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The Potential of Merbau (*Intsia bijuga*) Breeding in Industrial Plantation Forest Development in Indonesia

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Abstract

Merbau (Intsia bijuga) is one of the economically valuable tree species that is threatened by over-exploitation. Breeding efforts for merbau are still limited compared to other commercial species such as teak and acacia. This article reviews the literature related to the potential of merbau in the development of forest plantations in Indonesia, covering aspects of breeding, genetic diversity, and relevant propagation techniques to improve productivity and the sustainability of high-quality wood resources. The breeding strategies for merbau are specifically outlined to highlight their contribution to improving production efficiency, site adaptability, and resilience to environmental stress, thus strengthening merbau's role as a key species in the development of sustainable forest plantations. Through a systematic review of various studies, this review indicates that the genetic diversity of merbau is relatively high, as demonstrated by heterozygosity values obtained from isoenzyme and Random Amplified Polymorphic DNA (RAPD) marker studies, particularly in Papua and Eastern Halmahera. However, there remains a research gap in optimizing vegetative propagation techniques and long-term genetic testing, which limits the large-scale production and deployment of superior planting materials in industrial plantation forest development. This article presents a breeding scheme for potential sub-line to maintain genetic diversity while enhancing merbau productivity.

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INTRODUCTION

Merbau (*Intsia bijuga*) is one of the tropical tree species with significant economic and ecological value in Southeast Asia and the Pacific region. Its timber is widely recognized for its strength, durability, and attractive grain patterns, making it a preferred material for construction, flooring, and high-quality furniture (Martawijaya et al., 2005). The global demand for Merbau timber has continued to increase, leading to overexploitation and a decline in its natural populations within native habitats. Since 1998, the International Union for Conservation of Nature (IUCN) has classified the species as Vulnerable, highlighting the serious threats to its sustainability (Barstow, 2020).

Intsia bijuga is widely distributed across Southeast Asia and the Pacific islands, including Indonesia, Papua New Guinea, Philippines, and the Solomon Islands. This species grows in a wide range of habitats, from lowland forests and coastal areas to swamp forests. Its high ecological adaptability makes Merbau a promising candidate species for industrial plantation forest development (Sirami et al., 2019). However, the limited availability of superior planting materials and its relatively slow growth rate have hindered the optimal utilization of this species.

Efforts to domesticate Merbau in Indonesia are still constrained by several technical and non-technical challenges. From a technical perspective, fundamental information on its reproductive biology, pollination system, and the dynamics of genetic variation among provenances remains limited. From a non-technical perspective, low investment in forestry research, particularly for non-priority commercial species, has further hindered its development. In contrast to species such as *Tectona grandis, Acacia mangium, and Eucalyptus spp*., *I. bijuga* possesses comparable potential to supply high quality timber for industrial use (Sirami et al., 2019).

In the context of industrial plantation forest development, the potential of Merbau as a superior species is highly relevant for reducing dependence on dominant species such as *Tectona grandis* and *Acacia mangium*. In addition to its high-quality timber, this species also exhibits natural resistance to pests and diseases, providing a competitive advantage for its development in industrial plantation forests (Xu et al., 2023). *I. bijuga* can serve as an alternative species that supports the sustainable supply of high-quality timber while simultaneously strengthening genetic conservation outside its natural habitat (ex situ conservation). Therefore, the development of Merbau as a key species in industrial plantation forest programs represents a strategic opportunity to diversify sources of high-quality timber in Indonesia.

Breeding strategies for Merbau should encompass the identification of superior provenances, the management of genetic diversity, and the development of effective propagation techniques. These efforts directly support industrial plantation forest development by enhancing timber productivity, improving genetic adaptation to plantation site conditions, and ensuring the availability of adaptive, high-quality planting materials. Through this approach, the species is expected to contribute to the sustainable supply of high-quality timber while increasing the efficiency and resilience of plantation forest production systems in Indonesia. Furthermore, the application of advanced genomic technologies, such as genomic selection, has begun to emerge in tropical tree breeding programs, including its potential application to *I. bijuga* (Aronen et al., 2025; Lebedev et al., 2020). High-potential provenances are identified through progeny and provenance trials, while genetic diversity management is implemented to prevent genetic erosion that may threaten the sustainability of breeding programs. Efficient propagation techniques, both generative and vegetative, play a crucial role in supporting the large-scale production of superior planting materials.

To date, research on Merbau breeding strategies has been largely dominated by studies on genetic diversity using isoenzyme and RAPD markers, as well as short-term progeny trials. Long-term studies evaluating progeny performance up to the optimal rotation age (50–60 years) remain very limited. In addition, the development of vegetative propagation techniques, such as tissue culture and semi-hardwood cuttings, to accelerate the production of superior planting materials has not yet been fully optimized. These limitations indicate that current knowledge remains insufficient to support the large-scale deployment of improved merbau in industrial plantation systems.

Existing studies on merbau have established its high economic value, wide ecological adaptability, and relatively high genetic diversity based on conventional molecular markers and early-stage progeny trials. However, several critical aspects remain unresolved. Long-term progeny performance data up to rotation age are still lacking, limiting the reliability of early selection decisions. In addition, vegetative propagation techniques have not yet been optimized for large-scale application. Furthermore, the integration of advanced molecular approaches, such as Simple Sequence Repeats (SSR) and Single Nucleotide Polymorphisms (SNP), remains very limited in merbau breeding programs. These gaps are critical for industrial plantation development because they directly affect the availability, quality, and scalability of superior planting materials. Without reliable long-term genetic evaluation and efficient mass propagation systems, the deployment of genetically improved merbau in large-scale plantations remains constrained. Therefore, addressing these limitations is essential to accelerate merbau domestication and to support sustainable, high-productivity industrial plantation forests in Indonesia.

This study proposes a sub-line-based breeding approach that integrates the conservation of genetic diversity among provenances with intensive selection within sub-lines. This approach is inspired by the success of breeding programs in other tropical species, while being tailored to the biological and ecological characteristics of Merbau. It is expected to enhance both the productivity and wood quality of merbau without compromising its genetic diversity.

METHODS

This study employed a systematic literature review approach guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a transparent, structured, and reproducible study selection process. Data were collected through systematic searches in Google Scholar, Scopus, and Forestry Compendium using keywords such as "*Intsia bijuga*", "tree breeding", "genetic diversity", "progeny test", "vegetative propagation", and "industrial plantation forest". A total of 60 records were initially identified from these databases.

The screening process was conducted in several stages. First, a publication year filter was applied to include only studies published within the last 10 years (2015–2025), resulting in 40 relevant articles. Second, further screening was performed based on methodological relevance to merbau breeding and propagation, reducing the number of studies to 30 articles for full-text assessment. Finally, a detailed eligibility evaluation was conducted based on the alignment of each study with the research objectives, resulting in 25 studies being included in the qualitative synthesis. The overall study selection process is illustrated in Figure 1.

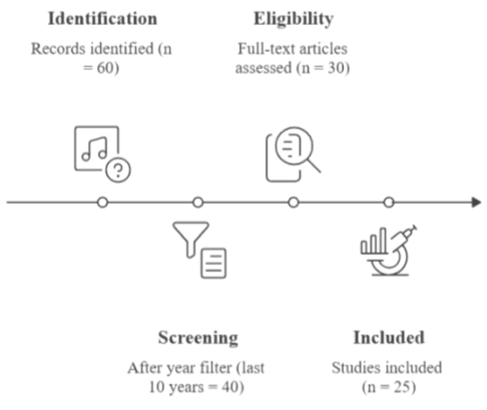

Figure 1. Study Selection Process

The inclusion criteria were defined as follows: (1) studies focusing on merbau (*Intsia bijuga*) or comparable tropical tree species; (2) studies addressing genetic diversity, breeding strategies, progeny trials, or propagation techniques; (3) peer-reviewed journal articles, conference proceedings, or scientific reports; and (4) studies conducted in tropical or subtropical regions, particularly those relevant to Indonesia. The exclusion criteria included: (1) studies not relevant to tree breeding or industrial plantation forestry; (2) publications lacking methodological clarity or scientific rigor; (3) duplicate or redundant studies; and (4) non-scientific sources such as opinion articles or unpublished materials.

To structure the synthesis of the selected studies, the PICO (Population, Intervention, Comparison, Outcome) framework was applied. The PICO components used in this study are presented in Table 1.

Table 1. PICO framework applied in this study

Component	Description
Population (P)	Merbau (*I. bijuga*) and comparable tropical tree species
Intervention (I)	Breeding strategies, progeny trials, and propagration techniques (generative and vegetative)
Comparison (C)	Different breeding approaches and propagation methods
Outcome (O)	Improved productivity, genetic diversity, adaptability, and suitability for industrial plantation forest development

The selected articles were analyzed qualitatively to evaluate existing merbau breeding approaches, the effectiveness of propagation techniques, and its potential application in industrial plantation forest development. The synthesis focused on identifying research gaps, methodological trends, and practical implications for improving the productivity and sustainability of merbau-based plantation systems.

RESULTS AND DISCUSSION

Basic Biology of Merbau (*I. bijuga*)

Merbau (*I. bijuga*) exhibits unique ecological characteristics that enable adaptation across a wide range of tropical environmental conditions. The high level of phenotypic variation among populations indicates strong local adaptation. *I. bijuga* is a large tree species that can reach heights of over 35 m and trunk diameters of up to 250 cm. Its natural habitat includes coastal forests, swamps, and lowland forests across Southeast Asia, Papua, and the Pacific region. Merbau also develops a robust root system capable of stabilizing soils in coastal areas prone to erosion, thereby playing an important role in maintaining ecosystem balance.

The reproductive biology of merbau (*I. bijuga*) is characterized by hermaphroditic flowers, a predominantly outcrossing (xenogamous) pollination system, and protandry, in which the male reproductive organs mature earlier than the female organs (Adinugraha et al., 2014a). The primary pollinators of merbau (*I. bijuga*) are insects and wind. However, the success of self-pollination is nearly negligible, underscoring the importance of outcrossing mechanisms in maintaining natural genetic diversity. In addition, the year-round flowering pattern observed in some populations provides opportunities for population selection based on improved flowering synchronization in breeding programs.

The natural distribution of merbau (*I. bijuga*) indicates the presence of ecological and genetic differentiation among provenances. Provenances from Papua and Halmahera Timur have demonstrated superior growth performance compared to those from other regions, such as Seram, which tend to exhibit slower growth rates (Adinugraha et al., 2014b; Pudjiono, 2017; Souza et al., 2021). This local adaptation constitutes an important consideration in breeding programs for selecting genetic sources that are well-suited to the environmental conditions of industrial plantation forest sites.

Merbau (*I. bijuga*) belongs to the family Fabaceae, subfamily Caesalpinioideae, and is distributed across Southeast Asia and the Pacific region. It typically grows in well-drained lowland forests, is often found on calcareous soils, and can adapt to elevations of up to 600 m above sea level (Sirami et al., 2019). Merbau (*I. bijuga*) exhibits relatively slow growth, with a natural rotation age ranging from 50 to 60 years (Rimbawanto & Widyatmoko, 2006).

Genetic Diversity of Merbau (*I. bijuga*)

The genetic diversity of merbau (*I. bijuga*) constitutes a fundamental basis for sustainable breeding programs. High genetic variation enables the selection of superior individuals with desirable trait combinations, such as rapid growth, resistance to pests and diseases, and high wood quality. Several studies have reported significant levels of genetic diversity within merbau populations, particularly in regions such as Papua and East Halmahera.

Another study conducted by (Zhang et al., 2020) using isoenzyme markers on four merbau (*I. bijuga*) populations - Waigo, Nabire, East Halmahera, and Seram - reported an average heterozygosity value of 0.404. This value is higher than the level of genetic diversity reported by (Rimbawanto & Widyatmoko, 2006) using RAPD markers, which reached only 0.296. The high level of heterozygosity indicates that substantial genetic diversity is still maintained within the populations, which is crucial for reducing the risk of inbreeding and enhancing population resilience to environmental changes.

The majority of genetic variation in merbau (*I. bijuga*) is concentrated within populations (intra-population diversity), accounting for approximately 93–95%, whereas genetic variation among populations (inter-population diversity) represents only about 5–7% (Lebedev et al., 2020; Russello et al., 2020). This pattern of genetic variation indicates that the selection of superior individuals is more effectively conducted within local populations rather than among populations. Therefore, merbau (*I. bijuga*) breeding strategies are primarily focused on improving genetic quality within each provenance through plus tree selection.

The presence of assortative mating, which leads to an excess of heterozygosity (negative Fis values) represents another factor that reinforces the genetic diversity of merbau (*I. bijuga*) (Russello et al., 2020). This pattern is attributed to the predominantly outcrossing (xenogamous) pollination system of merbau (*I. bijuga*), which facilitates extensive gene flow within populations. In addition, ecological factors such as heterogeneous habitat distribution and diverse site conditions further contribute to the high level of genetic variation.

However, there remains a lack of studies on the genetic diversity of merbau (*I. bijuga*) utilizing advanced molecular markers such as SSR (Simple Sequence Repeats) and SNP (Single Nucleotide Polymorphisms). These technologies have demonstrated high effectiveness in identifying adaptive alleles in other tropical tree species, particularly in the context of climate change (Borthakur et al., 2022). These markers provide higher resolution in characterizing population genetic structure, enabling more accurate identification of superior genotypes. Therefore, further research employing modern molecular marker technologies is essential to support more precise merbau (*I. bijuga*) breeding programs.

Breeding Strategies for Merbau (*I. bijuga*)

Genetic testing in merbau (*I. bijuga*), particularly through progeny trials, represents a crucial step in evaluating the genetic performance of selected plus trees. Although *Eucalyptus pellita*, *Larix olgensis*, and *Docynia delavayi* differ taxonomically from merbau, these species are considered relevant comparative models because they share several important characteristics in forest tree breeding, including long breeding cycles, progeny testing requirements, genotype × environment interactions, and the selection of superior genotypes for plantation development. Therefore, breeding approaches applied in these species provide valuable methodological references that can be adapted to merbau breeding programs. A study by (Fadwati et al., 2023) on *Eucalyptus pellita* in Kalimantan demonstrated that evaluating genetic parameters such as growth and wood density across different sites provides important insights for superior clone selection, an approach that is also applicable to merbau breeding. Furthermore, a study by (Li et al., 2025) highlighted the importance of integrating advanced molecular breeding technologies, such as CRISPR-Cas9 and genomic selection, to enhance tree adaptation to global environmental changes. This approach, as also emphasized by (Hamzekhanlu & Gailing, 2022), offers significant potential for strengthening merbau breeding programs in Indonesia. In addition, research by (Hardiyanto et al., 2025) in Sumatra on the productivity of *Eucalyptus pellita* following species replacement from *Acacia mangium* demonstrated that adaptive management practices such as phosphorus nutrient management and organic matter retention can enhance productivity and resilience to environmental stress. These findings have important implications for site management and merbau breeding in industrial plantation forests.

Similarly, (Xu et al., 2023) in their study on provenance selection of *Docynia delavayi*, showed that early-stage seedling growth variation analysis is effective in improving breeding efficiency, an approach that can be applied to merbau. Krainovic et al., 2023 further emphasized the importance of silvicultural management and species-specific growth modeling in optimizing timber production of native tree species in tropical restoration areas, which is also relevant for merbau plantation development. Previous studies (Adinugraha et al., 2014a; Sirami et al., 2019) have reported that the heritability of growth traits (height and diameter) in merbau ranges from moderate to high, with genetic correlations between these traits reaching 0.95–0.96. Additionally, (Zhang et al., 2020) in their study on *Larix olgensis*, demonstrated that multi-trait evaluation based on progeny trials can effectively improve the efficiency of superior family selection. This suggests that selection for one trait (e.g., diameter) can simultaneously improve correlated traits (e.g., height), thereby facilitating more efficient advanced selection in merbau breeding programs.

However, existing progeny trials in merbau (*I. bijuga*) have generally been limited to relatively young ages (around 5 years), whereas the natural rotation age can reach 50–60 years (Sirami et al., 2019). Consequently, early-stage progeny test results may still be strongly influenced by environmental factors, highlighting the need for long-term evaluation to ensure the consistency of genetic performance up to the productive phase (Tampang et al., 2024).

From a propagation perspective, merbau can be propagated both generatively and vegetatively. Generative propagation through seeds faces challenges due to prolonged dormancy caused by a hard seed coat, requiring scarification treatments to break dormancy (Barstow, 2020). Mechanical scarification followed by water soaking or chemical treatment using H_2SO_4 can increase germination rates by up to 100%.

For vegetative propagation, shoot cuttings treated with rooting hormones such as NAA have shown success rates of up to 71%, while the stump method derived from wildlings achieves survival rates of approximately 70% when directly planted (Ray et al., 2022). Although these vegetative techniques show considerable potential, their application at a large scale remains limited. In breeding programs, vegetative propagation is primarily used for multiplying selected superior trees in clonal seed orchards (CSO), whereas operational plantations predominantly rely on generative seeds produced from seedling seed orchards (SSO). Compared to commercially established plantation species such as *Eucalyptus* and *Acacia*, which already utilize efficient large-scale clonal propagation systems, vegetative propagation techniques in merbau remain relatively underdeveloped. This limitation reduces the efficiency of deploying genetically superior planting materials in operational plantations. Therefore, improving vegetative propagation methods, particularly tissue culture and clonal propagation systems, is essential to accelerate breeding gains, support large-scale plantation establishment, and enhance the productivity and uniformity of merbau plantations.

The development of tissue culture techniques for merbau (*I. bijuga*) represents a promising area for future research, particularly for producing large quantities of uniform planting material with improved environmental resilience (Aronen et al., 2025). In addition, vegetative propagation techniques such as cuttings, grafting, and air layering have been proven effective in accelerating the propagation of woody plants, as highlighted in the study by (Satpathi & Ramesh, 2025), which reviewed various vegetative propagation methods to enhance growth and stress tolerance in forest species. Although still limited in application, tissue culture offers a viable solution for the mass production of superior, uniform planting materials, as has been successfully demonstrated in several other tropical species (Aronen et al., 2025). Merbau breeding strategies aim to enhance productivity and wood quality through the planned management of genetic resources. Figure 1 illustrates the breeding population framework and the sub-line breeding strategy adopted in this program, designed to maintain genetic diversity while improving wood quality.

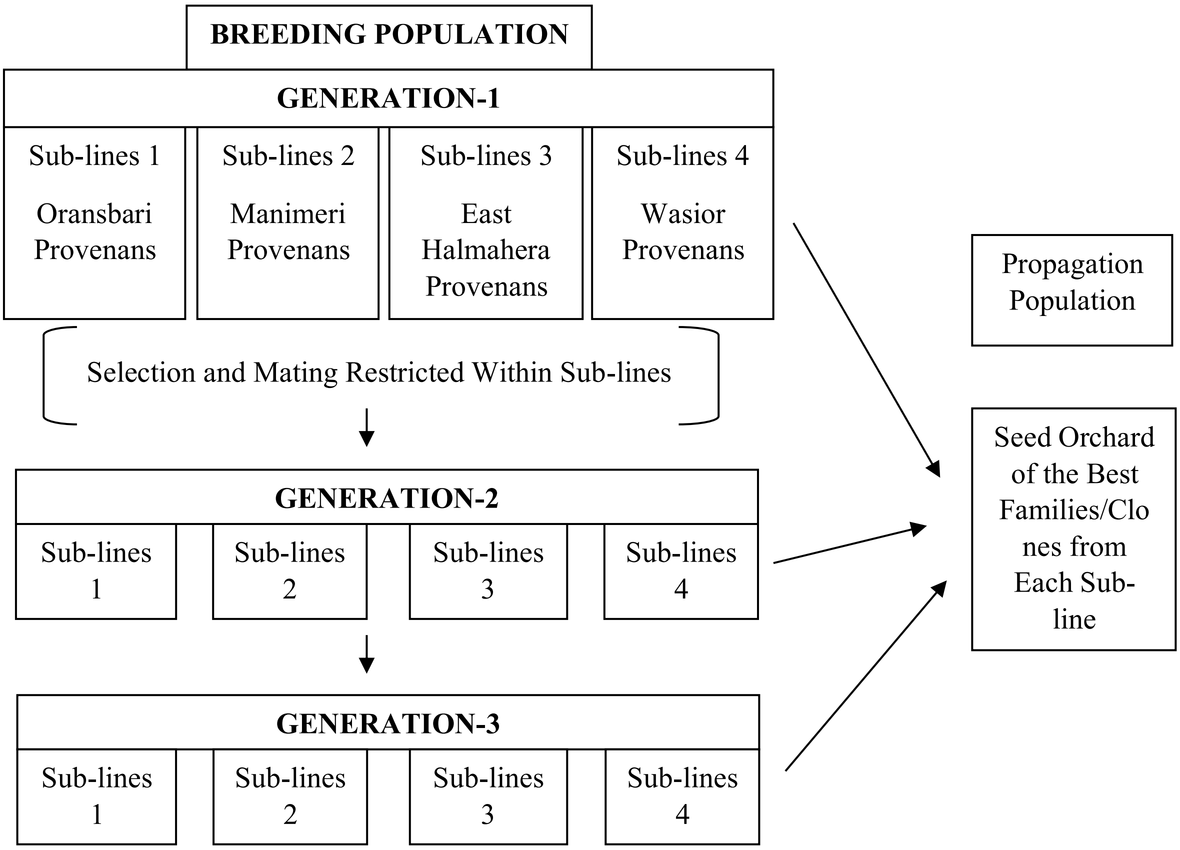

Figure 1. Breeding Population Scheme and Sub-Line Breeding Strategy of Merbau

One of the approaches adopted is the sub-line breeding system, which enables more effective management of genetic diversity both within and among provenances (Hardiyanto et al., 2025). This approach divides the breeding population into several sub-lines based on provenance, allowing intensive selection within each sub-line while minimizing genetic exchange among sub-lines to reduce the risk of inbreeding.

The selection of key provenances in this strategy is based on the results of previous progeny and provenance trials, which indicate that provenances from Papua and East Halmahera exhibit superior growth and wood quality (Sirami et al., 2019). Provenances such as Oransbari, Manimeri, East Halmahera, and Wasior were selected as the base populations for this breeding strategy in merbau (*I. bijuga*).

The strategic steps in merbau (*Intsia bijuga*) breeding include the following:

1. **Base Population Collection:** Identification and collection of plus trees from selected provenances exhibiting superior phenotypic traits such as height, diameter, and straight, cylindrical stem form (Islam et al., 2022).
2. **Sub-line Formation:** Division of the base population into sub-lines based on provenance to facilitate effective management and selection (Ramadan et al., 2018).
3. **Progeny Testing:** Implementation of progeny trials within each sub-line to evaluate the heritability of key traits such as growth performance, pest resistance, and wood quality (Adinugraha et al., 2014a). These trials are conducted across multiple sites to assess environmental adaptability.
4. **Seed Orchard Establishment:** Development of seedling seed orchards (SSO) and clonal seed orchards (CSO) based on progeny test results. The best individuals from each sub-line are selected for the production of improved seeds (Rimbawanto & Widyatmoko, 2006).
5. **Inbreeding Control and Relatedness Management:** Regulation of mating patterns among individuals within seed orchards to minimize inbreeding and maintain genetic diversity (Fadwati et al., 2023).
6. **Operational Population Development:** Establishment of operational plantation populations based on family-derived seeds from improved seed orchards. These populations are periodically

evaluated to support continuous improvement in future breeding cycles (Adinugraha et al., 2014a).

This scheme is designed to maintain genetic diversity at each stage while simultaneously improving wood quality. The sub-line strategy provides flexibility in population management, ensuring that if genetic degradation or disturbances occur in one sub-line, alternative genetic resources remain available in other sub-lines.

The integration of molecular marker technologies, such as SSR and SNP, can further strengthen genotype-based selection, improve selection accuracy, and accelerate breeding cycles in merbau (*I. bijuga*) programs (McLennan et al., 2025).

Implications for Conservation and Industry

Merbau (*I. bijuga*) breeding strategies are not only aimed at improving timber productivity and quality but also have significant implications for the conservation of genetic resources. By managing genetic diversity at the sub-line level, the risk of losing important alleles can be minimized, thereby supporting long-term genetic stability (Sirami et al., 2019).

From a conservation perspective, this strategy contributes to preserving local merbau provenances that may be threatened by environmental pressures or overexploitation. The use of clonal seed orchards (CSO) and seedling seed orchards (SSO) enables the development of high-quality seed sources that retain natural genetic diversity while providing superior planting material for land rehabilitation and reforestation programs.

For the forestry industry, merbau breeding strategies offer opportunities to diversify industrial plantation forest species by introducing high-value timber alternatives beyond *Tectona grandis*, *Acacia mangium*, and *Eucalyptus spp*.. Merbau timber, known for its strength and durability, represents a competitive product in international markets, particularly for construction and high-end furniture (Fadwati et al., 2023; Hardiyanto et al., 2025). With the implementation of structured breeding programs, merbau productivity is expected to increase by approximately 20–30% compared to natural populations, thereby supporting a sustainable supply of high-quality timber. The results of progeny testing can be directly applied in operational plantation programs through the selection of superior families and provenances for the establishment of seed orchards and plantation stock. Trees exhibiting superior growth performance, stem form, and adaptability can be propagated and deployed as improved planting materials in industrial plantation forests, resulting in more uniform stand development and improved timber yield.

Furthermore, well-planned breeding management opens opportunities for the development of genetic-based industries, including the production of improved seeds, tissue culture propagation, and related downstream products. This creates added economic value in the forestry sector while strengthening Indonesia’s position as a leading supplier of high-quality tropical timber in the global market (Ray et al., 2022). From an economic perspective, increased productivity resulting from genetically improved planting materials can enhance timber volume production per hectare and improve plantation management efficiency. Higher wood productivity and quality may also increase the commercial value of merbau timber in domestic and international markets, particularly for premium construction materials and high-end wood products.

However, the successful implementation of this strategy requires strong synergy among research institutions, industry stakeholders, and government agencies to ensure sustainable funding, effective technology transfer, and the adoption of breeding outputs in operational practices. Such collaboration is crucial to simultaneously address conservation challenges and industrial development needs. Several operational challenges also remain, including the high cost of long-term breeding programs, the extended rotation age of merbau, limited propagation technology, and the need for skilled human resources and supporting infrastructure. These constraints may limit the rapid implementation of large-scale breeding programs and therefore require long-term institutional and financial support.

CONCLUSION

The sub-line-based breeding strategy for merbau (*Intsia bijuga*) offers a balanced approach between genetic conservation and timber productivity improvement. Considering the high level of genetic diversity within merbau populations, a systematically designed breeding program can enhance wood quality while ensuring the sustainability of genetic resources.

The substantial genetic variation observed in merbau populations, particularly in provenances from Papua and East Halmahera, provides significant opportunities for the selection of superior individuals. Through the implementation of progeny trials and appropriate propagation techniques, merbau productivity can be substantially improved. The integration of molecular technologies, such as SSR and SNP markers, is also expected to accelerate and improve the accuracy of genetic selection in breeding programs.

Beyond productivity gains, this strategy contributes to the conservation of local provenances that are increasingly threatened by overexploitation and environmental change. It also supports the development of more diverse and sustainable industrial plantation forests in Indonesia.

Ultimately, strengthening collaboration among research institutions, industry stakeholders, and government agencies is essential for the successful implementation of this strategy. Such collaboration will ensure the long-term conservation of merbau genetic resources while enhancing the competitiveness of the national forestry sector.

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