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# Agarwood in peril: A systematic review of Philippine *Aquilaria* Lam. (Thymelaeaceae) integrating taxonomy, conservation, and pharmacology

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**ABSTRACT**

The genus *Aquilaria* Lam. (Thymelaeaceae) produces agarwood, one of the world's most commercially valuable non-timber forest products, yet the species-level evidence underpinning conservation and trade governance in the Philippines—a megadiverse archipelago with high endemism and active CITES-regulated commerce—remains fragmented. Following PRISMA 2020 guidelines, 165 records were identified, including 150 from six bibliographic databases and search platforms and 15 from other sources. After removal of 78 duplicates, 87 records were screened; 40 reports underwent full-text assessment, and 26 primary studies met the final inclusion criteria. Of the 21 accepted *Aquilaria* species recognized globally by Plants of the World Online (POWO), nine are native to the Philippines, whereas Co's Digital Flora of the Philippines (CDFP) recognizes eight; the discrepancy arises from the treatment of *A. decemcostata*, which POWO accepts as a distinct species but CDFP places within the synonymy of *A. cumingiana*. All eight CDFP-recognized species carry national threat designations, whereas five Philippine endemic taxa remain Data Deficient under the IUCN Red List, highlighting substantial gaps in contemporary population and distributional evidence. Pharmacological and phytochemical evidence is concentrated in *A. filaria* and *A. malaccensis*, while *A. cumingiana*, despite active cultivation in the Philippines, lacks a published phytochemical profile from Philippine-sourced agarwood. Ethnobiological evidence was similarly limited, with little documented information on community-specific uses, local ecological knowledge, resource management, or livelihood relationships involving Philippine *Aquilaria*. Seven priority knowledge gaps spanning integrative taxonomy, distributional and population surveys, phytochemical characterization, agarwood induction, regulatory alignment, and community-centered resource use were identified. This review provides, to our knowledge, the first integrated species-level synthesis of Philippine *Aquilaria* and establishes an evidence base for conservation governance, regulated trade, and sustainable resource development.

**Keywords:** CITES Appendix II; Conservation governance; Data deficiency; Endemic biodiversity; Non-detriment finding; 2-(2-Phenylethyl)chromone..

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## SIGNIFICANCE STATEMENT

This manuscript provides the first integrated species-level synthesis of Philippine *Aquilaria* Lam., a threatened genus that produces agarwood, one of the world's most valuable non-timber forest products. Using a PRISMA-guided review, the study integrates taxonomic, conservation, trade-governance, and pharmacological evidence to clarify major gaps affecting sustainable management and CITES non-detriment findings. It highlights unresolved species delimitation issues, particularly the treatment of *Aquilaria decemcostata*, and reveals substantial divergence between national and global conservation assessments: all eight CDFP-recognized Philippine species carry national threat designations, with seven classified as Endangered and *A. malaccensis* as Critically Endangered, while five Philippine endemic taxa remain Data Deficient under the IUCN Red List. The review also identifies uneven phytochemical and bioactivity research, including the absence of published chemical profiles from Philippine *A. cumingiana* populations. The review further identifies a major ethnobiological gap: Philippine-specific evidence remains scarce regarding community use, local ecological knowledge, resource management, livelihood relationships, and benefit-sharing associated with *Aquilaria*. By linking a nationally focused case study to broader issues in tropical biodiversity conservation, regulated trade, and natural-product development, this work provides a framework relevant to other agarwood-producing countries facing similar challenges in species documentation, conservation policy, and sustainable resource use.

## INTRODUCTION

Agarwood, the resin-saturated heartwood generated in response to damage or microbial infections in trees of the genus *Aquilaria* Lam. (Thymelaeaceae), is among the world's most valuable non-timber forest products. At prices of up to USD 100,000 $kg^{-1}$ for top-grade resin, it supports a luxury industry for perfume, incense, and traditional medicine throughout the Middle East, East Asia, and Southeast Asia (Hashim et al. 2016; Thompson et al. 2022). Despite the high commercial importance of this 21-species genus, the scientific evidence available at the species level remains markedly uneven. Chemical and pharmacological investigations have concentrated primarily on a limited number of commercially important species, whereas the ecology, geographic distribution, phytochemistry, and pharmacological properties of many other *Aquilaria* species remain poorly characterized (Gao et al. 2019; Thompson et al. 2022). This disparity is particularly relevant in countries where high species diversity and endemism coincide with substantial habitat and harvest pressures.

The Philippines represents an important example of this disparity. As one of the world's megadiverse countries and a major biodiversity hotspot experiencing severe biodiversity loss (Myers et al. 2000; Posa et al. 2008), the country supports nine of 21 accepted species of *Aquilaria* according to Plants of the World Online (POWO 2026), all of which are native to the Philippines and six of which are endemic. This diversity occurs against a background of extensive forest loss, directly increasing conservation concern for species with restricted distributions and limited ecological information. Forest coverage decreased from approximately 70% of the total national land area in the early 20th century to approximately 24% by 2020, with average annual loss rates of approximately 47,000 ha (Forest Management Bureau 2020). In addition to habitat loss, unauthorized harvesting and trade of wild agarwood have been reported across major Philippine islands, including Luzon, Mindanao, and Leyte (Sy and Melgar 2023). Available evidence on these activities does not establish the socioeconomic circumstances or motivations of individual harvesters; therefore, no attribution to specific communities or livelihood groups is made here. Despite the protection afforded to Philippine wildlife under Republic Act 9147 and the regulation of all species of *Aquilaria* under Convention on International Trade in Endangered Species (CITES) Appendix II, the convergence of high endemism, habitat loss, continuing harvest pressure, and incomplete species-level knowledge underscores the need for a stronger scientific basis for conservation and sustainable management of Philippine *Aquilaria*.

Global syntheses on *Aquilaria* have made foundational contributions. Ding Hou's (1960) Flora Malesiana treatment established the taxonomic baseline for Malesian species. Hashim et al. (2016) documented the pharmacology and ethnomedicine of *Aquilaria* spp. across Ayurvedic, traditional Chinese medicine, and Southeast Asian systems. Gao et al. (2019) classified 367 compounds from the four most-studied species into 11 molecular skeleton types, defining the genus's chemical space. Li et al. (2021) subsequently provided the most comprehensive chemistry-to-biosynthesis account of agarwood natural products, covering over 300 compounds and their biological activities; Wang et al. (2021) synthesized global data on *Aquilaria* species distribution, phytochemical profiles, pharmacological uses, and grading and induction methods. Thompson et al. (2022), in the most comprehensive trade-and-conservation treatment to date, identified the non-detriment finding deficit as the most pervasive CITES compliance risk across all range states. However, none

of these syntheses resolves the species-level questions most consequential for Philippine forest governance, such as which taxa are present, how they are distributed, what pharmacological value they hold, and whether the existing regulatory framework provides adequate protection.

Three structural deficits define the current state of knowledge for Philippine *Aquilaria* and motivate the present review. First, a taxonomic discordance exists between the globally authoritative POWO (2026) and the nationally authoritative Co's Digital Flora of the Philippines (CDFP; Pelser et al. 2011 onwards) over the number of Philippine species: POWO recognizes nine, CDFP recognizes eight, with the contested taxon being *Aquilaria decemcostata* Hallier f., a Luzon endemic known from a single type collection. Although this discrepancy is taxonomic in origin, its implications extend to species-level conservation assessment and governance because the recognition of individual taxa affects how their distributions, conservation status, and regulatory requirements are evaluated.

Second, conservation assessments remain markedly discordant across national and international frameworks. All eight *Aquilaria* species recognized by CDFP carry national threat designations, with seven classified as Endangered and *A. malaccensis* as Critically Endangered, whereas five of the six POWO-recognized Philippine endemics remain Data Deficient under the IUCN Red List. This contrast highlights the scarcity of contemporary population and distributional evidence underlying species-level conservation assessment despite precautionary national recognition. Recent floristic records, including those reported by Romeroso et al. (2024), further demonstrate that the documented distributions of Philippine Thymelaeaceae continue to be refined and that species-level monitoring remains incomplete. Third, documented pharmacological evidence is restricted to three species — *A. cumingiana* (Decne.) Ridl., *A. filaria* (Oken) Merr., *and A. malaccensis* Lam. — while the five Data Deficient endemic species have no phytochemical or biological-activity data in the literature included in this review, and the most commercially cultivated species (*A. cumingiana*) has no published agarwood chemical profile from Philippine populations. Taken together, these taxonomic, distributional, conservation, and pharmacological limitations demonstrate the absence of an integrated species-level evidence base for Philippine *Aquilaria*.

No systematic review currently consolidates, across all recognized Philippine *Aquilaria* species, the taxonomic framework under the two principal authorities, sub-country distributional evidence from verified herbarium records, conservation status under national and international frameworks, and species-resolved pharmacological and economic evidence. This study therefore addresses these gaps by conducting a systematic review of the recognized native species of Philippine *Aquilaria* based on the PRISMA 2020 guidelines. The review is designed to address four specific objectives: (1) to create a dual-authority species list for Philippine *Aquilaria* using the POWO and CDFP databases and document the taxonomic basis, nomenclature history, and implications of governance associated with any discrepancies among the authorities; (2) to gather verified sub-country-level distribution data from herbarium specimens, determine elevation ranges, and assess consistencies and discrepancies in conservation status based on the IUCN Red List, the current Philippine national threatened-plant framework under DAO 2026-20, and CITES Appendix II frameworks; (3) to synthesize the evidence base at the species level for pharmacology, phytochemistry, documented uses, and economics; and (4) to establish a structure and priority classification system for research priorities that identify the necessary evidence to address the seven key knowledge gaps that currently limit evidence-based conservation, CITES compliance, and sustainable commercial development of Philippine *Aquilaria*. Although the present review is primarily taxon-centered, sustainable conservation of commercially utilized *Aquilaria* also requires consideration of the communities and stakeholders involved in its use, cultivation, and management, an area that remains poorly represented in the available Philippine literature.

## MATERIAL AND METHODS

### Review Design and Reporting Framework

The systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al. 2021). The completed PRISMA 2020 checklist, indicating where each reporting item is addressed, is provided in Additional File 1. The PRISMA 2020 flow diagram (Figure 1) illustrates the stages of identification, screening, and inclusion of studies for this review. The review was not registered, and no formal review protocol was prepared. The study unit is the Philippine species of *Aquilaria*, and the primary outcomes of interest are: (i) taxonomic status under two authorities; (ii) sub-country distribution and elevation limits; (iii) IUCN conservation category, national conservation status under DAO 2026-20, and international trade status under CITES; and (iv) all species-specific data on pharmacology, phytochemistry, ethnobotany, and economics.

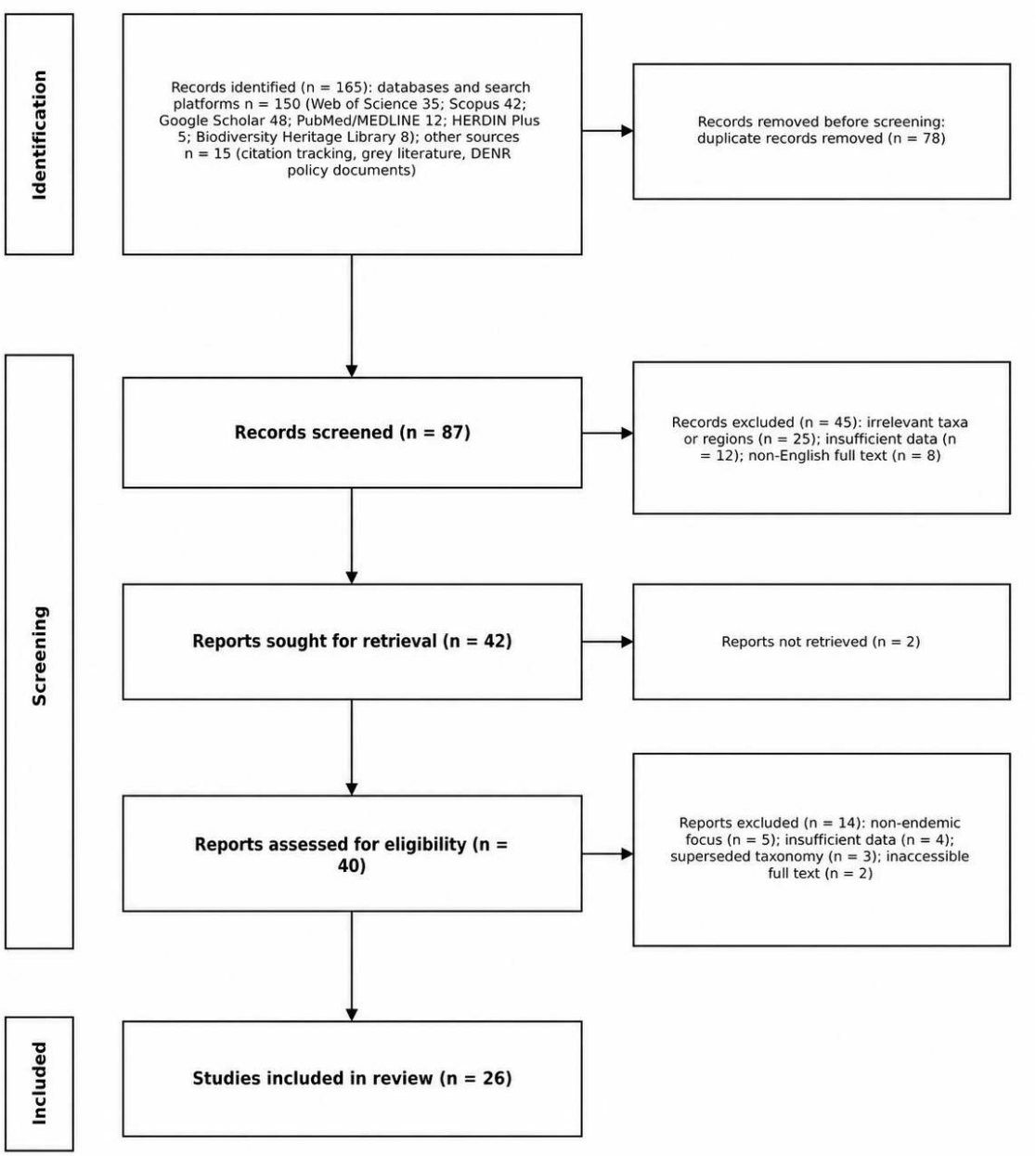



**Figure 1.** PRISMA flowchart of the study selection process.

## Search Strategy and Databases

Systematic literature searches were conducted between January and February 2026 across six bibliographic databases and search platforms, yielding 150 records (Web of Science, n = 35; Scopus, n = 42; Google Scholar, n = 48; PubMed/MEDLINE, n = 12; HERDIN Plus, n = 5; BHL, n = 8), with 15 additional records from other sources. Supplementary sources included the ITTO Technical Series (Thompson et al. 2022), DENR administrative orders, the CITES Species + database (UNEP-WCMC 2024), and the taxonomic databases POWO (2026) and CDFP (Pelser et al. 2011 onwards).

Search terms were organized into two conceptual blocks. The first comprised taxonomic and common-name terms associated with *Aquilaria* and agarwood ("*Aquilaria*," "agarwood," "gaharu," "oud," "lapnisan," and "palisan"), whereas the second comprised country- and locality-related terms ("Philippines," "Philippine," "Filipino," "Luzon," "Mindanao," "Visayas," and "Thymelaeaceae"). Terms within each

block were combined using the Boolean operator OR, and the two blocks were combined using AND. Search syntax and field restrictions were adapted to the requirements of each database or search platform. The complete, reproducible search strategy for every source-full search strings with field tags, applied filters, and the date each search was executed-is provided in Additional File 2. No publication-date restriction was imposed. The search was restricted to records for which an English-language full text could be assessed because validated translation resources were unavailable for consistent extraction and appraisal of technical taxonomic, phytochemical, and pharmacological information. The reference lists of all included studies and of three primary review articles (Hashim et al. 2016; Gao et al. 2019; Thompson et al. 2022) were hand-searched.

## Eligibility Criteria

Records were included if they (i) explicitly reported primary data on one or more *Aquilaria* species with confirmed or putative occurrence in the Philippines; (ii) provided data on taxonomy, distribution, phytochemistry, pharmacological activity, ethnobotany, conservation, ecology, propagation, or agarwood trade; and (iii) were published in peer-reviewed journals, authoritative institutional reports, or primary taxonomic databases. Only records with an assessable English-language full text were included. Records were excluded if they (i) reported exclusively on *Aquilaria* species absent from the Philippines; (ii) were conference abstracts, editorials, popular media, or non-peer-reviewed opinion pieces; (iii) reported only unvalidated in silico predictions; or (iv) could not be verified for authorship, publication venue, or data provenance. Pharmacological claims from non-indexed or predatory journals were excluded regardless of content. Ethnobotanical or traditional-use information was extracted when reported in otherwise eligible records; however, the search strategy was not designed as a dedicated ethnobiological search and therefore was not intended to comprehensively retrieve community-specific or local-use literature.

## Screening, Data Extraction, and Quality Assessment

Two reviewers (G.J.D.A. and J.A.H.M.) independently completed title-and-abstract screening using a standardized eligibility form. The same two reviewers independently assessed the full texts of potentially eligible reports against the predefined eligibility criteria. Disagreements at either stage were resolved through discussion and consensus between the two reviewers. Data from the included studies were extracted into a standardized form and cross-checked by both reviewers against the original reports. Any discrepancies in the extracted data were resolved through discussion and reference to the source article.

The following information was recorded in a structured table for each included study: species name with taxonomic authority; geographic location of collection and/or reported use, including elevation; plant part(s) examined; extraction methodology and solvents; compound classes and individual compounds identified; assay type; quantitative biological-activity endpoints, including $IC_{50}$ (the concentration required to produce 50% inhibition of the measured biological response) or equivalent measures; and conservation or regulatory status under the IUCN Red List, DAO 2026-20, and CITES Appendix II. Pharmacological and phytochemical studies were quality-assessed using five criteria: (i) authenticated voucher or commercially verified plant material; (ii) appropriate positive and negative controls; (iii) quantitative $IC_{50}$ or equivalent endpoints; (iv) inferential statistical analysis; and (v) independent replication. These criteria assessed botanical identity and traceability, assay validity, quantitative interpretability, statistical support, and experimental reproducibility, respectively. Studies failing to satisfy criteria (i)–(iii) were excluded from the pharmacological synthesis, whereas purely phytochemical studies were assessed primarily for botanical authentication and adequate analytical characterization, with assay-specific criteria applied only when biological activity was also evaluated. The per-study results of this appraisal are reported in Additional File 3. Where reported, species uses, ethnobotanical information, and common or vernacular names were recorded descriptively as presented in the included floristic, taxonomic, ethnomedicinal, and related sources. Because the search strategy was not specifically designed to retrieve ethnobiological literature or establish the provenance, cultural meaning, or community consensus associated with vernacular nomenclature and resource use, these data were treated as source-reported information rather than independently validated Local Ecological Knowledge. Accordingly, the absence of such information was not interpreted as evidence of absence of local use, and no community-level attribution or relationship between a vernacular name and a particular species use was inferred unless explicitly documented in the original source.

## Taxonomic Framework and Conservation Status Verification

Species nomenclature was verified against Plants of the World Online (POWO 2026; Royal Botanic

Gardens, Kew) as the global taxonomic reference and Co's Digital Flora of the Philippines (CDFP; Pelser et al. 2011 onwards) as the principal Philippine floristic reference. Growth form followed POWO, while sub-country distributional and elevational data were obtained from CDFP and Ding Hou (1960), supplemented by Romeroso et al. (2024). IUCN conservation categories followed the IUCN Red List Version 2024-2 (IUCN 2024). National conservation categories were extracted using DAO 2026-20, the current Updated National List of Threatened Philippine Plants and Their Categories, which was accessed and verified during manuscript revision (1 August 2026). Current CDFP conservation entries were cross-checked against this updated national framework. CITES status was verified using the Species+ database (UNEP-WCMC 2024). All *Aquilaria* species are included in CITES Appendix II, with the genus-wide listing entering into effect in 2005 (Thompson et al. 2022). The comparison between POWO and CDFP was intended to synthesize existing taxonomic treatments rather than independently reassess species boundaries. No new morphological examination of specimens or molecular phylogenetic analysis was undertaken; consequently, unresolved taxonomic discrepancies were retained as such and interpreted in the context of the available published evidence.

## Data Synthesis

Because the eligible studies were heterogeneous in design, species focus, and outcome measures, quantitative meta-analysis was not considered appropriate. Data were instead synthesized through structured tabulation and narrative comparison within predefined evidence domains. Direct counts were reported for study selection and species-level categories, while observed ranges (minimum–maximum) were reported where relevant for variables such as elevation and quantitative bioactivity endpoints. No pooled effect estimates, inferential statistical comparisons, or formal quantitative synthesis across studies were performed.

The results were grouped into five thematic categories: (1) literature search and study selection, reported in accordance with the PRISMA 2020 flow diagram; (2) species diversity, endemic species, and taxonomy; (3) geographical area of distribution and elevation; (4) conservation status and legal frameworks for each species; and (5) bioactivity and economic potential for each species. Data organization and tabulation were performed using Microsoft Excel for Microsoft 365 (Microsoft Corporation, Redmond, WA, USA), and figures were generated and assembled using Microsoft Excel and Microsoft PowerPoint for Microsoft 365 (Microsoft Corporation, Redmond, WA, USA).

# RESULTS

## Literature Search and Study Selection

The database and supplementary searches yielded 165 records (150 from six bibliographic databases and search platforms and 15 from other sources). After removing 78 duplicate records, 87 records underwent title and abstract screening, of which 45 were excluded (irrelevant taxa or regions, n = 25; insufficient data, n = 12; non-English full text, n = 8). Full-text reports were sought for the remaining 42 records; 2 could not be retrieved, leaving 40 reports to be assessed for eligibility. Of these, 14 were excluded based on full text (non-endemic focus, n = 5; insufficient data, n = 4; superseded taxonomy, n = 3; inaccessible full text, n = 2), yielding 26 primary studies that met the final inclusion criteria (Figure 1). A per-study quality appraisal of the eight pharmacological and phytochemical studies is provided in Additional File 3 (PRISMA 2020, items 11 and 18). All eight studies identified the plant material to the species level and characterized it analytically (criterion i), used appropriate assay controls, including named reference standards (acarbose; acarbose and genistein) in the $\alpha$-glucosidase studies (criterion ii), and reported quantitative $IC_{50}$ endpoints (criterion iii). Accordingly, all eight satisfied the mandatory criteria (i)–(iii), and none were excluded from the pharmacological synthesis (n = 0). Inferential statistics (criterion iv) and independent replication (criterion v) were reported inconsistently and were treated as non-exclusionary indicators of quality.

## Species Richness, Endemism, and Taxonomic Authority Concordance

Nine species of *Aquilaria* Lam. are recognized for the Philippines under the POWO (2026), compared with eight recognized by CDFP (Pelser et al. 2011 onwards). The difference results exclusively from the treatment of *Aquilaria decemcostata* Hallier f.: POWO accepts the taxon at species rank, whereas CDFP, following Ding Hou (1960), places its basionym *Gyrinopsis decemcostata* Hallier f. in the synonymy of *A. cumingiana* (Table 1). The two authorities also differ in the geographic resolution and ancillary conservation information provided, with CDFP supplying substantially more detailed Philippine locality information.

Of the nine POWO-recognized species, six are Philippine endemics: *A. apiculata* Merr., *A. brachyantha* (Merr.) Hallier f., *A. citrinicarpa* (Elmer) Hallier f., *A. decemcostata*, *A. parvifolia* (Quisumb.) Ding Hou, and *A. urdanetensis* (Elmer) Hallier f. The remaining three—*A. cumingiana*, *A. filaria*, and *A. malaccensis*—extend beyond the Philippine

archipelago into Borneo, the Maluku Islands, New Guinea, and Mainland Southeast Asia or South Asia, respectively (Ding Hou 1960; Pelser et al. 2011 onwards). An important growth-form distinction separates *A. brachyantha* and *A. parvifolia*, recorded by POWO as shrubs, from the remaining seven tree species (Table 2).

**Table 1.** Comparison of Philippine *Aquilaria* species recognized under POWO and CDFP, including taxonomic treatment, geographic resolution, and conservation relevance.

| Criterion | POWO (2026) | CDFP (Pelser et al. 2011 onwards) |
|---|---|---|
| **Species count** | 9 Philippine species (accepts *A. decemcostata*) | 8 Philippine species (synonymizes *A. decemcostata* under *A. cumingiana*) |
| **Contested taxon** | *A. decemcostata* Hallier f. accepted at species rank (type: BS 1114 Ramos, Luzon: Laguna, 1912) | *Gyrinopsis decemcostata* Hallier f. treated as heterotypic synonym of *A. cumingiana* (Ding Hou 1960) |
| **Growth form** | *A. brachyantha* and *A. parvifolia* explicitly designated as shrubs; all others trees | Growth form not explicitly stated; Flora Malesiana treatment (Ding Hou 1960) classifies these two taxa as shrubs |
| **Geographic resolution** | WGSRPD Level 3 ("Philippines" as single unit); no sub-country data | Sub-country: island group, province, and in some cases individual island; essential for range-size estimation and national prioritization |
| **Conservation status** | IUCN Red List categories; additionally records VU assessment for *A. decemcostata* absent from CDFP treatment | IUCN categories + current national DAO categories; seven CDFP-recognized species are EN and *A. malaccensis* is CR |
| **Endemism flags** | No formal endemism flag; inferred from single-country TDWG entry | Explicit '* Endemic to the Philippines' flag on qualifying species |
| **Synonymy depth** | Comprehensive; e.g. 13 synonyms for *A. malaccensis* spanning 1783–1893 | National-scope synonymy; fewer historical entries |

**Legend:** CR = Critically Endangered; EN = Endangered; VU = Vulnerable; all Philippine *Aquilaria* species are listed in CITES Appendix II (UNEP-WCMC 2024).

**Table 2.** Philippine species of *Aquilaria* Lam. (Thymelaeaceae): nomenclature, distribution, elevation, conservation status, and economic/medicinal uses

| Scientific Name | Reported Common / Vernacular Name(s) | Major Distribution | Elevation (m) | IUCN Status | DAO 2026-20 | Reported Economic / Medicinal Uses |
|---|---|---|---|---|---|---|
| Native species | | | | | | |
| *Aquilaria apiculata* Merr. *Endemic | lapnisan (Fil.) | MINDANAO: Bukidnon. Dry and mossy forests. | 1,100–1,800 | DD | EN* | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Known from two collections (Bukidnon) only; chemical investigation pending (Ding Hou 1960; Pelser et al. 2011 onwards). |
| *Aquilaria brachyantha* (Merr.) Hallier f. ≡ *Gyrinopsis brachyantha* Merr. *Endemic | lapnisan (Fil.) | LUZON: Cagayan; SAMAR. Low-elevation primary forest. | Low-elevation | DD | EN* | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Conservation status poorly known due to extreme data scarcity (Ding Hou 1960; Pelser et al. 2011 onwards). |
| *Aquilaria citrinicarpa* (Elmer) Hallier f. ≡ *Gyrinopsis citrinicarpa* Elmer *Endemic | lapnisan (Fil.) | MINDANAO: Agusan. Cloud forest. | 1,219 | DD | EN* | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Known from the type collection only (Elmer 13605, Agusan, 1912). No study of its chemical or biological properties was identified in the literature included in this review (Ding Hou 1960; Pelser et al. 2011 onwards). |

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**Table 2.** Philippine species of *Aquilaria* Lam. (Thymelaeaceae): nomenclature, distribution, elevation, conservation status, and economic/medicinal uses

| Scientific Name | Reported Common / Vernacular Name(s) | Major Distribution | Elevation (m) | IUCN Status | DAO 2026-20 | Reported Economic / Medicinal Uses |
|---|---|---|---|---|---|---|
| *Aquilaria cumingiana* (Decne.) Ridl. | palisan, lapnisan (Fil.) | LUZON (Camarines); VISAYAS (Bohol, Leyte, Cebu); MINDANAO (Bukidnon, Agusan, Davao); also Borneo, Maluku Islands (Indonesia). | 200–533 | VU | EN | **Agarwood trade:** Confirmed CITES Appendix II agarwood-producing species; one of two principal Philippine taxa under commercial cultivation via DENR Wildlife Culture Permits. Wild harvest prohibited under RA 9147 (Welgas-Briz 2022; Thompson et al. 2022). **Propagation:** IBA (500 ppm) vegetative propagation trials at Rajah Sikatuna Protected Landscape (Bohol) confirmed mass-production feasibility; longest root 15.25 mm ($p = 0.039$); highest secondary root count 5.19 ($p = 0.028$) (Piñon and Reyes 2021). **Note:** No published phytochemical or pharmacological profile exists for Philippine-sourced agarwood. |
| *Aquilaria decemcostata* Hallier f. ≡ *Gyrinopsis decemcostata* Hallier f. *Endemic [POWO-only taxon; synonymized under *A. cumingiana* in CDFP] | lapnisan (Fil.) | LUZON: Laguna (Dahican River; type locality only; single known collection, BS 1114 Ramos, 1912). Lowland riverine forest. | Not recorded | VU† | NL (not listed; CDFP treats as synonym of *A. cumingiana*) | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Agarwood capacity unconfirmed; no chemical, pharmacological, or ethnobotanical study was identified in the literature included in this review. Not separately listed under DAO 2026-20; protected under CITES Appendix II and RA 9147 as part of the Philippine *Aquilaria* assemblage (Hallier f. 1922; POWO 2026; Thompson et al. 2022). |

*Continued...*

**Table 2.** Philippine species of *Aquilaria* Lam. (Thymelaeaceae): nomenclature, distribution, elevation, conservation status, and economic/medicinal uses

| Scientific Name | Reported Common / Vernacular Name(s) | Major Distribution | Elevation (m) | IUCN Status | DAO 2026-20 | Reported Economic / Medicinal Uses |
|---|---|---|---|---|---|---|
| *Aquilaria filaria* (Oken) Merr. | palisan (Fil.) | EASTERN PHILIPPINES: Bucas Grande, Dinagat, Cagayan de Sulu; also Maluku Islands (Indonesia), Western New Guinea. | 0–1,300 | VU | EN | **Agarwood trade:** Confirmed CITES Appendix II agarwood-producing species; Philippine-sourced material is the subject of six independent phytochemical studies (2017–2024). **Antitumor:** PECs (incl. 4',7-dimethoxy-6-hydroxychromone) antiproliferative against 5 human tumor lines ($IC_{50}$ 25–38 µM); EBV-EA suppression confirmed (Suzuki et al. 2017). **Antidiabetic:** 12 new PEC derivatives; $\alpha$-glucosidase inhibition $IC_{50}$ 7.8–137.7 µM (cf. acarbose 743.4 µM) (Mi et al. 2021); 8,12-epoxyguaiane sesquiterpene (compound 5) $\alpha$-glucosidase inhibition $IC_{50}$ 253.2 µM (Mi et al. 2019). **Anti-inflammatory:** Aquifilarones A–D (PEC dimers); NO inhibition in RAW264.7 macrophages $IC_{50}$ 33.94–57.53 µM (Yang et al. 2023); additional PEC and bi-chromone dimers $IC_{50}$ 22.43–53.88 µM; tyrosinase inhibition $IC_{50}$ 27.71 µM (Yang et al. 2024; Wei et al. 2024). |

*Continued...*

**Table 2.** Philippine species of *Aquilaria* Lam. (Thymelaeaceae): nomenclature, distribution, elevation, conservation status, and economic/medicinal uses

| Scientific Name | Reported Common / Vernacular Name(s) | Major Distribution | Elevation (m) | IUCN Status | DAO 2026-20 | Reported Economic / Medicinal Uses |
|---|---|---|---|---|---|---|
| *Aquilaria malaccensis* Lam. | lapnisan, lanete (Fil.); agarwood, eaglewood (Eng.); gaharu (Malay); oud/oudh (Arabic); jinkoh (Jap.); chenxiang (Chin.) | Bangladesh, Borneo, India, Malay Peninsula, Myanmar, Sumatra; in the Philippines confined to LUZON: Camarines, Camarines Sur. | 0–2,700 | CR | CR | **Agarwood trade:** Principal global commercial agarwood species; top-grade heartwood valued at up to USD 100,000 $kg^{-1}$. Philippine cultivation under DENR Wildlife Culture Permits commenced 2021; wild collection and trade are subject to DENR authorization under RA 9147/DAO 2026-20; international trade is regulated under CITES Appendix II (Sy and Melgar 2023; Thompson et al. 2022). **Traditional medicine:** Ayurvedic, TCM, and Southeast Asian use as postpartum tonic, carminative, and remedy for epilepsy, fever, jaundice, and skin disease (Hashim et al. 2016). **Anti-inflammatory:** Leaf extract (epifriedelanol, luteolin ethers, acacetin, aquilarinenside E) inhibited LPS/IFN-$\gamma$-stimulated NO in RAW264.7; antilipoxygenase $IC_{50}$ 71.6 µg/mL (Eissa et al. 2022). **Antioxidant:** Quercetin, kaempferol, isorhamnetin, myricetin confirmed by LC/Q-TOF-MS; DPPH, ABTS, FRAP activity (Eissa et al. 2022). **Anticancer:** Essential oil cytotoxic against HeLa cells ($IC_{50}$ 79–129 µg/mL); leaf extract active against MCF-7 and K-562 lines; cubenol, agarospirol, aristolene identified as principal sesquiterpenes (Hashim et al. 2016; Chetia et al. 2025). **Antidiabetic:** Essential oil inhibited $\alpha$-amylase ($IC_{50}$ 30.78 µg/mL) and acetylcholinesterase ($IC_{50}$ 13.41 µg/mL) (Chetia et al. 2025). |

*Continued...*

**Table 2.** Philippine species of *Aquilaria* Lam. (Thymelaeaceae): nomenclature, distribution, elevation, conservation status, and economic/medicinal uses

| Scientific Name | Reported Common / Vernacular Name(s) | Major Distribution | Elevation (m) | IUCN Status | DAO 2026-20 | Reported Economic / Medicinal Uses |
|---|---|---|---|---|---|---|
| *Aquilaria parvifolia* (Quisumb.) Ding Hou ≡ *Gyrinopsis parvifolia* Quisumb. *Endemic | lapnisan (Fil.) | LEYTE; LUZON: Camarines Sur, Quezon. Forested slopes. | ∼1,000 | DD | EN* | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Known from four specimens only; agarwood capacity unconfirmed. No pharmacological, phytochemical, or ethnobotanical data were identified in the literature included in this review (Ding Hou 1960; Pelser et al. 2011 onwards). |
| *Aquilaria urdanetensis* (Elmer) Hallier f. ≡ *Gyrinopsis urdanetensis* Elmer *Endemic | lapnisan (Fil.) | LUZON: Benguet; MINDANAO: Agusan del Norte. Mossy forest on exposed ridges. | 1,600–1,700 | DD | EN* | No species-specific uses were identified in the literature included in this review. No pharmacological or phytochemical study meeting the review criteria was identified. Known from two collections only (Elmer 14195, Mt. Urdaneta, 1912). Highest-elevation Philippine *Aquilaria*; no study of its chemical constituents or agarwood potential was identified in the literature included in this review (Ding Hou 1960; Pelser et al. 2011 onwards). |

Nomenclature and distribution follow POWO (2026), Pelser et al. (2011 onwards), Ding Hou (1960), and Romeroso et al. (2024). All *Aquilaria* species are listed under CITES Appendix II (effective 2005; UNEP-WCMC 2024) and are protected under RA 9147. †*Aquilaria* decemcostata is accepted as a distinct species by POWO but is treated within the synonymy of *A. cumingiana* by CDFP and is therefore not separately named in DAO 2026-20; nevertheless, all *Aquilaria* spp. are covered by CITES Appendix II, and DAO 2026-20 provides that Appendix II plants are treated as Endangered for enforcement purposes. Common and vernacular names, as well as reported traditional or medicinal uses, are reproduced from the cited floristic, taxonomic, ethnomedicinal, and related sources and should be interpreted as source-reported information rather than independently validated Local Ecological Knowledge. Broad linguistic or geographic labels are retained only when explicitly reported by the source and should not be interpreted as universal usage within those populations. Where community-specific provenance was unavailable, no attribution to particular knowledge holders or communities was inferred. The occurrence of a vernacular name does not by itself establish a particular use, cultural significance, or one-to-one correspondence with a scientific taxon; likewise, the absence of use information from the included literature should not be interpreted as evidence that local or traditional uses are absent.

## Geographic Distribution and Elevational Range

Philippine *Aquilaria* species occur throughout the three main groups of islands in the archipelago: Luzon, the Visayas, and Mindanao. However, the data indicate a clear species-specific geographic disparity among these species (Table 2). The largest number of *Aquilaria* species has been documented to occur on Luzon. Species such as *A. brachyantha* (Cagayan), *A. cumingiana* (Camarines provinces), *A. decemcostata* (Laguna), *A. malaccensis* (Camarines provinces), *A. parvifolia* (Camarines Sur, Quezon), and *A. urdanetensis* (Benguet) have been identified. Only *A. apiculata* (Bukidnon), *A. citrinicarpa* (Agusan), and (in addition to Luzon) *A. urdanetensis* (Agusan del Norte) have been found on Mindanao. *Aquilaria filaria* populations in the Philippines are restricted to the Eastern Philippines (Bucas Grande, Dinagat, Cagayan de Sulu) and extend the range of this species to the Maluku Islands and western New Guinea (Ding Hou 1960; Pelser et al. 2011 onwards).

The elevation range across all of the Philippine *Aquilaria* species ranges from near sea level up to about 1,800 m above s.l. For example, among the Data Deficient endemics, *A. urdanetensis* is located at the highest elevations (1,600–1,700 m) in mossy forest along exposed ridges. Conversely, *A. apiculata* can be found between 1,100 and 1,800 m in both dry and mossy forests of Bukidnon. In terms of conservation, this elevational stratification has significant implications because the high-elevation mossy forest specialists have an increased risk of being disproportionately affected by climate-driven upward range shift, which will cause a decrease in their distributional area (Pelser et al. 2011 onwards; Thompson et al. 2022).

## Conservation Status and Regulatory Framework Analysis

Under the current Philippine national framework, DAO 2026-20 classifies seven of the eight CDFP-recognized *Aquilaria* species as Endangered and *A. malaccensis* as Critically Endangered. This differs from the IUCN framework, under which *A. malaccensis* is Critically Endangered, *A. cumingiana*, *A. filaria*, and *A. decemcostata* are Vulnerable, and five Philippine endemic taxa remain Data Deficient. *Aquilaria decemcostata* is not separately named in the national list because CDFP treats it within the synonymy of *A. cumingiana*. The principal cross-framework discrepancy therefore concerns the taxonomic treatment of *A. decemcostata* and the contrast between national threat classification and limited population and distributional information for several endemic taxa.

All *Aquilaria* spp. are included in CITES Appendix II, and their international trade is therefore regulated under CITES. For wild-sourced Appendix II specimens, export generally requires appropriate CITES documentation supported by a non-detriment finding demonstrating that the proposed trade would not be detrimental to the survival of the species (UNEP-WCMC 2024). At the national level, Republic Act 9147 regulates the collection, possession, transport, and trade of wildlife and requires the corresponding DENR authorization. The conservation-status comparison across the IUCN Red List, DAO 2026-20, and CITES frameworks is summarized in Figure 2.

## Species-Level Pharmacological and Economic Profile

The evidence base was concentrated in three species but differed markedly in type (Table 3; Figure 3). Pharmacological and phytochemical studies were identified for *A. filaria* and *A. malaccensis*, whereas the Philippine evidence identified for *A. cumingiana* concerned propagation rather than pharmacological activity. No pharmacological, phytochemical, or ethnobotanical study was identified for the five Data Deficient Philippine endemics *A. apiculata*, *A. brachyantha*, *A. citrinicarpa*, *A. parvifolia*, and *A. urdanetensis*.

***Aquilaria filaria.*** This Philippine *Aquilaria* species has the most extensively documented pharmacological profile, anchored in six independent peer-reviewed phytochemical investigations of Philippine-sourced agarwood conducted between 2017 and 2024. Antitumor activity was first reported by Suzuki et al. (2017), who isolated a new chromone and ten known phenylethylchromones (PECs) from methanolic extracts, with 4',7-dimethoxy-6-hydroxychromone demonstrating broad-spectrum antiproliferative activity against five human tumor cell lines ($IC_{50}$ 25–38 $\mu$M) and suppression of Epstein-Barr virus early antigen (EBV-EA)-induced tumor promotion at non-cytotoxic concentrations. A subsequent phytochemical investigation by Mi et al. (2019) isolated six 8,12-epoxyguaiane-type sesquiterpenoids from Philippine *A. filaria* agarwood; guaianolide (compound 5) demonstrated $\alpha$-glucosidase inhibitory activity ($IC_{50}$ 253.2 $\mu$M; cf. acarbose 743.4 $\mu$M), establishing the first antidiabetic evidence and sesquiterpenoid profile for this species. Antidiabetic potential was subsequently established by Mi et al. (2021), who reported 12 new 2-(2-phenylethyl)chromone (PEC) derivatives with $\alpha$-glucosidase inhibitory activity ($IC_{50}$ 7.8–137.7 $\mu$M), substantially more potent than the reference drug acarbose ($IC_{50}$ 743.4 $\mu$M). Anti-inflammatory activity was reported by Yang et al. (2023), who iso-

| Species | IUCN Red List (Version 2024-2) | DENR DAO 2026-20 (National) | CITES (International) |
|---|---|---|---|
| *A. urdanetensis* | DD | EN | App. II |
| *A. parvifolia* | DD | EN | App. II |
| *A. citrinicarpa* | DD | EN | App. II |
| *A. brachyantha* | DD | EN | App. II |
| *A. apiculata* | DD | EN | App. II |
| *A. decemcostata* † | VU | NL | App. II |
| *A. filaria* | VU | EN | App. II |
| *A. cumingiana* | VU | EN | App. II |
| *A. malaccensis* | CR | CR | App. II |

**Legend:**
CR = Critically Endangered (IUCN)
VU = Vulnerable (IUCN)
DD = Data Deficient (IUCN)
EN = Endangered (DAO 2026-20)
CR = Critically Endangered (DAO 2026-20)
NL = Not Listed (DAO 2026-20)
App. II - CITES Appendix II

**Figure 2.** Conservation status of nine Philippine *Aquilaria* under three regulatory frameworks. † *A. decemcostata* is assessed as Vulnerable (IUCN 2024; POWO 2026) but absent from DAO 2026-20 (Ding Hou 1960; Pelser et al. 2011 onwards).

lated four new PEC dimers—aquifilarones A–D—that inhibited lipopolysaccharide (LPS)-stimulated nitric oxide (NO) production in RAW264.7 macrophages ($IC_{50}$ 33.94–57.53 $\mu$M). Subsequent independent investigations by Yang et al. (2024) and Wei et al. (2024) yielded further PEC dimer series with anti-inflammatory ($IC_{50}$ 22.43–53.88 $\mu$M), tyrosinase-inhibitory ($IC_{50}$ 27.71 $\mu$M), and NO-suppressive ($IC_{50}$ 35.40 $\mu$M) activities, with absolute configurations resolved by single-crystal X-ray diffraction and electronic circular dichroism (ECD).

***Aquilaria malaccensis***. The critically endangered primary global agarwood species (IUCN CR; DAO 2026-20 Critically Endangered) is *Aquilaria malaccensis*. Globally, it remains the most extensively studied *Aquilaria* species in traditional medicine, ethnopharmacology, and commercial agarwood research (Hashim et al. 2016; Thompson et al. 2022). An extensive review of the history of the use of *A. malaccensis* for centuries in traditional medicine (Ayurvedic, traditional Chinese medicine, and Southeast Asia), including sedative, carminative, antiemetic, antiepileptic, and postpartum tonic uses, was conducted by Hashim et al. (2016). However, the studies included in the present review did not provide sufficient community-specific evidence to determine which Philippine communities historically used *A. malaccensis*, whether such practices remain current, or how local knowledge and resource access have changed through time. These traditional-use claims should therefore be interpreted at their reported geographic scale rather than attributed to Philippine communities without direct evidence. Eissa et al. (2022) further reported anti-inflammatory properties of the species using an ethanol leaf extract which con-

tained eight different compounds, including epifriedelanol, luteolin ethers, acacetin, aquilarinenside E, and iriflophenone glycosides, which inhibited LPS/IFN-$\gamma$-induced NO production in RAW264.7 macrophages and exhibited antilipoxygenase activity ($IC_{50}$ = 71.6 $\mu$g/mL). Additionally, antioxidant properties of the leaves were further confirmed using DPPH, ABTS, and FRAP assays (Eissa et al. 2022; Hashim et al. 2016). The anticancer properties of the species have also been demonstrated for both the essential oil ($IC_{50}$ = 79–129 $\mu$g/mL against HeLa cells) and the ethanolic leaf extract against MCF-7 breast cancer and K-562 chronic myeloid leukemia cells, where cubenol, agarospirol, and aristolene were identified as major bioactive sesquiterpenes (Hashim et al. 2016; Chetia et al. 2025). The antidiabetic properties of the species have also been demonstrated using essential oil inhibition of $\alpha$-amylase ($IC_{50}$ = 30.78 $\mu$g/mL) and acetylcholinesterase ($IC_{50}$ = 13.41 $\mu$g/mL) (Chetia et al. 2025). Commercial cultivation of the species was initiated in the Philippines during the latter part of 2021, under DENR wildlife culture permits (Sy and Melgar 2023).

***Aquilaria cumingiana***. *Aquilaria cumingiana* is an established agarwood-producing species (IUCN VU; DAO 2026-20 Endangered), distributed across Luzon, the Visayas, Mindanao, Borneo, and the Maluku Islands. As such, it represents one of the two main Philippine species cultivated for commercial agarwood (Welgas-Briz 2022; Thompson et al. 2022). Piñon and Reyes (2021) reported the successful large-scale mass production of *A. cumingiana* through vegetative means (rooted cuttings) using indole-3-butyric acid (IBA) and a low-cost rooting chamber within the Rajah Sikatuna Protected Landscape, Bohol: the largest mean root lengths ($p = 0.039$) were found in plants that had been treated with 500 ppm IBA (15.25 mm); additionally, untrimmed leaf laminas also yielded the greatest mean numbers of secondary roots ($p = 0.028$) (5.19). Although Piñon and Reyes (2021) demonstrated a commercially viable approach for the large-scale propagation of *A. cumingiana*, no peer-reviewed phytochemical or pharmacological characterization of Philippine-sourced *A. cumingiana* agarwood was identified. The resulting gap is therefore not one of cultivation feasibility but of product characterization: Philippine-grown material cannot yet be compared rigorously with chemically characterized agarwood from other species or geographic sources.

## Priority Knowledge Gaps

Integration of the taxonomic, distributional, conservation, chemical, and socioeconomic evidence identified seven priority knowledge gaps (Table 4). First, the molecular-phylogenetic status of *A. decemcostata* relative to *A. cumingiana* has not been resolved by any DNA-based study. Second, field surveys to establish extant population size, extent of occurrence, and habitat condition were not identified for any of the five DD Philippine endemics in the literature included in this review. Third, phytochemical and bioactivity screening of *A. apiculata*, *A. citrinicarpa*, and *A. urdanetensis* was not identified in the literature included in this review. Fourth, despite its active cultivation program, *A. cumingiana* has no published pharmacological or phytochemical profile for Philippine populations. Fifth, artificial agarwood induction protocols have not been developed for *A. filaria* in the Philippines, despite its confirmed chemical value. Sixth, the contrast between the Data Deficient IUCN assessments of five Philippine endemics and their Endangered classification under DAO 2026-20, together with the unresolved taxonomic treatment of *A. decemcostata*, identifies a cross-framework evidence gap requiring contemporary population data, formal reassessment, and taxonomic resolution (IUCN 2024; DENR 2026; Thompson et al. 2022). Seventh, the reviewed evidence provides little information on community-level use, local ecological knowledge, resource dependence, tenure and access, livelihood effects, or benefit-sharing associated with Philippine *Aquilaria*.

**Table 3.** Species-level pharmacological and phytochemical evidence for Philippine *Aquilaria*.

| Species | Bioactivity | Key Compounds | Quantitative Endpoint | Plant part; extract/solvent | Reference(s) |
|---|---|---|---|---|---|
| *A. filaria* | Antitumor / Antiproliferative | 4',7-dimethoxy-6-hydroxychromone; 10 known phenylethylchromones (PECs) | 5 human tumor lines; IC50 25–38 $\mu$M; EBV-EA suppression | agarwood; methanol | Suzuki et al. (2017) |
| | $\alpha$-Glucosidase inhibition (antidiabetic) | 12 new 2-(2-phenylethyl)chromone (PEC) derivatives | IC50 7.8–137.7 $\mu$M (cf. acarbose 743.4 $\mu$M) | agarwood; EtOAc | Mi et al. (2021) |
| | | 8,12-epoxyguaiane sesquiterpene (compound 5) | IC50 253.2 $\mu$M (cf. acarbose 743.4 $\mu$M) | agarwood; EtOAc | Mi et al. (2019) |
| | Anti-inflammatory | Aquifilarones A–D (PEC dimers) | LPS-stimulated RAW264.7; IC50 33.94–57.53 $\mu$M | agarwood; ethanol/EtOAc | Yang et al. (2023) |
| | Anti-inflammatory; tyrosinase inhibition | 12 new PEC dimers; 6 bi-chromone dimers | NO: IC50 22.43–53.88 $\mu$M; tyrosinase: IC50 27.71 $\mu$M | agarwood; ethanol/EtOAc | Yang et al. (2024); Wei et al. (2024) |
| *A. malaccensis* (leaves/oil) | Anti-inflammatory | Epifriedelanol, luteolin ethers, acacetin, aquilarinenside E, iriflophenone glycosides | LPS/IFN-$\gamma$ RAW264.7; antilipoxygenase IC50 71.6 $\mu$g/mL | leaf; ethanol | Eissa et al. (2022); Hashim et al. (2016) |
| | Antioxidant | Quercetin, kaempferol, isorhamnetin, myricetin, phenolic acids (LC/Q-TOF-MS) | DPPH, ABTS, and FRAP assays | leaf; ethanol | Eissa et al. (2022); Hashim et al. (2016) |
| | Anticancer | Cubenol, agarospirol, aristolene (sesquiterpenes) | HeLa cells IC50 79–129 $\mu$g/mL; MCF-7; K-562 cell lines | agarwood; hydro-distilled essential oil | Chetia et al. (2025); Hashim et al. (2016) |
| | Antidiabetic / enzyme inhibition | Essential oil volatiles | $\alpha$-Amylase IC50 30.78 $\mu$g/mL; acetylcholinesterase IC50 13.41 $\mu$g/mL | essential oil | Chetia et al. (2025); Hashim et al. (2016) |
| *A. cumingiana* | Vegetative propagation (not pharmacology) | IBA (indole-3-butyric acid) 500 ppm | Longest root: 15.25 mm ($p = 0.039$); secondary roots: 5.19 ($p = 0.028$) | stem cuttings | Piñon and Reyes (2021) |

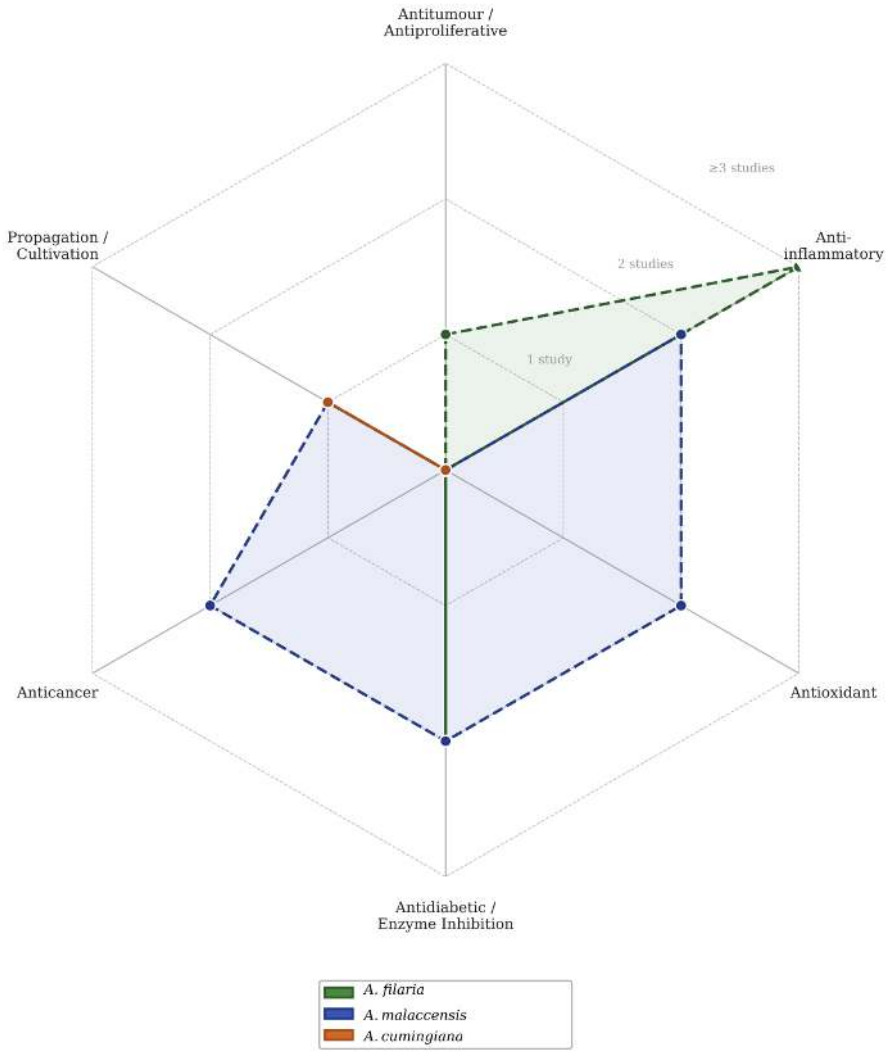



**Figure 3.** Radar chart of bioactivity breadth for the three pharmacologically characterized Philippine Aquilaria species. Scores (0–3) reflect the number of independent peer-reviewed studies per activity axis. Data sources: Table 3; Hashim et al. (2016); Suzuki et al. (2017); Mi et al. (2019, 2021); Piñon and Reyes (2021); Eissa et al. (2022); Yang et al. (2023, 2024); Wei et al. (2024); Chetia et al. (2025).

**Table 4.** Priority research agenda for Philippine *Aquilaria*: structured knowledge gap matrix.

| Knowledge Gap | Taxa Affected | Gap Type | Evidence Required to Close Gap | Priority |
|---|---|---|---|---|
| **KG-1:** Molecular-phylogenetic status of *A. decemcostata* | *A. decemcostata* vs. *A. cumingiana* | Taxonomic (T) | matK/ITS2 or chloroplast-genome sequencing of Laguna type-locality material and comparative *A. cumingiana* specimens; morphometric analysis | **Critical** |
| **KG-2:** Field surveys and population assessments for DD endemics | *A. apiculata*, *A. citrinicarpa*, *A. urdanetensis*, *A. brachyantha*, *A. parvifolia* | Distributional / Ecological (D/E) | Ground-truthed transect surveys; herbarium georeferencing; EOO/AOO estimation for formal IUCN reassessment and national conservation planning | **Critical** |
| **KG-3:** Phytochemical and bioactivity screening of uncharacterized tree endemics | *A. apiculata, A. citrinicarpa, A. urdanetensis* | Phytochemical (P) | Solvent extraction of heartwood/leaf; GC-MS/LC-HRMS profiling; in vitro bioassays (anti-inflammatory, antioxidant, cytotoxicity panels) | **High** |
| **KG-4:** Pharmacological profile of *A. cumingiana* agarwood | *A. cumingiana* | Phytochemical / Pharmacological (P) | Isolation and structural characterization of agarwood PECs and sesquiterpenes from Philippine-cultivated material; bioactivity validation aligned with Table 3 assay standards | **High** |
| **KG-5:** Artificial agarwood induction protocols for *A. filaria* | *A. filaria* | Agronomic / Biotechnological (A/B) | Fungal-inoculation and wound-induction trials under Philippine plantation conditions; GC-MS quantification of induced PEC and sesquiterpene yields | **High** |
| **KG-6:** Cross-framework conservation assessment and taxonomic-regulatory alignment | Five IUCN Data Deficient endemics + *A. decemcostata* | Governance / Regulatory (G/R) | Contemporary population, EOO/AOO, and habitat data to support IUCN reassessment of Data Deficient taxa; integrative taxonomic resolution of *A. decemcostata*; and incorporation of resolved species-level information into subsequent national conservation assessments. | **Critical** |
| **KG-7:** Community-centered evidence for sustainable use and conservation | Philippine *Aquilaria* spp. and relevant user/cultivator communities | Ethnobiological/ Socioeconomic/ Governance (E/S/G) | Participatory ethnobiological and socioeconomic studies documenting local knowledge, resource use and management, livelihood relationships, access, and benefit-sharing among communities and stakeholders associated with Philippine Aquilaria. | **Critical** |

**Legend:** KG = Knowledge Gap. DD = Data Deficient. EOO = Extent of Occurrence. AOO = Area of Occupancy. DAO = DENR Administrative Order. PEC = 2-(2-phenylethyl)chromone. GC-MS = gas chromatography–mass spectrometry. LC-HRMS = liquid chromatography–high-resolution mass spectrometry. Priority ratings follow IUCN SSC gap-analysis conventions (IUCN 2024).

## DISCUSSION

The principal implication of the POWO–CDFP disagreement is not an absence of protection for Philippine *Aquilaria*, but uncertainty over the biological status and appropriate species-level monitoring of the Laguna lineage described as *A. decemcostata*. This disagreement arises from the manner in which Ding Hou (1960) treated *A. cumingiana* in his Flora Malesiana description, adopting a broad morphological circumscription that incorporated the Laguna collection. Resolving this discrepancy will require an integrative taxonomic approach rather than reliance on database acceptance alone. Contemporary taxonomic revisions increasingly evaluate molecular phylogenetic evidence alongside morphology, nomenclatural history, and geographic patterns when reassessing species or generic boundaries (Hughes et al. 2022). Molecular evidence may be particularly informative in this case: Eurlings and Gravendeel (2005) demonstrated the utility of matK and trnL-trnF markers for resolving relationships within *Aquilaria*, while more recent work has applied chloroplast-genome approaches to closely related congeners in India (Das et al. 2025). For *A. decemcostata*, comparative analysis of material attributable to the Laguna lineage and authenticated *A. cumingiana* populations across the Luzon–Visayas–Mindanao region, integrating morphological and molecular evidence, would provide a stronger basis for reassessing its species status. Until such evidence becomes available, targeted field surveys and integrative taxonomic assessment remain necessary so that future species-level monitoring and national conservation assessments can reflect its resolved taxonomic status.

The need for stronger species-level evidence extends beyond taxonomy to conservation assessment and trade governance. National and international conservation frameworks currently portray different dimensions of risk for Philippine *Aquilaria*. Under DAO 2026-20, seven CDFP-recognized species are Endangered and *A. malaccensis* is Critically Endangered, whereas five Philippine endemic taxa remain Data Deficient under the IUCN Red List. The updated national classifications therefore provide precautionary threat recognition for taxa whose global assessments remain constrained by limited population and distributional evidence. Nevertheless, this evidence deficiency remains consequential because the scarcity of contemporary population, distribution, harvest, and trade data can constrain species-level monitoring and scientifically robust non-detriment findings for wild-sourced trade (Thompson et al. 2022). This limitation is particularly important for narrowly distributed taxa for which even basic information on extant populations remains scarce.

Ecological specialization may further compound these uncertainties. High-elevation taxa such as *A. urdanetensis* (1,600–1,700 m) and *A. apiculata* (1,100–1,800 m) occupy mossy or upland forest habitats that may be particularly vulnerable to climate-related range contraction (Forest Management Bureau 2020). Their representation by very few herbarium collections further limits assessment of current distribution, population size, and habitat condition. For such narrowly documented taxa, contemporary field surveys are needed not only to refine extent of occurrence and area of occupancy under IUCN Criterion B, but also to establish population baselines against which future decline and habitat change can be evaluated. The apparent precision of current conservation categories should therefore not obscure the substantial differences in the quantity and quality of biological evidence available among Philippine *Aquilaria* species.

A similar imbalance is evident in the pharmacological and phytochemical literature, which is concentrated in *A. filaria* and *A. malaccensis* and reflects the broader research bias toward commercially important *Aquilaria* taxa (Hashim et al. 2016; Gao et al. 2019). Philippine-sourced *A. filaria* nevertheless contributes distinct chemical evidence through the discovery of previously undescribed PEC dimers with anti-inflammatory and tyrosinase-inhibitory activities. These compounds expand the known chemical diversity of the species and provide a basis for future work on material authentication, quality assessment, and bioactivity-guided natural-product development, although their commercial relevance requires validation across populations and production batches. For *A. malaccensis*, leaf-based pharmacological evidence similarly suggests potential for non-wood utilization, but its applicability to Philippine material remains to be established. More broadly, the available literature provides little information on the Philippine communities historically or currently associated with *Aquilaria* use, limiting interpretation of how biological and commercial value intersects with local knowledge, resource access, and the distribution of benefits arising from agarwood utilization and commercialization (Carmo et al. 2026).

The contrast is especially apparent for *A. cumingiana*, for which advances in propagation have not been matched by comparable chemical characterization. Piñon and Reyes (2021) demonstrated the feasibility of relatively simple vegetative propagation, providing an important technical basis for plantation establishment, yet no peer-reviewed phytochemical or pharmacological characterization of Philippine-sourced *A. cumingiana* agarwood was identified. Chemical characterization would complement this cultivation progress by enabling comparison with other

commercial *Aquilaria* species, identifying potential chemical markers, supporting product authentication and quality research, and determining whether locally cultivated material contains bioactive or commercially relevant metabolites. These objectives should, however, remain conceptually distinct from conservation compliance. CITES non-detriment findings depend on evidence concerning legal origin, population impact, harvest, management, and trade rather than on phytochemical composition. Separating product characterization from conservation sustainability therefore avoids conflating the commercial quality of cultivated agarwood with the evidence required for responsible resource management.

Taken together, these gaps show that future research should extend beyond the conservation of *Aquilaria* solely as a threatened biological or commercially valuable resource. Taxonomic resolution of *A. decemcostata* (KG-1) requires integrative evidence, while reassessment of the Data Deficient endemics depends on contemporary population and distributional data (KG-2). Chemical and cultivation-oriented research (KG-3–KG-5) should likewise proceed without increasing pressure on poorly known wild populations. These biological priorities must be considered alongside the social contexts in which *Aquilaria* is named, used, managed, accessed, and valued, because economic value alone does not ensure either conservation benefits or improved livelihoods (Kiss 2004). The available literature provides little community-specific information on these relationships for Philippine *Aquilaria*. Because ethnobiological knowledge is locally grounded and context-dependent, vernacular terminology and reported uses detached from their social and cultural provenance should not be assumed to represent community-validated Local Ecological Knowledge (Fernández-Llamazares et al. 2024). Future research should therefore complement taxonomic, ecological, and phytochemical priorities with participatory studies of local knowledge, resource use and management, access, livelihoods, and benefit-sharing so that conservation strategies address both the persistence of *Aquilaria* populations and the human relationships associated with their sustainable use (Moon et al. 2019). These evidence gaps should also be interpreted in light of the methodological scope and limitations of the present review.

Several limitations should therefore be considered when interpreting the findings of this review. First, eligibility was restricted to records with assessable English-language full texts, which may have excluded relevant evidence reported in other languages. Second, although ethnobotanical and traditional-use information was extracted when encountered, the search strategy was not designed as a dedicated ethnobiological search; consequently, community-specific knowledge, resource-use practices, and livelihood relationships may be underrepresented. Third, the taxonomic and conservation synthesis relied on published floristic treatments, taxonomic databases, conservation assessments, and regulatory documents rather than primary re-examination of herbarium specimens or new molecular analyses. Unresolved taxonomic discrepancies, including the treatment of *A. decemcostata*, were therefore synthesized from the available evidence rather than independently resolved. Finally, substantial heterogeneity among the included studies in terms of taxa, plant materials, experimental designs, assays, and reported endpoints precluded quantitative meta-analysis and necessitated a structured descriptive synthesis. Accordingly, apparent gaps in the published literature should not necessarily be interpreted as evidence of the absence of biological, cultural, or economic importance.

## CONCLUSION

This systematic review provides the first integrated species-level synthesis of Philippine *Aquilaria*, revealing a genus in which high conservation and commercial importance contrasts with substantial gaps in taxonomic, distributional, ecological, and pharmacological knowledge. Habitat loss, harvest and trade pressures, sparse population data, and uneven research coverage collectively constrain species-level conservation assessment and sustainable resource management. Taxonomic incongruence between POWO and CDFP over *A. decemcostata* further complicates species-specific monitoring and conservation assessment. Resolving its relationship with *A. cumingiana* will require integrative taxonomic evidence combining molecular and morphological approaches. More broadly, the prevalence of Data Deficient Philippine endemics highlights the need for contemporary population and distributional data to strengthen conservation assessments and support scientifically robust CITES non-detriment findings. Pharmacological and phytochemical evidence remains concentrated in *A. filaria* and *A. malaccensis*. The structurally distinct 2-(2-phenylethyl)chromone derivatives reported from Philippine-sourced *A. filaria* expand the known chemical diversity of the genus and provide a basis for future authentication, quality assessment, and natural-product research. Conversely, the absence of published chemical characterization of Philippine-sourced *A. cumingiana* agarwood remains an important gap for product characterization despite advances in its cultivation. The seven priority knowledge gaps identified here provide a research agenda spanning integrative taxonomy, field-based conservation assessment,

phytochemical characterization, sustainable cultivation, regulatory alignment, and the need for complementary community-centered research on resource use and management.

## DATA AVAILABILITY

All data supporting this review are available within the manuscript and its Additional Files. The completed PRISMA 2020 checklist is provided in Additional File 1, the full search strategy for every source is provided in Additional File 2, and the per-study quality appraisal of the pharmacological and phytochemical studies is provided in Additional File 3. The study selection flow (Figure 1), characteristics of the included studies (Tables 2 and 3), and species-by-framework conservation status matrix underlying Figure 2 (Table 2) are reported in the manuscript. No primary datasets or analytic codes were generated, as this review synthesizes previously published sources.

## CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

## CONTRIBUTION STATEMENT

Designed the review framework and search strategy, Carried out literature searching, screening, and eligibility assessment, Extracted, organized, and synthesized the data, Interpreted the taxonomic, conservation, trade-governance, and pharmacological evidence, Reviewed, revised, and finalized the manuscript, Supervision: GJDA and JAHM. Wrote the first draft of the manuscript: GJDA

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