7.5 Integrated evaluation system

Future comparisons between log and substrate cultivation need to move beyond "single-indicator evaluation" toward "multi-dimensional integrated evaluation." Recent comprehensive assessments of different *G. lucidum* germplasm resources have begun to simultaneously include agronomic traits, developmental period, fruiting body yield, polysaccharides, triterpenoids, and potentially harmful metals. Different strains often exhibit different combinations of advantages: some have shorter developmental periods, some produce higher yields, some accumulate more bioactive components, while safety indicators may reveal an additional pattern of variation (Liu et al., 2026). Even within the same cultivation system, it is therefore difficult to define an "optimal" material using a single indicator. This limitation is even more evident when comparing log and substrate cultivation, because focusing only on total triterpenoids or polysaccharides would overlook many factors directly relevant to production.

Future production evaluation should therefore incorporate at least the following dimensions: biochemical quality, commercial quality, production performance, economic performance, and safety. Specific indicators may include major components such as polysaccharides and triterpenoids; cap thickness, fruiting body integrity, and marketable proportion; yield per unit cultivation material and production cycle; raw-material, labor, and facility costs; product grade, selling price, and net return; as well as safety indicators such as heavy metals and pesticide

residues. Miao et al. (2026) integrated chromatographic fingerprints, activity-related indicators, and chemometric analysis across different varieties and developmental stages and found that both variety and maturity stage altered the outcome of comprehensive quality evaluation. This further demonstrates that "overall quality" should not be represented by a single chemical indicator. For producers, the ultimate question is which production system can consistently generate marketable products that meet the requirements of the target market at an acceptable cost.

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Conflict of Interest Disclosure

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

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