Beyond Taxonomy: A Terroir-Based Framework for Defining and Grading Hainan Oud as an Independent Material Category

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Abstract

Agarwood—the resinous heartwood produced by wounded Aquilaria species—commands global market prices ranging from US$20 to US$6,000 per kilogram, with annual trade estimated at US$6–8 billion as of 2013–2014 (Tan et al., 2019, citing Abdin, 2014; Akter et al., 2013; more recent comprehensive market estimates are not available in the peer-reviewed literature). Despite this extraordinary economic significance, the industry operates without a standardized quality grading system applicable across production, commerce, and consumption contexts. Existing classification approaches—including Japan's six-category sensory system, Indonesia's SNI 7631:2018 standard, China's forestry industry standard LY/T 2904-2017, and various country-specific practices—rely on subjective sensory evaluation, vary by country, and fail to account for the material and chemical distinctiveness conferred by geographic origin. This paper proposes a terroir-based framework for defining and grading Hainan Oud—resinous heartwood originating from Aquilaria sinensis cultivated in Hainan Province, China—as an origin-defined material category with an independent grading framework, distinct from generic agarwood taxonomy. Drawing on an integrative synthesis of peer-reviewed phytochemical, botanical, and sensory science literature, combined with multi-generational practitioner knowledge from Hainan's production regions, this study addresses three research questions: (1) What measurable characteristics distinguish Hainan-origin material from agarwood of other geographic origins? (2) How can these characteristics be organized into a systematic, reproducible grading framework? (3) What implications does a terroir-based material category have for industry transparency, consumer protection, and sustainable sourcing? The resulting Hainan Oud grading framework—encompassing Origin Specificity, Formation Integrity, Resin Architecture, and Scent Signature—represents, to the authors' knowledge and based on a review of English- and Chinese-language peer-reviewed literature, the first formal application of terroir theory to aromatic wood materials and offers a replicable model for origin-based quality standardization in the broader agarwood industry.

Keywords: Hainan Oud, agarwood, Aquilaria sinensis, terroir, grading framework, material category, quality standardization, CITES, non-timber forest products, geographical indication

1. Introduction

1.1 The Agarwood Industry: Value Without Standards

Agarwood, known as chenxiang (沉香) in Chinese, oud in Arabic, jinkoh in Japanese, and gaharu in Malay, is among the most valuable non-timber forest products in global trade.

The resinous heartwood forms when trees of the genus Aquilaria (Thymelaeaceae) mount a defense response to physical injury, fungal infection, or other biotic and abiotic stressors, producing complex mixtures of sesquiterpenes and 2-(2-phenylethyl)chromones that accumulate over years or decades (Tan et al., 2019). The annual global market for agarwood has been estimated at US$6–8 billion as of 2013–2014, with wood chip prices ranging from US$20 to US$6,000 per kilogram depending on perceived quality, and premium-grade wood reaching substantially higher prices (Tan et al., 2019, citing Abdin, 2014; Akter et al., 2013).

Despite this extraordinary economic value, the agarwood industry lacks a universally accepted, internationally applicable quality grading system. While individual countries and regions have developed their own standards (see Section 1.2 and Section 2.4), Liu et al. (2017) observed that no standard quality grading system exists that can be applied across all agarwood-producing, commercial, and consumer contexts. Mohamed and Lee (2016) identified a fundamental structural problem: because agarwood passes through multiple levels of traders between collectors and end consumers, the grade can be readjusted and the price inflated or understated depending on the interest of the intermediary, leaving participants to rely heavily upon time-honored trust when concluding transactions. This absence of standardization has persisted into the era of advanced analytical chemistry; as recently as 2025, Baig et al. confirmed that no standardized system is available for grading resin quality.

The consequences of this standardization gap are significant. First, it enables widespread adulteration and counterfeiting. Feng et al. (2024) documented methods including high-pressure oil injection, soaking with spices to imitate high-quality agarwood, and substituting other wood species—particularly when processed into handicrafts such as beads, bracelets, and statues. Second, it impedes conservation efforts under the Convention on International Trade in Endangered Species (CITES), which has listed all Aquilaria species in Appendix II since 2004 (with A. malaccensis listed since 1995), but cannot enforce quality-based trade controls without agreed-upon material standards. Third, it prevents consumers from making informed purchasing decisions, concentrating market power among intermediaries who possess tacit evaluation knowledge.

1.2 The Limits of Existing Classification: Why Taxonomy Is Not Enough

Before proposing a new framework, it is necessary to examine why existing agarwood classification systems—each the product of centuries of trade practice—remain inadequate for standardized quality communication.

The most codified traditional system is Japan’s rikkoku gomi (六国五味) classification, which categorizes agarwood into six origin types (kyara, rakoku, manaban, manaka, sasora, sumatora) evaluated across five taste-smell dimensions (sweet, sour, hot, salty, bitter). This system, developed within the context of kōdō (incense ceremony), represents a sophisticated sensory taxonomy but is limited to trained practitioners, is not reproducible by instrumental methods, and does not account for formation history or material provenance verification (Compton and Ishihara, 2004).

Indonesia’s SNI 7631:2018 national standard provides a resin-saturation-based grading system that Hatta et al. (2024) used as the basis for deep learning classification, achieving

87.5% accuracy. China's forestry industry standard LY/T 2904-2017 establishes commercial grading criteria for agarwood products. The Chinese Pharmacopoeia (2020 edition) specifies Aquilaria sinensis (Lour.) Gilg as the only legal plant source for medicinal agarwood and sets minimum ethanol-soluble extractive content requirements.

In the trade market, at least five parallel grading systems coexist globally: alphabetic (C through AAA), water-sinking (floating to sinking), resin saturation (Super to Triple Super), size-based, and purpose-based classifications (Mohamed and Lee, 2016). As Mohamed and Lee (2016) documented, these systems are country-specific, vendor-interpreted, and mutually untranslatable—what one vendor classifies as Grade A, another may classify as Grade B.

At the regional level, some jurisdictions have developed more rigorous standards. Hainan Province—the geographic focus of this paper—has issued two local standards directly relevant to agarwood: DB46/T 421-2017 (Agarwood Identification), which specifies TLC, HPLC, and microscopic methods for authenticating agarwood from Aquilaria sinensis and Gyrinops salicifolia; and DB46/T 422-2017 (Agarwood Quality Grading), which establishes quality tiers based on PEC content (specifically 2-(2-phenylethyl)chromone and 2-[2-(4-methoxyphenyl)ethyl]chromone), ethanol-extractable content, and sensory evaluation (Hainan Provincial Bureau of Quality and Technical Supervision, 2017a, 2017b). China's forestry industry standard LY/T 2904 (Agarwood) provides a national-level commercial framework. These standards represent the most advanced formalized grading systems currently in operation for Chinese agarwood.

It is essential, however, to distinguish between two fundamentally different levels of standardization: **quality grading** and **category definition**. All existing systems—from Japan's sensory taxonomy to Hainan's DB46/T 422—operate at the quality grading level: they answer the question "How good is this agarwood?" by assessing material within a single, undifferentiated product category. None of these systems addresses the prior question of what kind of agarwood is being graded—that is, none establishes origin-specific material categories analogous to the distinction between Champagne and sparkling wine, or between Jamaica Blue Mountain Coffee and generic Arabica. Under DB46/T 422, Hainan-origin material and Guangdong-origin material with identical PEC content would receive the same quality grade, despite potentially distinct terroir contexts, formation histories, and sensory profiles.

The framework proposed in this paper operates at the category definition level. It does not compete with or replace DB46/T 422's quality grading methodology; rather, it establishes a prior step—defining Hainan Oud as a distinct material category—within which quality grading metrics (including those from existing standards) can then operate with greater precision and meaning.

1.3 The Missing Variable: Geographic Origin

A critical gap in existing agarwood research and classification is the systematic undervaluation of geographic origin as a determinant of material quality. While the concept of terroir—the ensemble of environmental, biological, and cultural factors that confer distinctive characteristics upon agricultural products from a defined region (OIV, 2010, as cited in Brillante et al., 2020)—has been rigorously applied to wine and increasingly

extended to coffee (Williams et al., 2022; Gonçalves et al., 2025), tea, and chocolate (Lucini et al., 2020), it has, to the authors' knowledge and based on a review of English- and Chinese-language peer-reviewed literature, never been formally applied to aromatic wood materials.

Yet the scientific evidence for origin-dependent variation in agarwood is substantial. Wang et al. (2018) demonstrated measurable chemical differences between A. sinensis agarwood from China, Vietnam, Indonesia, and Malaysia, with Vietnamese samples showing the highest moisture content (14.73%) attributed to tropical monsoon climate conditions, while Chinese samples showed the lowest (7.99%). Yu et al. (2021) found that agarwood from the Chi-Nan (QiNan) germplasm of A. sinensis cultivated in Hainan and Guangdong provinces exhibited dramatically different chemical profiles from ordinary agarwood: guaiane and eudesmane sesquiterpene derivatives—identified as crucial contributors to the unique fragrance of Chi-Nan agarwood—were present at significantly higher concentrations. Ma et al. (2024) quantified this difference further, reporting that QiNan ethanol extract content reached 40.02% compared to 15.89% in traditional agarwood, using samples from Danzhou City, Hainan Province.

These findings collectively suggest that Hainan Oud material possesses measurable characteristics distinguishable from agarwood of other geographic origins—a pattern consistent with terroir effects documented in other plant-derived products where reconfiguring "a taste of place" requires both material and symbolic quality attributes (Rosenberg, 2023).

1.4 Research Questions

This study addresses three interconnected research questions:

RQ1: What measurable material characteristics—encompassing geographic, botanical, chemical, and sensory dimensions—distinguish Hainan Oud material from material produced in other regions?

RQ2: How can these distinguishing characteristics be organized into a systematic, reproducible, and scientifically grounded grading framework?

RQ3: What are the implications of establishing a terroir-based material category for industry transparency, consumer protection, and the sustainable development of Hainan's Aquilaria sinensis resources?

1.5 Scope and Definitions

This paper introduces the term **Hainan Oud** as a proposed material category, distinct from the generic commercial term "oud" or "agarwood." As used throughout this paper:

> **Hainan Oud** is a material category proposed by Yigēn Labs, defined by four interlocking dimensions: geographic origin (Hainan Province, China), formation integrity (natural or certified induction processes), resin architecture (structural patterns of resin deposition within included phloem and ray tissues), and scent signature (the distinctive sensory profile attributable to the interaction of Hainan's terroir with the biochemistry of resin formation). The category is

defined by the conjunction of all four dimensions, not by any single dimension in isolation. The current botanical basis of Hainan Oud is Aquilaria sinensis, reflecting the species cultivated in Hainan today; however, the category definition is anchored in the four-dimensional framework rather than in a single taxonomic designation.

Why an origin-defined category rather than a subcategory within agarwood? The rationale for proposing Hainan Oud as an origin-defined category independent of—rather than nested within—agarwood rests on five conditions documented in the existing literature: four structural conditions indicating that subcategorization within the agarwood framework would be insufficient, and one scientific condition establishing that Hainan-origin material possesses the measurable distinctiveness required to constitute an independent category.

First, agarwood operates under a 300-fold price range (US$20 to US$6,000 per kilogram; Tan et al., 2019) without an internationally accepted grading standard (Liu et al., 2017; Mohamed and Lee, 2016; Baig et al., 2025). Within this environment, Mohamed and Lee (2016) documented that grades can be readjusted and prices manipulated by intermediaries at each level of the supply chain—conditions under which price and material quality may become systematically decoupled. Second, counterfeiting methods including high-pressure oil injection, spice soaking, and species substitution have been documented in the peer-reviewed literature (Feng et al., 2024), demonstrating that undifferentiated category membership provides insufficient assurance of material authenticity. Third, all Aquilaria species are listed in CITES Appendix II, and current species-level regulation does not incorporate mechanisms for origin verification or quality documentation at the material level, regardless of the provenance, sustainability, or production standards of specific material. Fourth, existing grading systems—including the most advanced regional standard, Hainan's DB46/T 422-2017—do not include geographic origin as a constitutive grading dimension (see Section 1.2); a subcategory operating within such a framework has no mechanism to elevate origin from incidental metadata to a defining attribute.

The four conditions above establish why remaining within the agarwood category is structurally insufficient. A fifth condition establishes why Hainan-origin material has the scientific basis to constitute an independently defined material category: peer-reviewed phytochemical evidence demonstrates that A. sinensis material from different geographic origins exhibits measurably distinct chemical compositions (Wang et al., 2018), and that Hainan-cultivated QiNan germplasm produces resin with specific sesquiterpene profiles—notably elevated guaiane and eudesmane derivatives—not found at comparable concentrations in material from other origins (Yu et al., 2021). This is not merely quantitative variation within a single material type; it is origin-dependent chemical distinctiveness of the kind that underpins terroir-based category definitions in viticulture and coffee science (see Section 5 for full evidence assembly).

Under these conditions, adding a sub-grade within agarwood would improve assessment precision within the existing category but would not address the foundational problem: consumers encountering the term "agarwood" receive no quality signal from the category name itself. An origin-defined category addresses this by making the category name the first layer of quality communication—just as a consumer encountering "Champagne" receives a quality signal before examining any grade or vintage designation.

This definition therefore positions Hainan Oud not as a subcategory of agarwood but as an origin-defined material category—structurally inspired by origin-based category distinctions in other industries, such as the Champagne–sparkling wine relationship in viticulture, where the category name encodes both origin and production standards. This analogy is structural rather than legal; Hainan Oud does not currently possess the legal, institutional, or empirical foundations that underpin established geographic designations such as Champagne's AOC. It does not currently hold geographic indication (GI) status under any national or international GI protection regime, though the framework proposed here could serve as a foundation for future GI applications (see Section 8.4).

The distinction between an origin-defined category and a subcategory is not merely terminological; it has substantive implications. A subcategory (e.g., "Hainan Agarwood") would remain within the definitional domain of agarwood, inheriting that category's regulatory frameworks, quality standards, and—critically—its undifferentiated market identity. Under such a structure, Hainan-origin material would continue to be evaluated by the same grading criteria as agarwood from any other origin, with geographic provenance treated as incidental metadata rather than a constitutive attribute. An origin-defined category, by contrast, establishes an independent definitional space in which origin is not incidental but foundational—the first dimension against which all subsequent quality assessments are conducted. This structural independence enables distinct quality standards, distinct market positioning, and distinct regulatory pathways, while the shared biological substrate (Aquilaria resin formation) is acknowledged as common heritage rather than categorical identity. The relationship is analogous to that between Champagne and Crémant: both are sparkling wines produced from overlapping grape varieties using similar methods, but they occupy distinct category spaces with independent quality standards.

The framework is intended to be extensible: the same terroir-based methodology could be applied to define origin-specific material categories for agarwood from other geographically and chemically distinct production regions (e.g., Vietnamese Oud, Cambodian Oud), each with its own four-dimensional definition.

2. Theoretical Framework

2.1 Terroir Theory: From Viticulture to Aromatic Materials

The concept of terroir, rooted in the French term terra (ground or land), has evolved from a geographically bounded descriptor into a multidimensional analytical framework. The International Organisation of Vine and Wine (OIV) defines terroir as the result of collective knowledge of the interactions between the environment and plants, mediated through human action and providing distinctive characteristics to the final product (OIV, 2010, as cited in Brillante et al., 2020). This definition encompasses three layers: (i) the physical environment, including climate, geology, soil, and topography; (ii) biological material and production practices; and (iii) cultural, socio-economic, and political dimensions.

Critically, terroir is not merely a geographic label but a causal framework: it proposes that specific, measurable product characteristics arise from the interaction of a defined set of environmental and human factors. Brillante et al. (2020) noted that the concept

of geographical origin can be applied to all crops and foods, and that terroir's current restriction to wine is not regulated, leaving it open to abuse and self-assessment without control. The extension of terroir analysis to new product categories is both scientifically legitimate and practically necessary.

Recent research has demonstrated the applicability of terroir concepts well beyond viticulture. In coffee, Williams et al. (2022) established that terroir encompasses species, variety, environmental conditions, agricultural parameters, and post-harvest processing, all of which combine to produce a unique sensory experience traceable to a specific origin. Gonçalves et al. (2025) demonstrated that data mining techniques could predict the presence of specific sensory notes in coffee based on soil and environmental attributes, providing empirical support for terroir as a measurable rather than merely rhetorical concept. Metabolomic studies can now biochemically discriminate between wines from vineyards separated by less than 2 kilometers (Roullier-Gall et al., 2014, as cited in Johnston-Monje et al., 2023). Origin-based labeling generates measurable price premiums: Café de Colombia-labeled coffee commands at least three times the price of unlabeled roasted coffee, while Jamaica Blue Mountain Coffee commands over thirteen times the premium (Teuber, 2010, as cited in Johnston-Monje et al., 2023).

The economic logic of origin-based designation is well documented in the geographical indication (GI) literature. The European Union's Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) system provides a legal framework in which every part of the production, processing, and preparation process must take place in the specific region (European Commission, 2024). Vandecandelaere et al. (2021) developed a participatory framework for assessing GI contributions to sustainability under the FAO-OriGIn Sustainability Strategy. These systems demonstrate that formalized origin-based classification can simultaneously serve consumer protection, producer economic interests, and environmental sustainability—objectives directly relevant to the agarwood sector.

This paper extends the terroir question to aromatic wood materials: can terroir theory provide a scientifically rigorous basis for defining and grading agarwood by geographic origin?

2.2 Chemotaxonomic Markers and Material Authentication

The scientific basis for origin-based agarwood classification rests on the established chemotaxonomic distinctiveness of Aquilaria sinensis resin. Sesquiterpenes and 2-(2-phenylethyl)chromone (PEC) derivatives constitute the two principal classes of bioactive compounds in agarwood (Tan et al., 2019, citing Naef, 2011). Over 150 compounds have been identified in agarwood from various sources, including approximately 70 sesquiterpenes and 40 PEC types (Naef, 2011, as cited in Tan et al., 2019). These two compound classes function as reliable chemotaxonomic markers: their presence, absence, and relative proportions distinguish authentic agarwood from non-agarwood material and differentiate material from different species and origins (Xie et al., 2020; Yu et al., 2021).

The chemotaxonomic significance of PECs for quality assessment is well documented. High-grade agarwood (kanankoh) contains PEC concentrations as high as 66.47%, compared to only 1.5% in lower-grade material (jinkoh) (Ishihara et al., 1993, as cited in Tan et

al., 2019). Xie et al. (2020) demonstrated that a specific PEC compound (5,6,7,8-tetrahydro-2-(2-phenylethyl)chromone, m/z 319.1) functions as a reliable chemical marker for agarwood authentication: this compound could not be detected in counterfeit agarwood, enabling rapid discrimination between authentic and counterfeit samples using liquid extraction surface analysis mass spectrometry (LESA-MS).

2.3 Resin Architecture as a Structural Marker

Beyond chemical composition, the physical architecture of resin deposition within agarwood provides an additional dimension for material authentication and grading. Feng et al. (2024) established that the resinous included phloem is a key characteristic structure of agarwood that can serve as a basis for authenticity identification. Their study, which included 20 authentic agarwood samples from 17 producing areas across 8 countries alongside counterfeited specimens (53 total), demonstrated that artificially simulated counterfeiting treatments failed to replicate the natural pattern of resin filling in included phloem tissue—a finding with direct implications for grading frameworks that incorporate structural analysis.

This structural approach complements chemical analysis by providing a non-destructive, visually assessable dimension of quality. The pattern of resin deposition in phloem and ray tissues reflects the temporal dynamics of the tree's wound-healing response and is therefore expected to be linked to formation conditions—including geographic origin, tree age, and induction method—though systematic comparative studies of resin architecture across production regions remain limited.

2.4 Regulatory Context: The Chinese Pharmacopoeia and National Standards

The regulatory environment for agarwood in China provides important context for the Hainan Oud framework. The Pharmacopoeia of the People's Republic of China (2020 edition) specifies Aquilaria sinensis (Lour.) Gilg as the only legal plant source for medicinal agarwood (chenxiang), with quality requirements including minimum ethanol-soluble extractive content and microscopic identification criteria for characteristic structures such as columnar calcium oxalate crystals and resinous included phloem (Chinese Pharmacopoeia Commission, 2020). China's forestry industry standard LY/T 2904-2017 (Agarwood) provides a national-level commercial framework for agarwood products.

At the provincial level, Hainan has developed the most detailed regional standards for agarwood in China. DB46/T 421-2017 specifies authentication methods (TLC, HPLC, and microscopic identification) for agarwood from A. sinensis and Gyrinops salicifolia (Hainan Provincial Bureau of Quality and Technical Supervision, 2017a). DB46/T 422-2017 establishes quality grading based on PEC content—specifically 2-(2-phenylethyl)chromone and 2-[2-(4-methoxyphenyl)ethyl]chromone—ethanol-extractable content, and sensory evaluation (Hainan Provincial Bureau of Quality and Technical Supervision, 2017b). Additionally, Li et al. (2024) documented quality evaluation of QiNan material according to both national pharmacopoeia and Hainan provincial standards.

These existing regulatory instruments serve essential functions in authentication and quality grading. However, they all operate within the agarwood category: they assess

whether material is agarwood (authentication) and how good it is (grading), but they do not address whether material from a specific terroir constitutes a distinct category of product. The Hainan Oud framework proposed in this paper is designed to complement—not replace—these standards by adding a category-definition layer that existing instruments do not address.

3. Literature Review: The State of Agarwood Science

This section surveys the existing body of peer-reviewed research on agarwood quality, authentication, and classification, organized to identify what the field has established, where critical gaps remain, and how the present study builds upon prior work.

3.1 What the Field Has Established

Chemical composition is species- and origin-dependent. The agarwood research community has produced a substantial body of phytochemical evidence demonstrating that resin composition varies across Aquilaria species, geographic origins, and induction methods. Wang et al. (2018) compared A. sinensis agarwood from China, Vietnam, Indonesia, and Malaysia using GC-MS, establishing that even within a single species, agarwood from different countries exhibited distinct chemical profiles and physical properties. Yen Van Thi et al. (2024) confirmed in a comprehensive review of 21 Aquilaria species that the composition of essential oils can vary depending on species, geographic origin, and extraction technique. Tan et al. (2019) catalogued over 150 compounds identified in agarwood, including approximately 70 sesquiterpenes and 40 PEC types (citing Naef, 2011), establishing these as the principal chemotaxonomic markers for the genus.

QiNan agarwood represents a chemically distinct subcategory. A growing body of evidence indicates that QiNan (奇楠) material—produced by a specific germplasm of A. sinensis—exhibits chemical characteristics quantitatively distinguishable from ordinary agarwood. Yu et al. (2021) demonstrated that guaiane and eudesmane sesquiterpene derivatives were present at significantly higher concentrations in QiNan than in ordinary agarwood, and that eudesmane derivatives were the most abundant sesquiterpene class in QiNan while eremophilane derivatives dominated ordinary agarwood. Ma et al. (2024) quantified the resin content difference: QiNan ethanol extract reached 40.02% compared to 15.89% in traditional agarwood. These studies establish that genetic germplasm, interacting with environmental conditions, produces measurably different material outcomes—a finding consistent with the terroir hypothesis.

Authentication methods are advancing but remain fragmented. Significant progress has been made in developing analytical tools for agarwood authentication. Xie et al. (2020) established LESA-MS as a rapid, non-destructive method capable of distinguishing authentic from counterfeit agarwood using the PEC marker m/z 319.1. Feng et al. (2024) demonstrated that microscopic analysis of resin distribution in included phloem provides a structural basis for authenticity identification across samples from 8 countries. Chowdhury (2025) advanced field-deployable authentication using smartphone-based handheld NIR spectroscopy with DD-SIMCA classification, achieving 100% sensitivity with no type-1 error in training sets. Baig et al. (2025) reviewed emerging AI and machine learning approaches that support rapid, automated identification based

on genetic and phytochemical data. Hatta et al. (2024) demonstrated deep learning classification of agarwood grades based on Indonesia's SNI 7631:2018 standard, achieving 87.5% accuracy.

Induction methods significantly affect chemical profiles. The relationship between agarwood induction technique and resulting chemical composition is well documented. Tan et al. (2019) provided a comprehensive comparison of natural, conventional (physical wounding), biological (fungal inoculation), and chemical induction methods, noting that chemical inducers are more suitable for mass production with easier quality control but that each method produces distinct chemical signatures. Baig et al. (2025) confirmed that advances in resin induction methods and chemical induction treatments are improving yield and quality, while noting that natural resin formation requires extended timeframes measured in decades. Liu et al. (2013) demonstrated the Agar-Wit whole-tree induction technique in Hainan A. sinensis plantations, establishing that this method could produce qualified material meeting Chinese Pharmacopoeia ethanol-soluble extractive content requirements within shorter timeframes.

3.2 What the Field Has Not Established

Despite substantial progress in individual dimensions of agarwood science, four critical gaps persist:

Gap 1: No integrated grading framework. Authentication methods, chemical profiling, and quality assessment remain separate streams of research. No study has synthesized these dimensions into a single, operational grading framework that practitioners can apply across the value chain. Each country maintains its own grading practices—Mohamed and Lee (2016) documented that the different grades and classes of agarwood result from long-standing grading practices adopted by the people of each country—but no internationally applicable standard exists.

Gap 2: Geographic origin is studied but not systematized. While multiple studies demonstrate origin-dependent chemical variation, no framework exists for translating this variation into defined material categories. The concept of terroir, which provides precisely this function in viticulture and increasingly in coffee science (Williams et al., 2022), has not been applied to agarwood. The field recognizes that origin matters but has not formalized how it matters or how to operationalize origin-based classification.

Gap 3: The Hainan production region is recognized but not defined as a distinct material category. Hainan Province is home to significant A. sinensis cultivation and a multigenerational agarwood production tradition. The province has developed authentication and quality grading standards (DB46/T 421-2017; DB46/T 422-2017), and Hainan material has recently received geographical indication certification trademark status (China Daily, 2024). However, these instruments operate within the agarwood category—they authenticate and grade Hainan-origin material as agarwood, not as an independently defined material category. Studies by Yu et al. (2021), Ma et al. (2024), and Feng et al. (2024)—all conducted by researchers affiliated with Hainan-based institutions—provide substantial data demonstrating the chemical distinctiveness of Hainan Oud material, but this data has not been organized into a formal category definition with terroir as its organizing principle.

Gap 4: The CITES regulatory framework operates at species level, not material level. All Aquilaria species are listed in CITES Appendix II, requiring trade permits regardless of origin, quality, or production method. This species-level regulation does not incorporate mechanisms for origin verification or quality documentation, regardless of the provenance or production standards of specific material. A material-level classification framework could complement CITES species-level protections by providing tools for origin traceability and material authentication that support—rather than circumvent—conservation objectives.

3.3 Where This Study Enters

The present study addresses these four gaps simultaneously by proposing an integrative framework that:

1. Synthesizes existing chemical, structural, and sensory research into a single four-dimensional grading system (addressing Gap 1);
2. Applies terroir theory as the organizing principle for origin-based material classification (addressing Gap 2);
3. Defines Hainan Oud as a formally documented material category with specified characteristics (addressing Gap 3);
4. Provides a material-level classification that complements CITES species-level protections (addressing Gap 4).

The methodological approach—integrative synthesis—is designed to build upon rather than replace existing research, treating published peer-reviewed findings as the evidentiary foundation and multi-generational practitioner knowledge as the experiential validation layer.

4. Methodology

4.1 Research Design: Integrative Synthesis

This study employs an integrative synthesis approach—a structured method for organizing existing verified findings from multiple disciplinary sources into a novel analytical framework. This approach draws on established integrative review methodology (Whittemore and Knafl, 2005) and framework synthesis methods (Carroll et al., 2013; Brunton et al., 2020), adapted for the purpose of constructing a new grading framework rather than summarizing existing ones. Unlike primary experimental research, integrative synthesis does not generate new empirical data; instead, it creates new knowledge by identifying previously unrecognized structural relationships among established findings and by systematically integrating formal scientific evidence with documented practitioner expertise.

The core innovation of this study is synthetic rather than empirical: it applies terroir theory—a well-established framework in viticulture and food science—to agarwood for the first time, using existing peer-reviewed phytochemical data as the evidentiary base. The analogy is architectural: the individual findings (chemical markers, structural features, origin-dependent variation) are verified building blocks produced by prior researchers; the framework that organizes these blocks into a coherent grading system is the contribution of the present study.

4.2 Evidence Sources and Selection Criteria

Evidence for this study was drawn from two categories of sources, with explicit differentiation maintained throughout:

Tier 1: Peer-reviewed scientific literature. The primary evidence base consists of peer-reviewed publications spanning phytochemistry, plant science, analytical chemistry, food science, geography, viticulture, and regulatory science, published between 2004 and 2025. Selection criteria required: (a) publication in a journal indexed by PubMed, PMC, Scopus, or Web of Science, or in a recognized academic book (Springer); (b) relevance to at least one of the four grading dimensions (origin, formation, resin architecture, scent); (c) verifiable data with traceable methodology. All citations in this paper have been verified against original source texts, with specific claims traced to their locations within source documents.

Tier 2: Practitioner knowledge. Experiential knowledge from multi-generational Hainan Oud practitioners in Hainan Province provides the qualitative foundation for sensory-dimension grading criteria and sub-regional terroir characterization. This knowledge was sourced through the research team's direct access to a multi-generational family-based supply chain in Hainan's agarwood production region, supplemented by informal consultations with practitioners in the Hainan trade network. The practitioner-derived claims cited in this paper reflect consensus observations reported consistently across multiple independent practitioners rather than the testimony of a single source. This knowledge is clearly distinguished from peer-reviewed evidence throughout the text using the notation "[Practitioner knowledge]" and is treated as hypothesis-generating rather than hypothesis-confirming. Future empirical studies will be needed to validate practitioner-derived claims through controlled experimental methods.

4.3 Framework Construction Process

The four-dimensional grading framework was constructed through a four-stage process:

Stage 1: Evidence extraction. Key findings relevant to material quality differentiation were systematically extracted from Tier 1 sources, organized by dimension (geographic, botanical, chemical, sensory).

Stage 2: Cross-disciplinary mapping. Terroir theory constructs from viticulture and food science (Brillante et al., 2020; Johnston-Monje et al., 2023; Rosenberg, 2023; Williams et al., 2022) were mapped onto agarwood-specific evidence to identify structural parallels and assess theoretical transferability.

Stage 3: Framework structuring. Extracted evidence and terroir constructs were organized into four interlocking dimensions, with each dimension defined by measurable or documentable criteria derived from Tier 1 evidence and supplemented by Tier 2 practitioner knowledge where peer-reviewed data was unavailable.

Stage 4: Retrospective consistency check. The completed framework was tested against published data to assess whether its dimensional structure could retrospectively account for quality differences documented in existing studies. This step constitutes a consistency assessment, not an independent validation, as the source data used for framework

construction and consistency checking overlap (see Limitations, Section 9.1).

4.4 Methodological Limitations

This methodology has four inherent limitations that must be acknowledged:

First, the framework is constructed from existing data rather than purpose-designed experiments. The chemical data cited was generated for diverse research objectives (authentication, pharmacological screening, species comparison) and was not collected with the specific aim of testing a terroir-based grading framework.

Second, practitioner knowledge, while valuable and often highly accurate, has not undergone the controlled testing required for scientific validation. Sensory assessments in particular reflect trained subjective evaluation rather than standardized instrumental measurement.

Third, the integrative synthesis approach cannot establish causal relationships; it can only demonstrate that existing evidence is consistent with the proposed framework. Establishing causality between specific terroir factors and specific material characteristics will require future controlled studies.

Fourth, the literature used to construct the framework and the literature used for the retrospective consistency check (Section 7) are not independent datasets. True prospective validation will require testing the framework against new data collected specifically for this purpose.

5. Hainan Oud Material Distinctiveness (Addressing RQ1)

This section assembles the evidence for Hainan Oud's material distinctiveness across the four dimensions that constitute the proposed grading framework.

A methodological note on evidence and category status. The evidence presented in this section is drawn from studies conducted within the agarwood research framework, as Hainan Oud—being a newly proposed category—has not yet generated its own independent research literature. This data is used here to support the scientific plausibility of the category definition: specifically, to demonstrate that Hainan Oud material exhibits measurable characteristics distinguishable from material of other origins, providing the empirical basis for an independent category designation. The use of agarwood-framework data to support an origin-defined category is not circular: just as early Champagne research drew on general viticulture science to establish the distinctiveness of the Champagne region's output, the present study draws on general agarwood science to establish the distinctiveness of Hainan's output. The claim is not that Hainan Oud is a distinct type of agarwood, but that the material produced in Hainan is sufficiently distinct to warrant designation as an origin-defined material category.

A note on competing explanatory variables. The evidence presented in this section includes both environmental data (e.g., Wang et al., 2018, demonstrating origin-dependent chemical variation across countries) and genetic data (e.g., Yu et al., 2021; Ma et al., 2024, demonstrating QiNan germplasm-specific chemistry). These two types of evidence support different causal mechanisms—terroir and genotype, respectively—and should not be conflated. Section 8.1 provides a detailed analysis of the competing explanatory variables

(induction method, genotype, and geographic origin) and their interaction, including recent evidence that planting area, rather than genotype alone, is the primary factor determining chemical composition in A. sinensis (Zhang et al., 2025). Readers are directed to Section 8.1 for the full treatment of this interpretive challenge; the evidence below is presented with this caveat in mind.

5.1 Dimension 1: Origin Specificity

Geographic context. Hainan Province (海南省), China's southernmost island province, lies between approximately 18°10'–20°10'N latitude and 108°37'–111°03'E longitude. The island's tropical monsoon climate, with annual mean temperatures of approximately 22.5–25.6°C, annual rainfall of 1,500–2,500 mm, and high humidity, creates environmental conditions distinct from other major A. sinensis production regions in mainland China (Guangdong, Guangxi, Yunnan) and Southeast Asia (Vietnam, Cambodia, Laos).

Evidence for origin-dependent chemical variation. Wang et al. (2018) established that A. sinensis agarwood from different Asian countries exhibits measurably different chemical compositions, with Chinese-origin agarwood showing the lowest moisture content (7.99 $\pm$ 0.13%) compared to Vietnamese (14.73 $\pm$ 0.08%), Indonesian, and Malaysian samples. This physical-chemical difference was directly attributed to climatic variation—a core terroir mechanism. The study confirmed that the main active ingredients in material from different habitats were sesquiterpenoids, aromatic species, and chromone compounds, with compositional ratios varying by origin. This cross-national comparison, controlling for species while varying geographic origin, provides the most direct evidence for terroir-driven material variation in A. sinensis (see Section 8.1 for discussion of competing explanatory variables).

Sub-regional variation within Hainan. Hainan's mountainous interior creates distinct microclimatic zones that practitioners have long recognized as producing material with different characteristics. The principal sub-regions include Wuzhi Mountain (五指山), Jianfeng Ridge (尖峰岭), and Bawang Ridge (霸王岭), each with distinct elevation profiles, rainfall patterns, and soil compositions. [Practitioner knowledge: These sub-regional distinctions are recognized within the Hainan Oud trade but have not been the subject of published comparative chemical studies. The present framework includes sub-regional origin as a documentable grading dimension while acknowledging that its chemical basis remains to be empirically validated.]

5.2 Dimension 2: Formation Integrity

The biological basis of resin formation. Defensive resin is not a constitutive component of healthy Aquilaria wood; it is produced as a defensive response to injury or infection. Tan et al. (2019) provided a comprehensive review of formation mechanisms, noting that a healthy Aquilaria tree does not produce resinous wood, leaving it worth next to nothing. The defense response triggers biosynthesis of sesquiterpenes through the mevalonic acid (MVA) and methylerythritol phosphate (MEP) pathways, with subsequent accumulation of PEC derivatives (Tan et al., 2019). Tan et al. (2019) noted that natural formation is characterized by unsustainable, undetermined, and extremely low yield, with resin accumulation occurring over years or decades.

Formation method affects material quality. Different induction methods produce chemically distinct results. Tan et al. (2019) compared natural factors, conventional physical wounding, biological inoculation, and chemical induction, establishing that natural formation yields the highest potential quality but with unsustainable, undetermined, and extremely low yield, while chemical induction offers fast results and high yields with more consistent output. The implication for grading is direct: formation method constitutes a material variable that must be documented for meaningful quality assessment.

Formation integrity as a grading criterion. The Formation Integrity dimension in the Hainan Oud framework captures whether the material was produced through natural wounding, certified induction methods, or undocumented processes. This dimension does not privilege natural formation over artificial induction per se; rather, it requires transparent documentation of formation history as a prerequisite for grading. An artificially induced specimen with fully documented formation history may score higher on Formation Integrity than a purportedly natural specimen with no verifiable provenance—because integrity refers to the completeness and verifiability of the formation record, not to a hierarchy of formation methods.

5.3 Dimension 3: Resin Architecture

Structural markers of authentic agarwood. Feng et al. (2024) established the scientific basis for resin architecture as a quality dimension by demonstrating that the resinous included phloem is a key characteristic structure of agarwood that can serve as a basis for authenticity identification. Their analysis of 20 authentic samples from 17 producing areas across 8 countries (alongside counterfeited specimens, 53 total) revealed that artificially simulated counterfeiting treatments failed to replicate the natural pattern of resin filling in included phloem tissue—a finding with direct implications for grading frameworks that incorporate structural analysis.

The phloem-ray resin network. The included phloem and ray tissues constitute the primary architectural sites of resin deposition in A. sinensis (Liu et al., as cited in Feng et al., 2024). The spatial distribution, density, and coloration of resin within this network reflect both the tree's biological response and the temporal duration of the formation process. High-quality Hainan Oud material exhibits dense, evenly distributed resin in both phloem and ray tissues, while lower-grade material shows sparse, uneven, or superficially concentrated resin patterns. [Practitioner knowledge: Experienced graders assess resin architecture through cross-sectional visual inspection, evaluating color gradation (from amber to deep black-brown), distribution uniformity, and the presence or absence of unfilled tissue gaps. These assessment criteria are widely used in the Hainan Oud trade but have not been formalized in published grading standards.]

QiNan resin architecture. Yu et al. (2021) documented that QiNan germplasm material exhibited distinctive phytochemical profiles, and Ma et al. (2024) confirmed higher total extractive content in QiNan (40.02%) versus ordinary agarwood (15.89%). While these studies focused on chemical rather than structural analysis, the substantially higher extractive content implies denser resin deposition—a structural characteristic assessable through the Resin Architecture dimension. As discussed in Section 8.1, QiNan's distinctive chemistry is primarily attributable to germplasm (Hou et al., 2022) rather than

geographic origin alone; the Hainan Oud framework treats genetic and environmental contributions as complementary inputs.

5.4 Dimension 4: Scent Signature

Chemical basis of scent differentiation. The sensory profile of Hainan Oud material is determined by its volatile compound composition, primarily sesquiterpenes (woody, spicy, balsamic notes) and PEC derivatives (sweet, fruity, long-lasting notes). Tan et al. (2019) noted that the types and derivatives of major compounds in agarwood are extremely wide and diverse, indicating the miscellaneous fragrance properties of agarwood from different species and regional sources. The relative proportions of these compound classes produce the characteristic scent that distinguishes high-grade from lower-grade material: Ishihara et al. (1993, as cited in Tan et al., 2019) found that PEC content in high-grade kanankoh reached 66.47%, compared to only 1.5% in lower-grade jinkoh.

Origin-specific scent characteristics. Yu et al. (2021) identified guaiane and eudesmane sesquiterpene derivatives as crucial contributors to the unique fragrance of QiNan material from Hainan and Guangdong provinces. This finding establishes that specific sesquiterpene classes contribute to origin-distinguishable scent profiles—the sensory dimension of terroir.

Scent assessment methodology. The Scent Signature dimension presents the greatest methodological challenge, as sensory evaluation is inherently subjective. The proposed framework addresses this by requiring structured sensory documentation rather than a single quality score. Key parameters include: initial note profile (first 30 seconds of warming), mid-note development (sustained warming), base note persistence, cooling behavior, and the presence or absence of off-notes (burnt, chemical, or discordant aromas that may indicate adulteration or processing defects).

A note on "cool touch" (liánggǎn, 凉感). The cooling or tingling sensation reported when high-quality Hainan Oud material contacts skin is widely and consistently reported by practitioners across the Hainan production region. [Practitioner knowledge] This phenomenon has not been systematically studied in the peer-reviewed literature. Cool-touch is included in this framework as a documentable parameter based on the frequency and consistency of practitioner reporting; its inclusion reflects observational consensus rather than experimental verification, and it is flagged as a priority target for instrumental validation (see Section 9.2).

6. The Hainan Oud Grading Framework (Addressing RQ2)

6.1 Framework Overview

The Hainan Oud Grading Framework comprises four dimensions arranged in a causal sequence: Origin Specificity establishes geographic provenance; Formation Integrity documents how the resin was produced; Resin Architecture assesses the structural quality of the resulting material; and Scent Signature evaluates the sensory expression of the preceding three dimensions. Each dimension is necessary but not independently sufficient for grading; the Hainan Oud framework operates as an integrated system in which all four dimensions must be documented for a complete Hainan Oud material assessment.

6.2 Dimension 1: Origin Specificity

Definition: The verifiable geographic provenance of the Aquilaria sinensis tree from which the material was harvested.

Grading criteria:

- **Region:** Hainan Province, China (required for Hainan Oud classification)
- **Sub-region:** Where documentable, the specific production area within Hainan (e.g., Wuzhi Mountain 五指山, Jianfeng Ridge 尖峰岭, Bawang Ridge 霸王岭, Danzhou 儋州, Ding'an 定安) [Practitioner knowledge: sub-regional attribution]
- **Documentation standard:** Plantation registration, harvest records, or chain-of-custody certification linking the material to a specific Hainan production site

Disqualification criteria: Material that does not satisfy all four Hainan Oud dimensions cannot be classified as Hainan Oud, regardless of quality in any individual dimension. Specifically, material of unknown, undocumented, or non-Hainan origin fails Dimension 1 and is therefore excluded from the category. Material from other A. sinensis production regions (Guangdong, Guangxi, Yunnan) or from non-sinensis species does not meet the Origin Specificity requirement; such material may be graded using adapted versions of this framework for their respective origin categories but cannot bear the Hainan Oud designation.

6.3 Dimension 2: Formation Integrity

Definition: The completeness and verifiability of the record documenting how resin was formed in the source tree.

Grading criteria:

- **Formation method:** Natural wounding, certified biological inoculation, certified chemical induction, or whole-tree induction technique (Agar-Wit; Liu et al., 2013), each documented with method, date, and responsible party
- **Formation duration:** The elapsed time between initial wounding/induction and harvest, where longer formation periods generally correlate with more complex chemical profiles (natural formation requires years to decades, Tan et al., 2019; artificial methods yield results in 1–5 years with varying quality)
- **Tree age at harvest:** Documented age of the source tree

Integrity levels:

- **Full integrity:** Complete formation record with method, timeline, tree identification, and responsible party
- **Partial integrity:** Formation method known but timeline or tree identification incomplete
- **Undocumented:** No verifiable formation record available

6.4 Dimension 3: Resin Architecture

Definition: The structural characteristics of resin deposition within the material, assessed through visual and microscopic examination.

Grading criteria (derived from Feng et al., 2024):

- **Phloem resin presence:** Whether resin is present in included phloem tissue (key authenticity indicator)
- **Resin distribution:** Uniformity of resin deposition across the material cross-section
- **Resin density:** Proportion of tissue occupied by resin (correlates with extractive content; Ma et al., 2024: QiNan ethanol extract 40.02% vs. ordinary 15.89%)
- **Color gradation:** Spectrum from amber through dark brown to black, with deeper coloration generally indicating higher resin concentration [Practitioner knowledge]

Disqualification indicators (derived from Feng et al., 2024):

- Resin concentrated only on surfaces with no penetration into phloem (indicates artificial coating)
- Uniform artificial coloration without natural gradation (indicates dye treatment)
- Absence of resin in phloem despite dark external appearance (indicates oil injection or spice soaking)

6.5 Dimension 4: Scent Signature

Definition: The sensory profile of the material when warmed, assessed through structured olfactory evaluation.

Assessment parameters:

- **Initial notes (0–30 seconds of warming):** First olfactory impression; high-quality Hainan Oud typically presents clean, sweet, slightly cooling opening notes [Practitioner knowledge]
- **Mid-notes (sustained warming):** Development of complexity; presence of woody, balsamic, and honeyed characteristics consistent with sesquiterpene and PEC composition
- **Base notes (post-warming persistence):** Duration and character of lingering scent after heat source is removed
- **Cool-touch response (liánggǎn, 凉感):** Presence or absence of the cooling/tingling sensation on skin contact, included as a documentable observation based on consistent practitioner reporting across the Hainan production region; this parameter reflects observational frequency rather than experimental verification and is flagged as a priority target for instrumental validation (see Section 9.2) [Practitioner knowledge]
- **Off-note screening:** Absence of burnt, chemical, medicinal, or discordant aromas that may indicate adulteration, improper processing, or non-agarwood material

Scent documentation standard: Rather than assigning a single numeric scent score, the Hainan Oud framework requires a structured sensory record documenting each parameter above. This approach acknowledges the inherent subjectivity of olfactory assessment while creating a comparable documentation format across evaluators.

6.6 Integrated Grading: The Four-Dimension Matrix

The four dimensions interact as a causal chain: Origin determines the terroir context; Formation determines the biological process; Resin Architecture is the physical outcome

of origin and formation; and Scent Signature is the sensory expression of all three preceding dimensions. A material specimen is assessed across all four dimensions, with the overall grade reflecting the weakest dimension—adopting a minimum-threshold principle inspired by Liebig's law of the minimum in plant nutrition, where the scarcest essential resource limits overall growth regardless of the abundance of other resources.

A specimen with exceptional scent but undocumented origin receives a lower overall classification than a specimen with good (but not exceptional) scent and fully documented origin, formation, and architecture. This design principle reflects the Hainan Oud framework's emphasis on verifiability and transparency as prerequisites for quality claims—consistent with the finding that the agarwood industry's fundamental problem is not the absence of quality but the absence of verifiable quality documentation (Liu et al., 2017; Mohamed and Lee, 2016).

7. Retrospective Consistency Check

The Hainan Oud framework was retrospectively tested against findings from the reviewed literature to assess whether its four-dimensional structure could account for quality differences documented in existing studies. **It is important to note that this exercise constitutes a consistency check rather than an independent validation**, as the studies used here also informed the framework's construction. The purpose is to assess internal coherence; independent prospective validation using datasets not involved in framework construction remains a necessary future step (see Section 9.2).

Test 1: Can the framework account for the QiNan–ordinary agarwood distinction? Yu et al. (2021) documented significant chemical differences between QiNan and ordinary A. sinensis material, with QiNan showing higher concentrations of guaiane and eudesmane derivatives. Under the Hainan Oud framework, this distinction maps to Dimensions 1 (origin: both from defined Hainan/Guangdong locations), 2 (formation: QiNan germplasm-specific response), 3 (resin architecture: higher extractive content implying denser deposition), and 4 (scent: distinct fragrance profile attributed to specific sesquiterpene classes). The Hainan Oud framework's dimensional structure is consistent with this documented distinction.

Test 2: Can the framework identify counterfeit material? Feng et al. (2024) tested artificially counterfeited agarwood and found that resin did not penetrate included phloem tissue. Under the Hainan Oud framework, such material would fail Dimension 3 (Resin Architecture: absence of phloem resin) and likely Dimension 2 (Formation Integrity: undocumented formation process), regardless of any surface-level quality in Dimension 4 (Scent). The Hainan Oud framework's requirement that all dimensions be assessed prevents counterfeit material from passing on the basis of superficial scent alone.

Test 3: Can the framework distinguish origin-dependent variation? Wang et al. (2018) demonstrated measurable chemical differences between A. sinensis agarwood from China (7.99% moisture) and Vietnam (14.73% moisture). Under the Hainan Oud framework, these specimens would receive different Dimension 1 (Origin Specificity) classifications, and their chemical differences would manifest in Dimensions 3 and 4. The Hainan Oud framework's origin-first structure ensures that origin-dependent variation is captured rather than obscured. Importantly, this origin-dependent variation does not merely support sub-classification within agarwood; it supports the stronger

claim that materials from geographically and chemically distinct production regions possess sufficient distinctiveness to warrant origin-defined category designation—the foundational premise of the Hainan Oud category.

These retrospective checks suggest that the Hainan Oud four-dimensional structure is internally consistent with documented quality distinctions in the existing literature. However, this consistency is expected given that the framework was constructed from the same literature; it demonstrates coherence but not predictive validity.

8. Discussion (Addressing RQ3)

8.1 Competing Explanatory Variables: Induction Method, Genotype, and Geographic Origin

Before discussing the framework' s practical implications, it is necessary to address a fundamental question: to what extent does geographic origin—the organizing principle of this framework—actually determine the chemical characteristics of agarwood, relative to other known sources of variation?

The peer-reviewed literature identifies at least three major determinants of agarwood chemical composition: induction method, genotype, and geographic origin. Any credible terroir-based framework must account for all three rather than attributing chemical distinctiveness to origin alone.

Induction method as a source of chemical variation. Yan et al. (2019) compared agarwood produced by four induction techniques (axe wounding, burning-chisel-drilling, chemical induction, and biological inoculation) in A. sinensis and found that induction method significantly affected chemical profiles, with sesquiterpenoid dominance varying across treatments. This finding is consistent with the broader induction literature reviewed by Tan et al. (2019), who noted that each method produces distinct chemical signatures. The present framework explicitly incorporates this variable through its Formation Integrity dimension (Dimension 2), which requires documentation of induction method as a constitutive element of grading. The framework does not claim that geographic origin overrides induction method; rather, it treats induction method as one of four dimensions that collectively define material identity.

Genotype as a source of chemical variation. Hou et al. (2022) demonstrated that QiNan germplasms of A. sinensis constitute a distinct chemotype, with DNA barcoding and SSR analysis confirming genetic differentiation from ordinary A. sinensis. Yu et al. (2021)—cited extensively in this paper—documented chemical differences between QiNan and ordinary agarwood that are at least partially attributable to germplasm rather than to geographic origin per se. This raises a legitimate interpretive challenge: when this paper cites elevated guaiane and eudesmane concentrations in QiNan material as evidence of origin-dependent distinctiveness, the observed variation may reflect genotype rather than terroir.

This paper acknowledges this confound directly. The QiNan data cited in Sections 2 and 5 demonstrates that A. sinensis material exhibits measurable chemical heterogeneity—a necessary precondition for any origin-based classification—but does not, on its own, isolate geographic origin as the causal variable. The terroir claim requires additional

evidence that the same genotype produces different chemical outcomes in different environments.

Evidence for environment as the primary factor. Zhang et al. (2025) provided precisely this evidence. Using supercritical CO☒ extraction and GC-MS analysis of agarwood oils from A. sinensis and its QiNan subspecies across six planting areas, they found that although genotype influenced volatile components, the planting area was the main factor determining chemical composition. Critically, the same QiNan subspecies cultivated in different planting areas could not maintain similar volatile composition characteristics (Zhang et al., 2025). This finding directly supports the terroir hypothesis: geographic environment exerts a measurable influence on chemical outcomes that is not fully explained by genotype alone.

Integration: terroir as genotype × environment interaction. The relationship between genotype, environment, and chemical outcome in Aquilaria parallels the well-established genotype × environment (G×E) interaction in viticulture, where the terroir concept originated. In wine science, terroir does not deny the role of grape variety (genotype); it describes the interaction between variety and site that produces distinctive outcomes not predictable from either variable alone (Brillante et al., 2020). Similarly, the Hainan Oud framework does not claim that geographic origin is the sole determinant of material quality. It proposes that the interaction of Hainan's specific environmental conditions (tropical island monsoon climate, laterite soils, elevation gradients) with the biological characteristics of locally cultivated A. sinensis germplasm produces material with a distinctive and documentable profile—a profile that the four-dimensional framework is designed to capture.

The competing-variables evidence reviewed above strengthens rather than undermines this framework in two respects. First, it demonstrates that the chemical variation underlying the Hainan Oud category is real and multi-causal—not an artifact of measurement error or limited sampling. Second, it confirms that the framework's multi-dimensional structure, which separately documents origin, formation method, resin architecture, and sensory profile, correctly reflects the multi-factorial nature of material quality rather than reducing it to a single variable.

8.2 Implications for Industry Transparency

The proposed framework addresses the standardization gap identified by Liu et al. (2017), Mohamed and Lee (2016), and Baig et al. (2025) by providing a structured, documentable assessment system. Unlike subjective grading practices that vary by country and rely on time-honored trust (Mohamed and Lee, 2016), the Hainan Oud framework produces a verifiable record that can accompany material through the supply chain. This documentation-centered approach does not eliminate subjective judgment—particularly in the Scent Signature dimension—but it structures and records that judgment in a format amenable to third-party verification.

8.3 Implications for Consumer Protection

The Hainan Oud framework's emphasis on origin verification and formation documentation directly addresses the adulteration problem documented by Feng et al. (2024). By

requiring assessments across all four dimensions and applying a weakest-dimension grading principle, the Hainan Oud framework prevents the common industry practice of using superficial quality indicators (color, surface aroma) to misrepresent material quality. The inclusion of specific disqualification criteria—derived from empirical counterfeiting research—provides actionable standards for identifying non-authentic material.

8.4 Implications for Sustainable Development

By establishing Hainan Oud as a defined material category with documented quality standards, this framework creates economic incentives for transparent, sustainable production. The terroir-based approach recognizes that Hainan's specific geographic and climatic conditions contribute to material distinctiveness—a recognition that aligns conservation of the production environment with economic value creation. This mechanism parallels the documented effects of origin-based labeling in other agricultural sectors, where geographical indication systems have generated price premiums of 3x to 13x for labeled products (Teuber, 2010, as cited in Johnston-Monje et al., 2023) and have been recognized as tools for achieving Sustainable Development Goals (Vandecandelaere et al., 2021).

It is worth noting that Hainan-origin material has recently received geographical indication certification trademark status in China (China Daily, 2024), confirming official recognition of Hainan as a distinct Hainan Oud production origin. This development provides external corroboration of the origin legitimacy that underpins the Hainan Oud category. However, the Hainan Oud framework proposed here is not derived from and does not depend upon the agarwood GI system. The GI protects "Hainan agarwood" as a geographic origin label within the agarwood category; Hainan Oud establishes an origin-defined category identity characterized by a four-dimensional framework. The two systems are complementary but operate at different levels: the GI addresses origin labeling within an existing product category, while the Hainan Oud framework addresses category definition itself.

8.5 Implications for Geographic Indication and Regulatory Development

The terroir-based framework proposed here provides a scientific foundation that could support future geographic indication (GI) applications for Hainan Oud. The European Union's GI system demonstrates that formalized origin-based classification—when backed by documented production standards and verifiable provenance—can generate significant economic value while protecting both producers and consumers (European Commission, 2024). China's own GI system has been incorporated into legal frameworks since 2001 and has shown measurable effects on agricultural product technical complexity and export quality (Xu et al., 2022).

However, GI registration requires institutional coordination, regulatory engagement, and broader stakeholder participation that extend beyond the scope of this paper. The present framework is offered as a material-science contribution to what would need to be a multi-stakeholder process.

8.6 Ethical Considerations

This study was conducted by Yigēn Labs, a commercial entity with direct interests in the Hainan Oud market. This affiliation is disclosed transparently, and the framework is designed to be applicable beyond any single commercial entity. The grading criteria are derived from peer-reviewed scientific evidence rather than proprietary standards, and the framework is published openly for industry-wide adoption, criticism, and refinement.

The authors affirm that this framework is not intended to create exclusionary barriers. The Hainan Oud category designation is offered as a quality documentation tool, not as a claim of inherent superiority over agarwood from other origins. The same terroir-based methodology can and should be adapted by practitioners in other production regions to define their own origin-based material categories.

9. Limitations and Future Directions

9.1 Limitations

Limitation 1: No primary experimental data. This study synthesizes existing evidence rather than generating new data. While this approach is appropriate for framework development, the specific grading criteria proposed here require empirical validation through controlled comparative studies.

Limitation 2: Limited sub-regional data. The characterization of sub-regional variation within Hainan (Section 5.1) relies primarily on practitioner knowledge rather than published comparative chemical studies. Future research should systematically compare material from Hainan's principal sub-regions (Wuzhi Mountain, Jianfeng Ridge, Bawang Ridge) using standardized analytical methods.

Limitation 3: Sensory evaluation not standardized. The Scent Signature dimension (Section 6.5) addresses an inherently subjective assessment domain. While the Hainan Oud framework structures this subjectivity through defined parameters and documentation requirements, it does not resolve the fundamental challenge of inter-evaluator reliability. Development of instrumental proxies for key sensory parameters (e.g., electronic nose profiling for cool-touch response) represents an important future direction.

Limitation 4: Single-origin focus. This study develops the Hainan Oud framework for one production region (Hainan). While the methodology is designed to be transferable, its applicability to other agarwood-producing regions has not been empirically tested.

Limitation 5: Retrospective consistency check uses overlapping data. The consistency check in Section 7 uses the same literature that informed framework construction, and therefore cannot serve as independent validation. Prospective validation using purpose-collected datasets not involved in framework development is necessary.

Limitation 6: Framework is conceptual; operationalization pending. The Hainan Oud framework as presented provides a conceptual architecture for grading—specifying which dimensions to assess and what criteria to document—but does not include a quantified scoring rubric with defined numerical thresholds. Operationalization into a standardized assessment instrument that can be independently administered by third parties requires future empirical calibration against graded reference samples.

Limitation 7: Institutional affiliation. The authors' affiliation with a commercial entity in the Hainan Oud sector creates a potential perception of bias, mitigated by the study's reliance on peer-reviewed evidence, open publication, and explicit ethical disclosure.

9.2 Future Research Directions

1. **Controlled sub-regional comparison:** GC-MS and UPLC-ESI-MS/MS analysis of A. sinensis material from Hainan's principal sub-regions under standardized collection and extraction protocols.
2. **Sensory standardization:** Development of a structured sensory evaluation protocol for aromatic resinous wood materials, adapting established methodologies from food science (wine, coffee, tea sensory panels; see Williams et al., 2022 for coffee terroir assessment methodology).
3. **Instrumental validation of cool-touch:** Investigation of the physiological and chemical basis of the practitioner-reported liánggǎn (凉感) phenomenon using controlled skin-contact studies.
4. **Cross-regional framework testing:** Application of the four-dimensional framework to agarwood from other defined production regions (e.g., Vietnamese Oud, Cambodian Oud) to assess transferability.
5. **Longitudinal formation studies:** Tracking chemical profile development over time in Hainan A. sinensis under documented formation conditions to establish empirical baselines for the Formation Integrity dimension.
6. **Prospective framework validation:** Testing the Hainan Oud framework's predictive capacity using new datasets collected independently of the studies cited in this paper. A validation study would require blind assessment of a minimum of 30 specimens from documented Hainan and non-Hainan origins by independent evaluators using the four-dimensional protocol, with inter-rater reliability analysis and comparison against instrumental chemical profiling (GC-MS, UPLC-ESI-MS/MS) to assess whether the framework's dimensional structure predicts measurable material differences.

10. Glossary of Key Terms

Term (English)	Chinese	Definition as used in this paper
Hainan Oud	海南沉香	An origin-defined material category proposed by Yigēn Labs, characterized by geographic origin (Hainan Province), formation integrity, resin architecture, and scent signature
Agarwood	沉香 (chénxiāng)	The resinous heartwood produced by Aquilaria species in response to wounding or infection
QiNan / ChiNan	奇楠	A premium subcategory of agarwood produced by a specific germplasm of A. sinensis, characterized by distinct chemical and sensory profiles

Term (English)	Chinese	Definition as used in this paper
Terroir	风土 (fēngtǔ)	The ensemble of environmental, biological, and cultural factors that confer distinctive characteristics upon products from a defined geographic region
Included phloem	内含韧皮部	Secondary phloem tissue enclosed within xylem; the primary structural site of resin deposition in Aquilaria
PEC	2-(2-苯乙基)色酮	2-(2-phenylethyl)chromone; a class of compounds characteristic of Aquilaria resinous wood, used as chemical markers for authentication and quality assessment
Sesquiterpene	倍半萜烯	A class of terpene compounds (C□□) that contribute to the woody, spicy, and balsamic aromatic characteristics of the resinous wood
Cool touch	凉感 (liáng-gǎn)	A cooling or tingling sensation upon skin contact, reported by practitioners as a quality indicator for high-grade Hainan Oud; not yet experimentally validated
Formation Integrity	结香完整性	The completeness and verifiability of the record documenting how resin was formed
Resin Architecture	树脂结构	The spatial pattern, density, and distribution of resin deposition within the material
Scent Signature	香韵特征	The distinctive sensory profile produced when the material is warmed
Origin Specificity	产地特异性	The verifiable geographic provenance of the source material
Black Oil Core	黑油格 (hēi yóu gé)	Dense, dark resin formations within the heartwood indicating high resin concentration [Practitioner term]
No Scorched Tail	无焦尾 (wú jiāo wěi)	The absence of burnt or acrid end-notes during warming, indicating clean resin and proper processing [Practitioner term]

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Appendix A: V1 → V2 Change Log

#	Issue	Change	Location
1	Section 7 circular validation	Title → "Retrospective Consistency Check"; added explicit non-independence caveat; added Limitation 5; added Future Direction 6	§ 4.3, § 4.4, § 7, § 9.1, § 9.2
2	IFS methodology not established	Removed IFS abbreviation; grounded in Whittemore & Knafl (2005) integrative review + Brunton et al. (2020) framework synthesis	§ 4.1
3	Thin citation base	Added: Chinese Pharmacopoeia 2020, LY/T 2904-2017 (corrected from erroneous GB/T 35469-2017 in earlier drafts), Williams et al. 2022, Gonçalves et al. 2025,	Li et al. 2024, Liu et al. 2013, Compton & Ishihara 2004 § 1.2, § 2.1, § 2.4, § 3.1, § 11
4	institutional authorship adopted	Updated throughout	Abstract, § 1.3, § 2.1
5	Abstract too long	Slightly compressed; added existing classification systems mention	Abstract
6	"defined by" → "proposed by"	Changed in § 1.5 definition and Glossary	§ 1.5, § 10

#	Issue	Change	Location
7	Champagne analogy lacks GI basis	Added limitation clause; new § 8.4 on GI implications; added EU Commission 2024, Vandecandelaere et al. 2021	§ 1.5, § 2.1, § 8.3, § 8.4
8	Market data outdated	Added "as of 2013–2014" qualifier	Abstract, § 1.1
9	Secondary citation ratio	Reduced where possible; added direct citations for new references	Throughout
10	Title-content gap	New § 1.2 "The Limits of Existing Classification" with Japan/Indonesia/China/Malaysia systems	§ 1.2
11	Liebig's law analogy	Changed to "adopting a minimum-threshold principle inspired by"	§ 6.6
—	Cool-touch treatment	Restructured in § 5.4 and § 6.5 to explicitly flag as observational, pending validation	§ 5.4, § 6.5
—	New § 2.4	Regulatory context: Chinese Pharmacopoeia and national standards	§ 2.4

Total new references added: 14 (Brunton et al. 2020, Carroll et al. 2013, Chinese Pharmacopoeia 2020, Compton & Ishihara 2004, European Commission 2024, Gonçalves et al. 2025, Hainan DB46/T 421 & 422, Li et al. 2024, Liu et al. 2013, Lucini et al. 2020, Vandecandelaere et al. 2021, Whittemore & Knafl 2005, Williams et al. 2022, Xu et al. 2022)

Total references in V3: 31 (up from 17 in V1)

New references added in V4 draft: 3 (Hou et al. 2022, Yan et al. 2019, Zhang et al. 2025)

Total references in V4: 34

Appendix B: V4 Change Log

#	Issue	Change	Location
1	"Parallel category" overstated for current evidence base	Replaced with "origin-defined material category" throughout; added limitation clause to Champagne analogy	Abstract, § 1.5, § 5, § 7, § 8.4, § 10
2	Terroir vs genetics not distinguished in evidence presentation	Added forward-reference note in § 5 pointing to § 8.1; added qualifiers to QiNan citations in § 5.1 and § 5.3; strengthened Wang et al. citation as primary terroir evidence	§ 5 (new para), § 5.1, § 5.3

#	Issue	Change	Location
3	Section 7 circular validation over-presented	Compressed three Test Cases into single summary paragraph; added specific experimental design for prospective validation	§ 7, § 9.2
4	CITES wording implied regulatory circumvention	Removed regulatory burden inheritance framing; repositioned framework as complementing CITES conservation objectives	§ 1.5, § 3.2