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Review Article

The potential of *Arenga pinnata* (Wurmb) Merr. for enhancing soil health, food, energy, and water security in Indonesia: A comprehensive review

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ABSTRACT

Sugar palm (*Arenga pinnata* (Wurmb) Merr.) is a type of multipurpose palm with significant economic and environmental value and is widely distributed in Indonesia. All parts of the sugar palm plant organs, from the leaves to the roots, can be utilized, giving it great potential as a superior commodity such as coconut and oil palm. Our review highlighted there are several limitations for developing *A. pinnata* on an industrial scale. Currently, the *A. pinnata* industry operates mainly on a household scale, with raw materials sourced from natural stands rather than large-scale cultivation. Additionally, there is no breeding program for *A. pinnata* trees, resulting in variety and often low sap yields. Traditional management practices further hinder business development and market competitiveness. To promote *A. pinnata* as a superior commodity for food, energy, and water conservation in Indonesia, several strategies can be implemented: 1) Training and capacity building to increasing farmers' knowledge and skills in cultivating this species, 2) Optimizing the production process and product value chain development of palm sugar and other products such as candy seed, starch, and fibres, 3) Fostering collaboration among stakeholders, especially the government, through policies that support farmers in developing and marketing their products, 4) Promote *A. pinnata* in watershed rehabilitation and agroforestry for its deep roots that enhance water infiltration, prevent erosion, boost biodiversity, and retain soil moisture. These strategies will help enhance the productivity of *A. pinnata*, improve farmer welfare, and contribute to environmental sustainability.

1. Introduction

Arenga pinnata (Wurmb) Merr. commonly known as the sugar palm, is a valuable commodity that supports the livelihoods of local farmers by providing a diverse array of products (Azhar et al., 2019; Martini and Roshetko, 2011). Virtually, every part of the plant can be harnessed to create a wide spectrum of food items, beverages, construction materials, household implements (such as broom stick, handle of knife, ax, and hoe), bio-composites, and medicinal aids (Bismarck et al., 2005; Damayanti et al., 2012; Laksananny and Pujirahayu, 2017; Martini and Roshetko, 2011; Rahman et al., 2020, 2021). Calculations indicate that *A. pinnata* can yield around 60 economically viable products including starch, palm sugar and bioethanol, with some holding potential for exportation (Rawung et al., 2021). Moreover, *A. pinnata*, from an ecological perspective, plays a crucial role in supporting biodiversity. Additionally, it contributes to soil and water conservation efforts, as its

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strong root system helps stabilize the soil and prevent erosion (Withaningsih et al., 2021).

In Indonesia, *A. pinnata* thrives across 29 provinces, spanning an area of 64,025 hectares (Directorate General of Estate Crops, 2021). The species naturally thrives in diverse habitats, from tropical lowlands to elevations ranging between 200 and 1500 m above sea level (Gunawan et al., 2018; Kaunang and Martini, 2012; Martini and Roshetko, 2011; Mogea et al., 1991; Withaningsih and Nurislamidini, 2021). However, it exhibits optimal growth in mountainous regions with ample rainfall and demonstrates resilience in harsh topographical conditions (Bernhard, 2007; Gunawan et al., 2018; Kaunang and Martini, 2012; Martini and Roshetko, 2011; Withaningsih and Nurislamidini, 2021). *A. pinnata* is found in extensive forest stands across 16 provinces, encompassing various land types in Aceh, North Sumatra, West Sumatra, South Sumatra, Bengkulu, Lampung, Banten, West Java, Central Java, East Java, South Kalimantan, North Sulawesi, South Sulawesi, West Sulawesi, and Maluku (Withaningsih and Nurislamidini, 2021).

Commonly, brown sugar is the primary product of sap-based *A. pinnata* processes. However, the productivity of sap and sugar varies across regions due to traditional processing methods guided by local knowledge. For instance, in North Sumatera the sap production/ha is 50 L, and the palm sugar product is 15–18 % while in East Kalimantan the sap production is 100 L/ha which can produce 15 % of palm sugar (Bernhard, 2007; Mariati et al., 2013; Martini and Roshetko, 2011; Rompas et al., 1996). Despite its immense potential, the full capacity of *A. pinnata* remains largely untapped due to limited technological advancements and information. Consequently, communities rely on naturally occurring *A. pinnata* trees in forests, although these hold significant genetic diversity, while cultivation remains limited (Haryjanto et al., 2011; Rinawati et al., 2021). This presents an opportunity to enhance plantation forest productivity through targeted breeding programs.

Further, Indonesia's government continues to prioritize food, energy, soil, and water security in its medium-term development plan (Antara, 2024), of which *A. pinnata* can substantially contribute. This paper aims to review and synthesize available information on *A. pinnata*, encompassing species characteristics, natural distribution, genetic diversity, utilization, potential for conservation, and strategies to optimize potential *A. pinnata* products. The knowledge derived from the review will be a valuable reference for wider stakeholders such as planners, land managers, and policymakers to develop *A. pinnata* as one of the primary commodities in Indonesia.

2. Methods

The study begins by identifying the scope of the literature review. Publications in both English and Indonesian from 2000 to 2023 were examined. The review focuses on *Arenga pinnata*, food, energy, water conservation, soil conservation, and Indonesia. Search engines were used to screen all relevant literature within these scopes. In the initial search phase, keywords and search phrases were employed in Google Scholar, Mendeley, SpringerLink, and Scopus. Reputable journals, conference proceedings, and several books related to the potential of *A. pinnata* for food, energy, and soil-water conservation in Indonesia were selected.

The initial search yielded an extensive number of publications (over 12,000). In the second step, selection was refined based on keywords or phrases found in the title, abstract, and full text. More specific keywords or phrases were used, such as candy palm seed/starch/palm sap for food, bioethanol for energy, local wisdom for soil-water conservation, and strategies for product improvement. Additional relevant keywords such as potency, production, processing, and products were also included. After removing duplicates, 183 items of remaining literature were chosen based on relevance (Fig. 1).

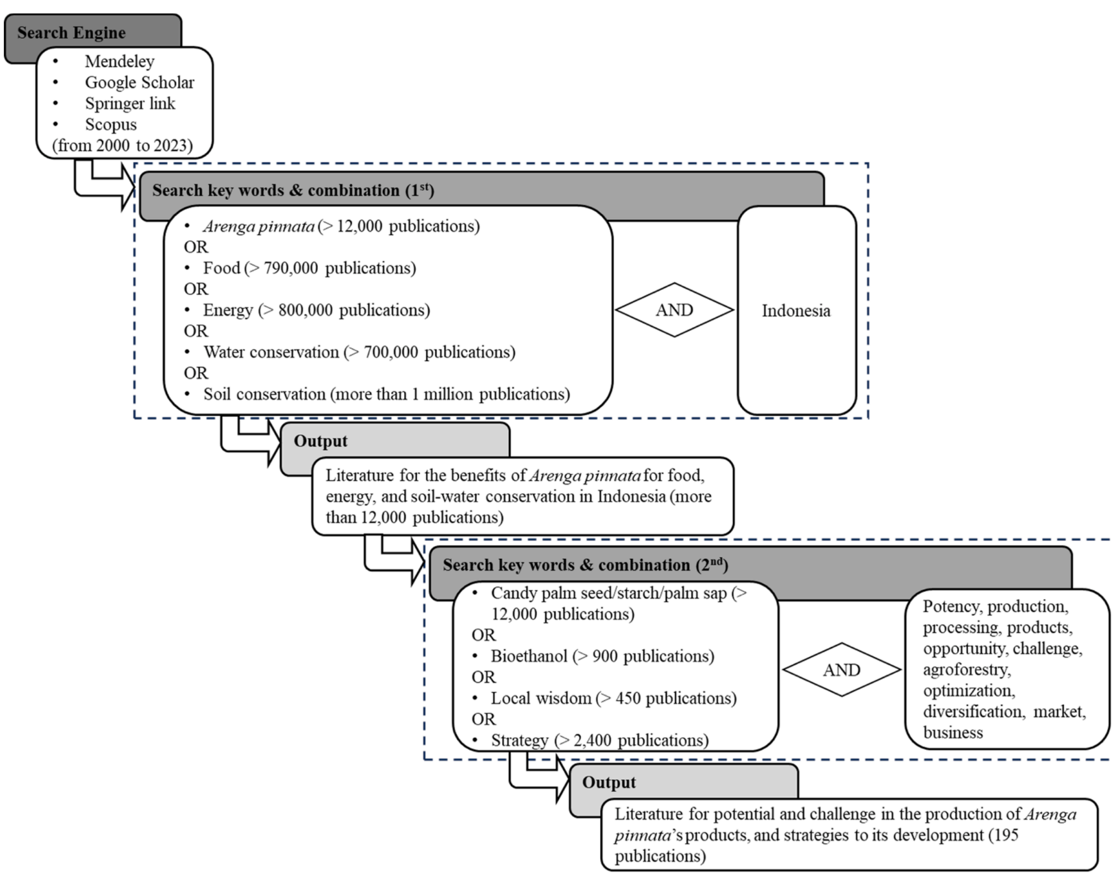

Fig. 1. The literature selection process in the study.

The selected literature was read in detail to compile relevant points for the focus on the big potency of *A. pinnata*, i.e. food, energy, and soil-water conservation. Specific characteristics, distribution and the status of cultivation of *A. pinnata* were used to determine the detailed review of each potency. For potential economy, the food potential of *A. pinnata*, the review focuses on products from candy palm seed, starch, and palm sap, while energy potential was focused on bioethanol. The productivity of raw materials, processing of the products, market potential, and analysis of opportunities and challenges for product development were explained in detail. For potential ecology, the detail described the essential role of *A. pinnata* in soil and water conservation.

Further scientific analysis was conducted to formulate strategies for improving the potential of *A. pinnata* for sources of food, energy, and soil-water security based on the potential products, their opportunities and challenges in the future that were previously explained. For enhancing the productivity of *A. pinnata* products, the strategies were defined to provide a better quantity and quality of raw materials, as well as the knowledge and skills of forest farmers. Furthermore, the diversification of the products and expanding businesses and markets were analyzed as other strategies to improve the utilization of *A. pinnata* (Fig. 2).

3. Characteristic, distribution, and cultivation of *A. pinnata* in Indonesia

3.1. Species characteristics

Arenga pinnata, commonly known as the sugar palm, belongs to the Arecaceae family (ITIS, 2023). It is a solitary, unbranched palm that typically reaches a height of 15–20 m, with a diameter of about 30–40 cm. The leaflets are dark green on the upper side and whitish beneath, giving the trees a dirty-greenish appearance. The leaf sheaths cover the trunk, with fibrous margins and black hairs, commonly known as *ijuk* or *injuk*. The palm's first flowering occurs at an age of 10 to 12 years, but it can sometimes flower as early as 5 to 6 years. The average flowering period for an untapped tree is 4 to 6 years. Typically, 6–8 inflorescences at the top of the trunk are female, while those at the lower nodes are male. The tree dies after a lifespan of 12 to 20 years, depending on the site, climate, and genotype (Mogea et al., 1991).

The male flower clusters are about 1.3 m in length, purple in colour, and have an unpleasant odour. The female flower clusters are longer than the male clusters and slowly ripen into glossy, brown, plum-sized fruit. Flowering starts at the uppermost leaf axil and proceeds downward to the lowest leaf axil. The downward flowering position is in line with the age of the tree. After the age of 20 years, the production of palm sap decreases. The palm tree is productive until the age of 25 years (Fatriani et al., 2012) and after the fruits in the lowest leaf axil have ripened, the tree slowly dies (Lantican and Haagen, 2014).

A. pinnata can grow in a wide range of habitats, from tropical lowlands to highlands up to 1500 m above sea level (Heyne, 1950; Martini and Roshetko, 2011; Mogea et al., 1991). The species can thrive in extreme land topography with varying slope levels of about 8–47 % in mountainous areas and various soil types, especially sandy loam soils (Bernhard, 2007), with temperatures in the range of 20–26 °C (Bernhard, 2007; Withaningsih and Nurislamidini, 2021). As a common and dominating riparian plant, *A. pinnata* thrives in silty sandy riverbank soils and sandy soils but cannot flourish in acidic soils (Azhar et al., 2019). The species is usually found in areas with high rainfall of over 1500 mm/year (Gunawan et al., 2018; Kaunang and Martini, 2012; Martini and Roshetko, 2011).

3.2. Distribution

In Indonesia, *A. pinnata* grows in 29 Provinces with an area of 64,025 ha in 2020 which has been estimated to have reduced to 63,244 in 2022 (Fig. 3) (Directorate General of Estate Crops, 2021). The population is dominated by 58.46 % productive trees, while the rest are immature plants at 25.58 %, and damaged plants at 15.97 %. Ten provinces are key population centers for the species including Aceh, North Sumatra, Bengkulu, Banten, West Java, Central Java, South Kalimantan, North Sulawesi, South Sulawesi, and Southeast Sulawesi with over 2000 hectare areas of *A. pinnata* in each province (Directorate General of Estate Crops, 2021). *A. pinnata* were found in diverse land uses such as primary forests, secondary forests, production forests, community forests, agricultural lands, plantations, mixed dry agricultural lands, rice fields, settlements, and open lands (Withaningsih and Nurislamidini, 2021).

The extensive distribution of *A. pinnata* populations in Indonesia is supported by high genetic diversity (Haryjanto et al., 2011; Rinawati et al., 2021). Haryjanto et al. (2011) reported four populations of the species in Java, Kalimantan, Bengkulu, and Sulawesi. Isozyme markers indicated that the genetic diversity within these populations is 0.4381, while the diversity between populations is 0.0702. Another study using Simple Sequence Repeat (SSR) markers found that heterozygosity values varied from 0.100 to 0.725, indicating genetic diversity within sugar palm populations (Terryana et al., 2020). High genetic diversity within the population indicates the high potential of palm sugar for productivity improvement through genetic breeding. Although the genetic distance between populations is relatively small, it is still important to consider geographical distribution when collecting genetic material for breeding purposes.

3.3. Cultivation

The cultivation of *A. pinnata* in many locations still relies on natural regeneration. For example, stands in North Sumatra, North Sulawesi, and West Java have originated from natural regeneration (Gunawan et al., 2018; Martini and Roshetko, 2011; Withaningsih and Nurislamidini, 2021). In Samarinda and Kutai Barat, cultivation depends on both natural regeneration and transplants (Fatah and Sutejo, 2015). Seed dispersal by common palm civets (*Paradoxurus hermaphroditus*) indirectly supports *A. pinnata*'s natural germination and distribution in the habitat (Gunawan et al., 2018). However, seed dormancy poses a challenge for regeneration due to the thick seed coat and the imbalanced plant growth regulators that both stimulate and inhibit seed germination (Hamzah, 2015; Purba et al., 2014).

Natural regeneration of *A. pinnata* often occurs alongside other trees and plants, such as *Pinus merkusii, Albizia chinensis*, kaliandra (*Calliandra sp*), and annual crops like bamboo (*Bambusa sp*), durian (*Durio zibethinus*), jackfruit (*Artocarpus heterophyllus*), or seasonal crops like cassava (*Manihot esculenta*), banana (*Musa paradisiacal*), coffee (*Coffea sp*) or rice (*Oryza sativa*) (Withaningsih and Nurislamidini, 2021). Additionally, natural regeneration of *A. pinnata* has been observed along the riverbanks mixed with other species such as bamboo (*Bambusa vulgaris*) or figs (*Ficus variegata*) (Soeprobowati et al., 2021).

Farmers typically manage the natural regeneration of *A. pinnata* dispersed by animals, such as insect pollinators or civets, with irregular spacing (Iskandar and Iskandar, 2021; Kartina et al., 2021; Withaningsih and Nurislamidini, 2021). In addition to natural regeneration, *A. pinnata* is also developed through plantation systems in some areas, with spacing of 5–9 m in monoculture or agricultural systems (Fatah and Sutejo, 2015). Small-scale *A. pinnata* cultivation in community forests, using mixed cropping patterns, yields productivity comparable to that in natural forests. The sap production, palm sugar and fruits production in community forests are 7.14 L/tree, 1028 kg/ha/year, and 1500 kg/ha/year respectively, while from natural forests, sap production reach 10 L/tree, 600 kg/ha/year of palm sugar and 3600 of fruits production (Martini et al., 2012).

Several pests have been reported to attack *A. pinnata*, including *Oryctes rhinoceros* (palm rhinoceros beetles) (Janick and Paull, 2008), *Rhynchoporus ferrugineus* (red palm weevils), bats (Effendi, 2010; Sebayang, 2016; Siregar, 2016), *Sexava* sp. (katydid) (Sebayang, 2016),

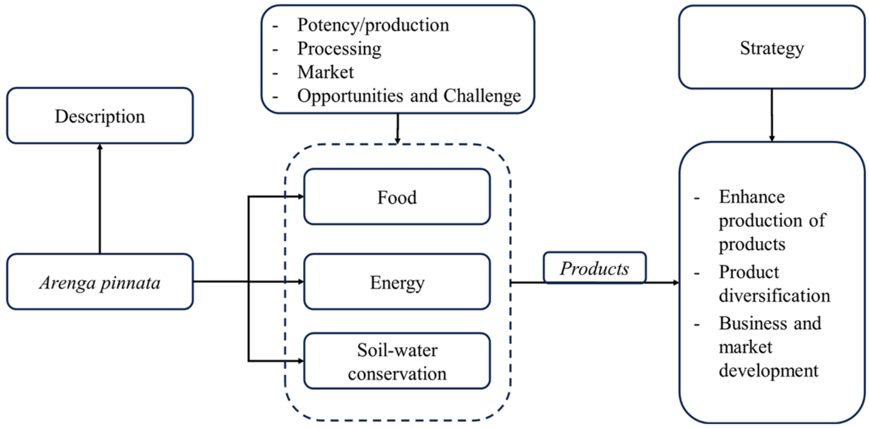

Fig. 2. The logical framework of the review.

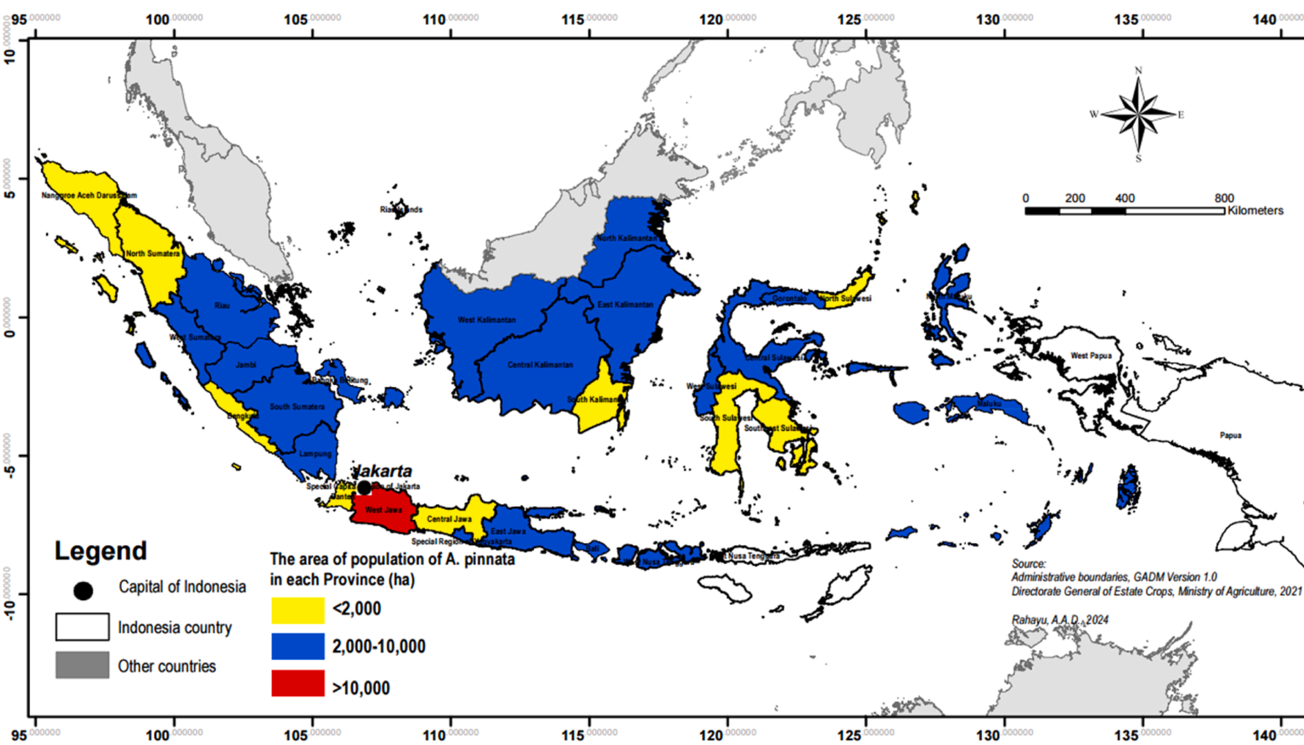

Fig. 3. Map of *A. pinnata* population areas in Indonesia.

Artona sp. (coconut moth) (Effendi, 2010), and wild boars (Samal et al., 2020). Common diseases affecting *A. pinnata* include leaf spot disease caused by the fungi *Helminthosporium* sp. (Effendi, 2010; Sebayang, 2016), *Pestalotiopsis palvarium* (Effendi, 2010; Lasut, 2012), *Ceratocystis paradoxa* (Effendi, 2010; Siregar, 2016), and *Fusarium oxysporum* (Effendi, 2010). Stem rot disease, caused by fungus *Ganoderma pseudoferreum*, also affects this plant species (Janick and Paull, 2008).

4. Potential of *A. pinnata* for food

As a native plant of Indonesia, *A. pinnata* has long been utilized by local communities. Historical evidence indicates that this species has been in use since the Majapahit kingdom during the East Javanese period around 1450 AD, particularly for its sap (Kieven, 2013). The commercial value of *A. pinnata* is evident from its role as a trade commodity with the Dutch East India Company (VOC) (Spence, 1999; Watuseke, 1992). Various parts of *A. pinnata* have been used for different purposes: the leaves for making brooms and bird cages, the fibers for roofing, and the trunks/wood for firewood. Additionally, parts of the plant are used as food sources, including candy palm seeds, starch for flour, and male flowers, which are harvested for their sap (Azhar et al., 2019; Lempang et al., 2012).

4.1. *Candy palm seed*

The candy palm seed of *A. pinnata*, known locally as *kolang-kaling*, is a popular food item in the community. Typically, these seeds are harvested from female flower buds of non-productive or untapped trees, ensuring that sap production is not affected (Ministry of Agriculture of the Republic of Indonesia, 2013). A hundred grams of candy palm seeds contain 27 kcal of energy, 6 g of carbohydrates, 1.6 g of fiber, 24.3 mg of phosphorus, and 9.1 mg of calcium (Aeni et al., 2020). Research by Harahap et al. (2018) highlights the significant nutritional benefits of candy palm seeds, noting their high fiber content which aids digestion, helps prevent obesity and colon cancer, and lowers blood cholesterol levels. With a starch content of 74.58 %, candy palm seeds promote satiety and suppress appetite, making them suitable for dietary purposes (Harahap et al., 2018). Additionally, they are rich in vitamin C (162.04 mg/100 g), which enhances immune function and provides antioxidant benefits. They also contain substantial amounts of calcium (0.59 %) and iron (1.58 ppm), offering a viable alternative source of these essential minerals (Harahap et al., 2018).

A single *A. pinnata* tree can produce 5–10 bunches of fruit, each containing 20–30 kg of seeds. In East Java, productive trees can yield 100–200 kg of seeds per tree per season. In North Sulawesi, production reaches about 270 kg per tree per season (Sylvana et al., 2022), whereas Laksananny & Pujirahayu (2017) reported that *A. pinnata* trees in the agroforestry system of Kendari People's Forest Park could produce approximately 230 kg per tree.

Harvesting candy palm seeds for food involves simpler steps compared to collecting *A. pinnata* sap. First, trees with ripened fruits are selected and the fruits are collected. The rind of the collected fruits is then peeled through boiling. After peeling, the seed flesh is soaked and then flakes. The flakes are ready for sale (Simbolon et al., 2020). A single farmer can produce up to 50 kg of candy palm seeds per day (Handayani et al., 2023). In North Sumatra, farmers can process up to 600 kg of candy palm seeds per month (Simbolon et al., 2020).

[1]In Indonesia, candy palm seeds have economic value in local markets, especially during Ramadan, with prices ranging from IDR 11,000–20,000 per kg (Handayani et al., 2023; Sylvana et al., 2022). Thus, from each tree producing 100–200 kg of candy palm seed per season, farmers can earn approximately IDR 1,100,000-2,000,000 per season[1].

4.2. Starch

The pith from the trunk of *A. pinnata* holds potential for producing starch flour. This flour is typically made from unproductive trees (Soeseno, 1992). A tree that is 15–20 years old can yield 60–70 kg of starch. The flour from *A. pinnata* contains 89.31 % carbohydrates (75.92 % amylopectin and 24.08 % amylose), with a protein level of 0.48 %, a fat level of 0.07 %, and a moisture content of 10 % (Barlina et al., 2020).

The production of flour from the trunk involves several processing stages. First, the trunk is cut into smaller sections and then grated using a grater machine. This process produces pith and trunk bark. The pith should be stirred and filtered promptly to prevent discoloration from white to brownish yellow due to the oxidation. This reaction is caused by the cell destruction in the process that leads to the oxidation of the phenolic compound (Mayer, 1986). Stirring and filtering extract the starch from the pith. The extracted starch is then placed in a settling tank. After several hours, the water is drained, and the starch deposit is transferred to plastic sacks. To reduce moisture content, the sacks are hung overnight. The final step is sun-drying. On sunny days, this process takes one day, but during rainy days, it can take 3 to 4 days. The dry starch flour reaches maximum viscosity at 80 °C (Thoriq et al., 2022).

During the rainy season, the starch flour may develop a brown colour (Thoriq et al., 2022). This browning reaction is a characteristic of flour from *A. pinnata* and is caused by both enzymatic and non-enzymatic reactions. To whiten the flour, bleaching agents such as sodium metabisulfite or hydrogen peroxide are commonly used (Nugroho et al., 2019).

A. pinnata flour is used as a primary or additional ingredient in various products, including vermicelli noodles, complementary foods, edible films (Barlina et al., 2020), meatballs, bread, and other traditional food (Nugroho et al., 2019). However, using the trunk for flour production requires cutting down trees, even if they are unproductive. This practice can impact the sustainability of *A. pinnata* if natural forests are utilized without cultivation efforts, potentially leading to reduced production (Makkarennu et al., 2021).

4.3. Palm saps

4.3.1. Sap production

The most widely used part of *A. pinnata* trees is the sap. Tapping *A. pinnata* sap is a traditional cultural practice that has been passed down through generations, serving as a primary livelihood for communities living near forests abundant in palm trees (Febriyanti et al., 2017). The sap is first harvested from trees aged 8–10 years, marked by the appearance of mature male flowers (Soeseno, 1992). Mature male flowers are characterized by their bloom, yellow stamens, a strong odor when near the tree, sticky sap around the flower clusters, and flowers that are dark green, black, or purple black. Each male flower bunch can be tapped daily for 5–7 months, depending on the bunch's length, the number of segments, and the tree's fertility (Harahap, 2017). In a year, each tree can produce 3–4 bunches, with each bunch yielding 900–1600 L of sap (Rachman, 2009).

Samudra (2011) outlined the sap harvesting process, which involves four key activities: preparation, knocking the inflorescences, cutting off the inflorescences, and tapping the sap. Preparation includes setting up a bamboo ladder for climbing, cleaning the stem of fibers and dirt, and removing fronds. Once prepared, the worker climbs the tree and knocks the mature inflorescence before tapping the sap. Knocking, done with a piece of wood, is performed from the tip of the inflorescence towards the base, and vice versa. This process enlarges the pores of the inflorescence and softens the bunch, facilitating the flow of sap. After knocking, the inflorescence is cut off with a knife. However, *A. pinnata* can no longer produce sap after 10 years of continuous tapping (Tarmizi, 2017). The decline is due to the increasing age of sugar palm trees, which alters plant physiology and morphology, leading to reduce in sap production the damage to the tapping areas of the sugar palm trees (Fatriani et al., 2012; Wardani et al., 2020).

Farmers use *A. pinnata* sap to make fresh juice (Azhar et al., 2019) or process it into various forms of palm sugar, including palm sugar syrup, moulded palm sugar, and crystalline (powdered/coarse) palm sugar (Saputro et al., 2019). Palm sugar is the primary product derived from the sap, and its production is widespread across Indonesian islands. The quantity of palm sugar produced depends on sap production, which is influenced by both tree genetics and environmental factors. Areas characterized by moderate precipitation and humidity levels typically provide increased sap production. Excessive precipitation can dilute the sap, whilst low humidity may result in diminished sap flow (Hai et al., 2024). There are two main accessions of *A. pinnata* in Indonesia: Genjah Aren (characterized by smaller, shorter trees) and Aren Dalam (larger, taller trees). Genjah Aren typically produces 5 to 25 L of sap per bunch daily, whereas Aren Dalam yields 15–25 L (Rompas et al., 1996). Additionally, factors such as soil fertility, topography, and climate impact sap production (Widyantara, 2019). In addition, a moderate negative correlation is observed between light intensity beneath the tree stand and the sugar content of the sap, implying that reduced light intensity may contribute to decreased sugar concentration (Nirawati et al., 2020). The variability in sap production across provinces or islands is detailed in Table 1.

Although the sap production varies, the sugar yield from *A. pinnata* sap remains relatively consistent across different locations. In North Sumatera and Bengkulu, the sugar content of the sap ranges from 15 to 18 % (Apriyanto and Setiadi, 2016; Martini and Roshetko, 2011). Similarly, in East Kalimantan (Fatah and Sutejo, 2015), West Java (Natawijaya et al., 2018), and Sulawesi (Sylvana et al., 2022), one liter of sap can be processed into 0.1–0.15 kg (10–15 %) of palm sugar.

4.3.2. Palm sugar

In Indonesia, sugar cane production in 2022 has reached 2.4 million tons. However, domestic production falls short of total sugar needs,

[1] 1 USD=IDR 15,532

Table 1
Potential trees and sap production across different provinces in Indonesia.

No	Province	Potential trees for sap production/ per farmer)	Sap production (per tree)	Sources
1	North Sumatera	5–6 trees/day	11 L/day or 50 L/ha	Martini & Roshetko (2011)
2	Bengkulu	*No data*	8.7 L/day	Apriyanto & Setiadi (2016)
3	Lampung	8 trees/ha	18.4 L/day	Indriyanto (2023)
4	West Java	*No data*	20.8 L/day	Natawijaya et al. (2018)
5	East Kalimantan	4–5 trees/day	50 L/day or 900–1600 L/ year	Fatah & Sutejo (2015); Komara & Kurniawan (2021)
6	North Sulawesi	8–10 trees/day	7–40 L/day	Yamamoto et al. (2021)
7	South Sulawesi	8–10 trees/day	31–72 L/day	Syahidah et al. (2021); Yamamoto et al. (2021)
8	Southeast Sulawesi	10 trees/day	60 L/day	Tomomatsu et al. (1996)
9	East Nusa Tenggara	6 trees/day	25 L/day	Suka et al. (2020)
10	West Nusa Tenggara	15 trees/day	7.5–10 L/day	Kelompok Tani Hutan Giri Madya (2022)
11	Bali	4 trees/day	13.23 L/day	Widyantara (2019)

necessitating annual imports of approximately 6 million tons to meet demand (BPS-Statistics Indonesia, 2023). Palm sugar, derived from *A. pinnata*, emerges as a potential supplementary sugar source even though its annual production reaches up to 20,376 tons, which is relatively modest compared to the country's total sugar needs. It can contribute to reducing Indonesia's import dependence and mitigating the domestic sugar shortage (Syahidah et al., 2021). Palm sugar can be an alternative to using cane sugar for some food preparations, so it reduces the dependency on cane sugar. Additionally, palm sugar has advantageous nutritional properties compared to cane or beet sugar, including higher levels of glucose, sucrose, protein, fat, potassium, phosphorus (Rumokoi, 1990; Sapari, 1994), as well as vitamins B1, B2, B3, B6, niacin, ascorbic acid, and calcium (Ardiana, 2019; Sarkar et al., 2023). Brown sugar from *A. pinnata* contains lower calories (373 calories) compared to white sugar (396 calories) (Heryani, 2016).

However, the production of brown sugar from *A. pinnata* sap in Indonesia largely relies on traditional methods. Sap is collected nightly from palm trees and must be processed swiftly to prevent deterioration. It is filtered to remove contaminants and then cooked in a large kettle over a wood-fired stove at temperatures exceeding 100 °C until it thickens and develops a caramel aroma (Maryani et al., 2020). Palm sugar is commonly produced in solid, crystal, or granulated forms, but it can also be made into liquid sugar (Lempang et al., 2012). Glucose needs to be added to prevent sugar crystallization in liquid palm sugar to meets Indonesian National Standards (Setiawan, 2020).

Typically, palm sugar production is conducted by individual forest farmers or small village-scale groups, with products sold directly to buyers, either independently or through cooperative arrangements (Hikmah et al., 2022; Mokuna et al., 2017). In some cases, farmers sell fresh sap directly to producers of palm sugar (Lalisang, 2018; Pongoh, 2016).

Farmers who handle packaging often have shorter marketing channels as they sell directly to end consumers. Conversely, the storage function, which involves accumulating processed products over time and in larger volumes, is typically managed by wholesale institutions that purchase from multiple farmers or producers (Hidayat et al., 2017; Sinaga and Aisyah, 2022; Yanti et al., 2019). These marketing institutions generally control the largest volumes of products in the supply chain. The influence of wholesalers and large retailers on the final product price tends to be significant, as their decisions largely affect consumer prices (Deperiky et al., 2019; Gojali et al., 2015; Sumadi et al., 2020).

Marketing channels for palm sugar include various agencies, such as direct farmers, collectors who gather from farmers, local wholesalers, large wholesalers (especially those targeting broader markets beyond local districts), retailers, and palm sugar processing or packaging plants that sell to consumers. Channels with extensive marketing areas typically feature a value chain where a dominant proportion of product volume is managed by the palm sugar processing industry (Gobel et al., 2020; Prihantini et al., 2022). Export-oriented palm sugar marketing often involves formal or informal cooperation with farmers and collectors to ensure stable prices and significant marketing volumes (Fathurrohman et al., 2022; Ikhwana et al., 2019).

The palm sugar industry plays a crucial role in the income of farmers who rely on *A. pinnata*. On average, farmers' income from this industry accounts for about 97.46 % of their total earnings (Andira et al., 2018). Additionally, housewives involved in processing candy palm seeds (peeling and pounding) contribute approximately 30 % to their family's income (Kurniawan, 2021).

In Indonesia, the average income of forest farmers from food products is more than IDR 1 million/month. The ratio of revenue-cost (R/C) and benefit-cost ratio (B/C0 of *A. pinnata* products in several locations was more than 1. This means that the revenue and profit were more than the cost spent on production. It shows that the business is profitable and feasible to run (Table 2). Despite its relative feasibility, the *A. pinnata* farming business is still in the growth stage and requires more optimized development efforts. The limited raw materials originating from natural stands and the scarcity of cultivation activities require more effort in future development. Additionally, the limited knowledge and skills of forest farmers need to be improved in producing better quality of *A. pinnata*'s food products to meet the market demand.

4.3.3. Other products

The sap from *A. pinnata* contains 80–85 % of water and 15 % of sucrose (Yunita et al., 2017). Microorganisms convert sucrose into glucose and fructose, which subsequently form organic acids and alcohol through fermentation (Choong et al., 2016). This fermentation process creates various products from palm sap such as nata pinnata, vinegar, and alcohol. Nata pinnata is a dessert that is chewy with a soft texture and white colour (Barlina and Lay, 1994). It contains over 97 % water, 0.82 % fibre, and 0.15 % protein but is low in vitamin C, fat, potassium, and phosphorus. Nata pinnata is produced by adding 2.5 g of Ammonium Sulfate (ZA) fertilizer into one liter of palm sap to obtain a yield of about 94.22 % (Lempang, 2006).

In eastern Indonesia, palm sap is processed into a local alcoholic drink by the community and is served during traditional ceremonies and communal activities (Suka et al., 2020). Kismurtono (2012) revealed that the highest alcohol yield from palm sap fermentation is achieved using 25 % starter, 0.4 % NPK, and 5 % baker's yeast, resulting in roughly 12 % yield (89 % alcohol concentration) of the raw material. If the fermentation process continues, vinegar or lactic acid is created from the palm sap, which serves as an effective taste enhancer for food (Maliza et al., 2021). To expedite vinegar production, *Hornstedtia rumphii* seed powder is added to the sap, which is then dried under sunlight or boiled (Soeseno, 1992).

Several obstacles remain in the utilization of *A. pinnata*, and the proposed solutions are relatively difficult to implement. For example, the local community around Lake Toba, North Sumatra, is familiar with activities related to the utilization of this species, such as collecting fruits, extracting seeds, planting, harvesting, and processing palm sugar products. However, *A. pinnata* trees mainly come from natural growth, and modern cultivation is rare. Product diversification from palm sap in Indonesia is also uneven across different locations due to varying levels of knowledge among communities.

Technically, post-harvest constraints of *A. pinnata* sap include:

Table 2
Production, income, and feasibility of *A. pinnata*'s business from natural stands[21].

No	Products	Production scale	Income	Feasibility	Location	Sources
1	Food and non-food	SMEs with 240 kg palm sugar /month (IDR 13,000/kg)	10,110,000/month (IDR)	R/C = 2.84	Pastap Julu Village, Tambangan District, Mandailing Natal Regency, North Sumatra Province Batang Gadis National Park	Azhar et al. (2020)
2	Palm sugar	SMEs of palm sap with 32 L per farmer	1583,000/month (IDR)	R/C = 3.0	Palm agriculture in Nagori Sihaporas, Pamatang Sidamanik District, Simalungun Regency, North Sumatera	Tuah & Ambarita (2022)
3	Palm sugar	SMEs of sugar	231,357.14/day (IDR)	R/C = 1.31	Ujung Gading Village, Lembah Melintang District, West Pasaman Regency, West Sumatera	Saleh et al. (2020)
4	Palm sugar	SMEs of sugar	NPV 31,544,279 (IDR)	B/C = 2.26 and IRR = 64.91 %	Cisewu Sub District, Garut District, West Java	Maryati (2019)
5	Palm sugar	SMEs of sugar	448,046/week (IDR)	R/C = 4.7	Sumowono Subdistrict, Semarang Regency, Central Java	Andaryogi et al. (2022a)
6	Granulated palm sugar/ ant sugar	SMEs of ant sugar	24,007,100/year (IDR)	R/C = 1.55	Batu Ampar Village, Tanah Laut Regency, South Kalimantan	Susi & Millati (2021)
7	Palm sugar, granulated sugar/ant palm sugar, sugar palm juice	SMEs with sugar 15,332,019/ year (IDR), Ant palm sugar (9163,072/year (IDR), and 1467,500 (IDR)	26,456,591/year (IDR)	Feasible	KPH Ajatappareng Unit II Barru Regency, South Sulawesi	(Mahmud, 2022)
8	Palm sugar	SMEs sugar industry	7771,412/month (IDR)	R/C = 3.60	Dulamayo Selatan Village, Telaga District, Gorontalo Regency, Sulawesi	Habibu et al. (2022)
9	Palm sugar	SMEs	374,894/month (IDR)	R/C = 2.0	Pringga Jurang Utara Village, Montong Gading District, East Lombok Regency	Hidayat & Soimin (2021)
10	Palm sugar	SMEs sugar makers	1193,912.67/month or 14,326,952.07/year (IDR)	R/C = 1.8	West Nusa Tenggara which is directly adjacent to the Mount Rinjani National Park	Webliana & Sukma Rini (2020)
11	Fruits (*kolang kaling*)	SMEs	1441,362.44/month (IDR)	R/C = 2.5	Tumbukan Dalig Village, Raya District, Simalungun Regency, North Sumatera Province	Simbolon et al. (2020)
12	Flour	SMEs with 234.12 kg/day of dry starch flour	17,343,394/month (IDR)	B/C ratio = 1.63 and IRR = 29.30 %	Rancakalong District, Sumedang Regency, West Java	Thoriq et al. (2022)

1. Sugar production process. The tapped sap must be treated promptly to prevent fermentation. In some regions, traditional methods involve adding specific wood to the sap to prevent deterioration. Haryoso et al. (2020) identified four plant species utilized as pakêt (wood to prevent sap deterioration): purut wood (*Dysoxylum parasiticum* Osbeck), badung wood (*Garcinia parvifolia* (Miq.) Miq.), mundah leaves (*Garcinia dulcis* (Roxb.) Kurz.), and bintangur leaves (*Callophylum soulatri* Burm. f.).
2. Processing expenses. The production costs, particularly for fuel, are significant when converting palm sap into brown sugar or other products, often exceeding the selling price. For example, palm sugar production costs can reach IDR 600,000/week, of which 18 % is the cost of wood fuel and the income earned is only IDR 567,000/week in Central Java (Andaryogi et al., 2022b). Investigating alternative fuels to reduce manufacturing expenses is vital.
3. Cultural and economic influences. There is a tendency to process palm sap into either brown sugar or alcoholic drinks, depending on the local culture and economic significance

5. Potential of *A. pinnata* for energy

5.1. Potential for bioethanol

Data from the Ministry of Energy and Mineral Resources of Indonesia shows that the production capacity for bioethanol fuel grade has only reached 40,000 kL per year, far short of the 696,000-kL requirement (Wisnubroto, 2023). *A. pinnata* is recognized as a potential crop for yielding bioethanol to support energy security due to the abundant and year-round availability of palm sap. The high calorific value of bioethanol from this species makes it a viable fuel source (Ansar et al., 2021b). Studies indicate that palm sap biofuel can produce between 4610 and 13,000 L of ethanol per acre per year (Elbersen et al., 2010), demonstrating significant potential to fill the gap in bioethanol production capacity. Considering estimated area of *A. pinnata* in Indonesia is 64,025 hectares (Directorate General of Estate Crops, 2021), and it may produce 4,6 to 13 kL ethanol per acre or 1.86 - 5.26 kL ethanol per hectare (Elbersen et al., 2010), thus the estimated potency of *A. pinnata* for bioethanol production could reach 119,186 to 336,830.50 kL. This product only fulfills half of the national demand for bioethanol.

The initial processing, fermentation, and refining step are critical to generating bioethanol from palm sap (Pavlečić et al., 2017; Zhang et al., 2016). Freshly harvested palm sap, with a neutral pH, degrades rapidly and must be handled immediately (Bekmuradov et al., 2014; Ho et al., 2008; Naknean et al., 2010). Due to the susceptibility of degradation of palm sugar to external factors, Bušić et al. (2018) emphasize that tapping and distribution during processing are key to acquiring bioethanol from palm sugar. Kismurtono (2012) further explains that the quality of raw materials significantly impacts the bioethanol yield from fermented palm sap (Length et al., 2009; Oguri et al., 2011; Saqib et al., 2013). Microorganisms (*Saccharomyces cerevisiae* bacteria) thrive and release hydrogen ions after tapping, leading to the production of organic acids and changes in pH (Idiata and Lyasele, 2014; Ishak et al., 2013). The pH level of palm sap is crucial to determining its quality (Ho et al., 2007), with a pH of 6–7 considered optimal for ethanol production (Tan et al., 2015). However, maintaining sap quality at a neutral pH is challenging.

The amount of bioethanol produced from *A. pinnata* can fluctuate based on the procedure and conditions during production. Researchers found that bioethanol concentration from palm sap could vary between 32.3 % and 75.6 % following fermentation (Ansar et al., 2021a). The highest concentration and yield of bioethanol were 47.62 % (v/v) and 48.14 % when using a 35 % volume starter with 100 rpm agitation (Ansar et al., 2021a). Another study indicated that the starch-free *A. pinnata* trunk could also be used to produce bioethanol, with an ethanol yield of 95.0 g/kg and maximum glucose yield (Kusmiyati et al., 2018). The separate hydrolysis and fermentation (SHF) method produced more ethanol (8.11 g/L) than the simultaneous saccharification and fermentation (SSF) process (3.95 g/L) according to Kusmiyati et al. (2018).

Although researchers have converted palm sap into bioethanol, the methods remain basic and cannot achieve ethanol concentrations higher than 95 % (Ansar, Putra, et al., 2019). According to Ansar et al. (2019), multilevel fermentation with a molecular sieve is required to produce absolute ethanol with a 99 % alcohol concentration. The treatment of palm sap before processing is crucial for bioethanol production. Environmental factors during tapping and transportation, as well as the fermentation process, can easily degrade palm sap.

5.2. Bioethanol production

The production process of bioethanol (Ansar et al., 2021a) can be described below:

a. The process of fermentation

Palm sap is fermented for three to six days in a fermentation container with a mixture of Fermipan yeast (*Saccharomyces cerevisiae*), lime, and coconut shell charcoal. The ethanol yield increases with fermentation duration, but once optimal conditions are met, ethanol content tends to decrease. This is due to the reduced availability of glucose in the substrate and the additional reaction that occurs as fermentation time increases. Specifically, ethanol oxidizes to acetic acid, resulting in lower ethanol content as the conversion rate of glucose to ethanol becomes less than the oxidation rate of ethanol to acetic acid. According to Deesuth et al. (2015), the ideal fermentation period for producing ethanol using *Saccharomyces cerevisiae* is three days.

b. The first distillation

The first distillation uses an instrument without temperature control. The duration of the initial distillation process is not specified but is based on filling a 50 ml pycnometer. The distillation process concludes when the pycnometer is fully filled.

c. The final distillation stage

To extract ethanol from the fermented solution, the mixture is heated to a temperature above ethanol's boiling point, 78 °C. The evaporated ethanol is then condensed back into liquid form via a pipe.

d. Distillation results

Post-distillation, the volume of the distillate and the percentage of total ethanol content in the palm sap are measured and stored in an Erlenmeyer flask.

e. Bioethanol testing

Bioethanol is tested as a fuel using a 4-stroke engine. First, the motorcycle engine starts with premium fuel to warm it up. The fuel tank pipe is then disconnected and attached to the ethanol fuel hose. Any residual premium fuel in the carburetor is removed by unscrewing the carburetor exhaust cap bolt.

[2] SMEs= small medium entrepreneurship; IDR= Indonesian Rupiah, 1 USD=IDR 15,532; NPV= Net Present Value; R/C= revenue-cost ratio; B/C ratio= benefit-cost ratio; IRR= Internal Rate of Return

5.3. Opportunities and challenge

The adaptability of *A. pinnata* for bioenergy production is highlighted by its inclusion among tree species suitable for bioenergy generation in degraded and marginal areas in tropical climates (Borchard et al., 2018). Utilizing this species for bioenergy production offers several potential environmental benefits. Firstly, its cultivation can improve soil quality and biodiversity due to its deep-rooted nature and sustained growth features (Lavelle, 2011). This can lead to enhanced soil health and ecosystem resilience (Lavelle, 2011; Sharma et al., 2016). Pierret et al. (2016) assert that deep roots are essential for ecosystem services including pedogenesis, groundwater regulation, streamflow moderation, soil carbon sequestration, and the preservation of soil moisture. Extensive roots can also establish homes for varied microbial communities by exuding metabolites and organic materials into the rhizosphere (root zone). This promotes biodiversity and improves soil health. Secondly, bioenergy production from *A. pinnata* has the potential to reduce greenhouse gas emissions, thereby helping to mitigate climate change and support environmental sustainability. A study conducted in 'Biopertalite E-25′ (25 % bioethanol blended in gasoline) could reduce 86 % and 30.6 % for CO and CO_2 emission respectively compared to 'Pertalite E-0′ (Iskandar et al., 2022). The cultivation of sugar palm is recognized for its capacity to preserve soil and water, while sequestering substantial quantities of carbon in its sizable stems, in comparison to other monocotyledonous plants (Fadhilla et al., 2023; Yudhiantami et al., 2021). This underscores its function in diminishing atmospheric CO_2 and facilitating climate change mitigation initiatives. Thirdly, bioenergy production from *A. pinnata* is likely to achieve a positive energy balance, meaning that the energy output from *A. pinnata* exceeds the energy input required for its growth and processing, illustrating its efficiency and sustainability for biofuel production. Lastly, *A. pinnata* tolerance of drought conditions make it a viable bioenergy source in areas prone to water scarcity. Its ability to thrive in harsh conditions can facilitate sustainable energy production without exacerbating water shortage issues (Lavelle, 2011). Attributes underscore sugar palm's potential as a sustainable and eco-friendly bioenergy source that aligns with environmental conservation and climate change mitigation efforts.

However, the application of *A. pinnata* for bioenergy generation faces several challenges despite its significant potential. The processing of *A. pinnata* biomass for biofuel production involves technical obstacles and requires effective methods to extract and convert the raw material into usable biofuels (Ansar et al., 2021b). Commercializing bioenergy products from this species encounters issues related to market acceptance, distribution networks, and economic feasibility, which need to be addressed for effective large-scale deployment (Imraan et al., 2023). Efficient bioethanol production from palm sap necessitates advanced optimization procedures, including the selection of suitable inoculums like *Saccharomyces cerevisiae*, which require careful management to maximize output (Ansar et al., 2021b). *A. pinnata* provides environmental advantages, including drought resistance and soil improvement, due to its resilient root system, which acts as a natural stabilizer by intertwining soil particles, reducing erosion risks, improving groundwater retention, conserving soil moisture during dry spells, and accessing deep water reserves inaccessible to shallow-rooted crops (Faadhilah et al., 2023; Fadhilla et al., 2023; Gunawan et al., 2018). However, concerns regarding its cultivation's effects on biodiversity and ecosystems necessitate responsible management (Lavelle, 2011). Processing *A. pinnata* sap for biofuel production requires specialized procedures to enhance their properties for bioenergy applications, adding to the complexity of the manufacturing process. Additionally, for bioenergy, the higher concentration of palm sap bioethanol increases the viscosity of the fuel mixture (Arenga bioethanol and premium fuel), but the heating value is lower (Ansar et al., 2020). Overcoming these challenges through technical advancements, sustainable practices, and market strategies is essential to fully realize *A. pinnata's* potential as a renewable energy source.

6. Potential of *A. pinnata* for soil and water conservation

In the ecosystem, *A. pinnata* significantly contributed to biodiversity and environmental protection. Its potential for water conservation is notable due to its ability to conserve both soil and water (Yudhiantami et al., 2021). Some ways in which *A. pinnata* can contribute to water security include:

6.1. Soil conservation

The roots of *A. pinnata* play a crucial role in soil and water conservation and erosion prevention (Fadhilla et al., 2023; Gunawan et al., 2018; Heriberta et al., 2021). Its deep root system contributes to soil stabilization and water conservation (Smits, 1988). *A. pinnata* has a fibrous root system, which consists of many fibrous roots and root hairs that are shallow, wide, and have numerous root branches. These roots can quickly penetrate the subsoil, making them effective at holding soil particles and preventing erosion. The roots of a mature palm tree are large and strong, reaching lengths of up to 10 m (Idris et al., 2021; Iskandar and Iskandar, 2021; Rinawati et al., 2021; Sari, 2021), with a depth of 3–15 m and a width of 10 m (Mulyanie and Romdhani, 2017; Smits, 1988). Additionally, stands of *A. pinnata* can conserve soil by storing relatively more carbon than other agricultural monocot plants (Yudhiantami et al., 2021). Soil organic carbon has an essential contribution to soil fertility by protecting soil physical properties of soil and stabilizing soil organic matter (Deb et al., 2015).

6.2. Water retention

A. pinnata excels in rainwater retention. Each leaf midrib can hold 1–2 L of rainwater for several hours. Additionally, *A. pinnata* can store and absorb up to 200 L of water, reaching its maximum water absorption capacity in just three years (Mulyanie and Romdhani, 2017). The roots of the species can regulate groundwater, contributing to the hydrological cycle, and its ability to retain large volumes of rainwater aids in flood control (Idris et al., 2021).

Furthermore, the trunk of *A. pinnata* also stores water. Vascular bundles (xylem and phloem) are distributed throughout the trunk, with water parenchyma cells functioning to store water as a reserve. The trunk holds the largest portion of water due to its volume, making it a significant organ for water storage (Mulyanie and Romdhani, 2017).

6.3. Local wisdom for soil and water conservation

A. pinnata embodies local wisdom, encompassing cultural values of respect and adaptability to the environment and life based on traditional norms. Though often stereotyped as primitive, these living values and practices remain effective instruments for environmental conservation in the post-modern age (Indrawardana, 2012; Yuldanti et al., 2016). In Magelang, Central Java, there is a rule that prohibits the cutting of *A. pinnata* due to its use in water conservation (Wibowo, 2022). A study by Febriyanti et al. (2017) revealed that in Banten, West Java, the local community considers *A. pinnata* a tree of life, believing that "if you find it, you will live and not be miserable". The traditional techniques of planting, tapping, and processing *A. pinnata* have been passed down through generations (Hidayana and Lahpan, 2022). Cliffs planted with *A. pinnata* have abundant water and are highly effective at storing and retaining it. This was proven in Minahasa when a flood in 2000 caused severe landslide damage to cliffs without *A. pinnata*, while cliffs with *A. pinnata* experienced no landslides (Mulyanie and Romdhani, 2017).

Additionally, forests and trees play a crucial role in soil and water conservation within agroforestry systems (Sudomo et al., 2023). *A. pinnata* is well-suited for agroforestry due to its characteristics, such as being an evergreen plant with high water requirements and moderate wind tolerance. It is best planted on steeper slopes, easily eroded lands, or in single or double rows near field boundaries, where it contributes to soil stability without requiring large areas of land (Mogea et al., 1991). Integrating *A. pinnata* into agroforestry systems can provide economic benefits, contribute to the conservation of non-timber forest products (Adalina and Sawitri, 2021) and improve soil health. Local knowledge of utilizing and managing *A. pinnata* in agroforestry systems is also found in Cianjur, West Java (Fig. 4).

Fig. 4. *A. pinnata* in mix-garden agroforestry.
Source: Gunawan et al. (2018).

A. pinnata can also adapt to certain agroforestry systems in areas with limited soil and water conditions, given appropriate management practices. This practice plays a crucial role in enhancing agroecological, social, and economic resilience (Dumrongrojwatthana et al., 2020; Martini et al., 2012). A study in West Nusa Tenggara found that sugar palm regeneration in agroforestry gardens is reasonably sustainable, with clustered distribution due to seed dispersal by Rinjani civets (*Paradoxurus hermaphroditus rinjanicus*). Farmers believe that seeds from their feces grow faster than those naturally planted near the main tree (Haryoso et al., 2020). Notable palm-based agroforestry centres are found in Halmahera Regency (Maluku Province) and Batanghari Regency (Jambi Province), where numerous plant species are cultivated on agroforestry land with sugar palm as the main crop (Heriberta et al., 2021; Ruslan et al., 2018).

Despite its many environmental advantages, the development of *A. pinnata* for soil and water conservation faces several challenges. The challenges include:

i. Conversion of agricultural land and plantations into physical developments such as offices, housing, and village expansion.
ii. *A. pinnata* regeneration involves a relatively long dormancy period and has a low germination capacity.
iii. The natural population of *A. pinnata* is decreasing due to many old, non-productive trees, and efforts to rejuvenate this population have not been optimal.
iv. Sustainable *A. pinnata* cultivation supports conservation, but poor management can cause habitat loss, conflicts, and soil and water degradation by reducing moisture retention and increasing erosion.
v. High demand for *A. pinnata* products (such as palm sugar and sap) during feasts can cause overharvesting, stressing trees and lead to habitat loss, erosion, and reduced water retention.
vi. Cutting of *A. pinnata* for horse fodder (Indasary et al., 2019; Martini et al., 2012; Musdalifah et al., 2022; Silalahi, 2020; Surya et al., 2018; Tamrin et al., 2015).

7. Strategies for enhancing *A. pinnata* as source of food, energy, and water conservation

7.1. Optimization of production of *A. pinnata*'s products

The development of *A. pinnata* through cultivation practices is still limited due to the lack of knowledge, skills, and effort by farmers. In contrast, the natural population decreases gradually because of several factors, such as land conversion for other types of land use and the decline of productive trees. To increase and ensure the sustainability of *A. pinnata* productivity, several strategies should be formed, including proper cultivation techniques, plant breeding, and improved knowledge and skills of farmers.

7.1.1. Cultivation techniques

Several aspects need to be considered in *A. pinnata* cultivation techniques, including climatic and soil conditions, mother trees, nurseries, propagation, and seedling techniques, as well as planting and maintaining plants (Ikhsan et al., 2021). Seeds are an important source of propagation for plant cultivation. Natural regeneration can be enhanced by planting fruit-producing trees in mixed orchards to attract *Paradoxurus hermaphroditus*, which helps distribute *A. pinnata* seeds through their feces (Gunawan et al., 2018). However, for the sustainability of the *A. pinnata* population, it cannot rely solely on civet-assisted regeneration. Farmers can attempt propagation by breaking seed dormancy using proper treatments. Seed dormancy can be addressed by pre-treatment before seed sowing. Application of H_2SO_4 followed by storing in an incubator at 40 °C reduces the dormancy period to 2–6 months (Parikesit et al., 2021), whereas natural germination requires 6–24 months (Mashud et al., 1989). Soaking seeds in water at 75 °C for 15 min and applying plant hormones like gibberellin (concentrate 150 ppm) effectively break dormancy and increase the germination rate to about 65 % (Purba et al., 2014).

7.1.2. Tissue culture

Tissue culture can be another solution for addressing *A. pinnata* regeneration issues. The types of plant tissue culture methods most recognized in practice are organ culture (organogenesis), callus culture (callogenesis), suspension culture, protoplast culture and another culture (George et al., 2008). Seed culture and embryo culture are different categories of plant tissue culture that is commonly practiced (Chawla, 2002). The plant tissue culture of sugar palm is still at an early stage. Established plant Tissue culture protocols of sugar palm may be useful for the commercial production of pure line seedlings in order to conservation of its germplasm and are particularly important for establishing crop improvement studies through biotechnological intervention.

7.1.2.1. Embryo culture. Embryo culture is one of the earliest types of tissue culture techniques and has been shown to be of the greatest of greatest value to plant breeders (Dunwell, 1986). Embryo culture shortens the breeding cycle of a plant species by overcoming seed dormancy (Bridgen, 1994). Arsyad et al. (2013) established an embryo culture protocol in Arecaceae with the aim to evaluate the relationship between embryo age and different nutrient medium composition on the rate of *in vitro* germination and plant development within a given period of time. Embryos excised from fresh fruits at 15 and 30 months after anthesis were used as explants. At the end of the study, it was reported that the explants from the 15-month-old fruits had the highest rate of germination (90 %), while explants obtained from 30-month-old fruits promoted 72 % of the germination rate. germination. The growth and development of cultures were not influenced by the different composition of the nutrient medium. composition of the nutrient medium, although abnormalities were observed in the formation of the haustorium and cotyledonary petioles. were observed.

In another study, Abdullah et al. (2015) reported an established methodology of aseptic seedlings production of sugar palm via embryo culture. Given the prolonged germination of sugar palm seeds under nursery planting, plant tissue culture method was observed to promote rapid regeneration of aseptic seedlings within a relatively short period of time. Immature embryos as explants were extracted from surface sterilized immature fruits and inoculated on basic MS (Murashige and Skoog, 1962) medium and MS medium modified with different concentrations of 6-benzylaminopurine (BAP). Results obtained after 8 weeks of observation showed that 60 % of explants cultured on MS medium supplemented with lower concentrations of BAP promoted rapid regeneration in the forms of enclosed sheath and radicles. Adventitious shoots development was only visible after 32 weeks. The highest percentage shoots regeneration was eventually observed from the explants cultured on free-hormone MS medium with 90 % shoots emergence after 24 weeks. Complete aseptic seedlings were successfully established after 32 weeks.

7.1.2.2. Organogenesis. The ability to develop adventitious roots and shoots through plant tissue culture (organogenesis) is considered to be the paramount importance in plant tissue culture (Dodds and Roberts, 1985). Muda et al. (2019) reported direct organogenesis in Arecaceae using immature zygotic embryos and basal stem segments excised from aseptic seedlings as explants. All explants were inoculated on MS medium containing different concentrations of plant growth regulators (PGRs) and the organogenic potential of the explants was monitored. Within 8 weeks of culture, the explants tested were responsive, but the number of shoots and roots were significantly influenced by the composition of PGRs in the culture medium. Optimum organogenesis response was observed from basal stem explants cultured on MS + 1.0 mg/L kinetin (Kin) + 2.0 mg/L 1-naphthaleneacetic acid (NAA) with 90 % regeneration rate, 9 adventitious shoots and 25 roots. Frequent subculturing of the regenerated shoots on basal MS basal medium (MS0) optimized the further development of the plantlets. Meanwhile, immature zygotic embryo explants inoculated on MS + 2.0 mg/L BAP + 2.0 mg/L NAA showed an optimal rate (70 %) of root regeneration. It was also reported that embryo explants inoculated with MS + 2.0 mg/L BAP + 1.0 mg/L gibberellin acid (GA_3) + 1.0 mg/L silver nitrate ($AgNO_3$) was found to be to promote optimal adventitious shoot regeneration (10 shoots) in culture. MS + 3.0 mg/L Indole-3-butyric acid (IBA) promoted abundant rooting of the cultures. The whole plantlets were later acclimatized on planting medium prior to transplanting under greenhouse conditions.

7.1.2.3. Greenhouse acclimatization. The hardening and acclimatization process of plantlets are the most critical steps in determining the success of plant tissue of plant tissue culture (Purohit, 2012). The acclimatization phase was used in the conventional plant tissue culture method in which the developed plantlets or micro cuttings grown in vitro were transferred to the ex-vitro environment for growth. The acclimatization procedure of sugar palm was reported by Muda and Awal (2018). The aim was to investigate the appropriate components of growing media for successful acclimatization of aseptic and clonal seedlings clonal sugar palm seedlings prior to their introduction under greenhouse conditions, the procedure was carried out in two phases. In the first phase, aseptic and clonal seedlings were deflasked, washed and transferred to new culture containers containing MS salt solution after incubation at a temperature of 25 ± 2 °C for 2 weeks. Later, for the second stage procedure, the subsequent plantlets were treated with fungicide and planted in plastic pots filled with plastic pots filled with different growth media for acclimatization. The highest rate of plantlet survival (100 %) after 4 weeks of acclimatization was observed on the soil:peat moss: perlite substrate mixture at a ratio of 2:2:1, followed by the final result of 80 % survival after 4 months of transfer to soil.

Seed dormancy, lack of quality of planting material and inadequate variety evaluation are hampering commercial *A. pinnata* cultivation. Plant tissue culture technology offers hope for successful rapid and mass propagation, as this method shortens the long cycle of plant growth through conventional breeding. Plant tissue culture also benefits crop improvement studies through biotechnological interventions.

7.1.3. Agroforestry systems

Agroforestry systems can be applied to develop *A. pinnata* by combining it with other economically valuable species and/or crops. Adjusting the spacing, thinning, and replacing unproductive plants with *A. pinnata* can increase land productivity, production sustainability, and farmers' income (Ikhsan et al., 2021; Zuhud et al., 2020). Spacing of *A. pinnata* for plantation was 9 × 9 m in mixed garden, or 6 × 16 m in polyculture system (Bernhard, 2007). In mixed garden, *A. pinnata* can combine with crops, such as coconut, clove, vanilla, coffee and cacao or woody and fruit plants, such as durian, jackfruit, *Maesopsis eminii, Mangifera foetida*, and *Archidendron pauciflorum.* The production of palm sugar from those systems can contribute to farmer's income around IDR 650,000–3000,000/month (Adalina and Sawitri, 2021; Martini and Roshetko, 2011).

7.1.4. Tree breeding

As previously noted, the cultivation of *A. pinnata* predominantly depends on natural regeneration. Thus, for long-term strategy, tree breeding for *A. pinnata* is needed to maintain the genetic variation of this species in its natural habitat. Rijzaani et al. (2017) assembled a draft of the *A. pinnata* genome. The total length of the genome obtained was 1, 175,552,447 bps, or about 85 % of the estimated size of the *A. pinnata* genome. From this genome, many SSR markers were identified. Knowledge of the *A. pinnata* genome, including SSR markers in large numbers, would be beneficial for various genetic studies, the future development of *A. pinnata*, and the selection of germplasm for breeding.

Tree breeding can also improve the productivity of *A. pinnata* by establishing seed sources characterized by high genetic quality. From these seed sources, superior seeds can be produced to enhance fruit yield, sap yield, and the quality of saps and fibers.

7.1.5. Farmers' knowledge and skills

In addition to improving and maintaining the *A. pinnata* population, enhancing farmers' knowledge and skills are essential for increasing productivity. It is necessary to spread knowledge through effective socialization and counseling to increase understanding of maintaining and managing *A. pinnata* trees. A forum may be formed to include farmers from various regions, allowing them to share information and create regional cooperation. Collaboration in terms of meeting the demand for *A. pinnata* products by supplying the necessary requirements can be developed. Community empowerment can be pursued to achieve these goals, requiring support from all stakeholders, including the government, NGOs, community institutions, and other local assistants (Zuhud et al., 2020).

7.2. Diversification products of A. pinnata

Optimizing products from *A. pinnata* involves diversifying its current offerings to expand the market and improve product utility. For instance, the fruit (*kolang-kaling*) can be processed into various products like jelly candy or jelly drinks, which have a longer shelf life. Jelly candy made from *A. pinnata* can be mixed with honey (Silaen and Ginting, 2020), pineapple (Nababan, 2023), pumpkin (Fitriana et al., 2020), or *Ocimum sanctum* (Dewi, 2022) to enhance its characteristic (pH, water level, crude fiber, sugar level, texture, color essence, and taste). Additionally, incorporating native species like grass jelly into *A. pinnata* jelly drinks can cater to consumer demand for healthy food and beverages (Rujito et al., 2020).

The starch from *A. pinnata* has the potential for a base material in making edible films. Edible films are thin, continuous layers made from edible materials, used for food packaging and protection against damage from oxygen, water, light, and microbes, as well as preventing contamination (Rahmawati et al., 2016). They can also prevent the loss of volatile compounds that give food products their special aroma (Falguera et al., 2011).

Fibers can be produced from the trunk/stem of *A. pinnata*. Sugar Palm Fiber (SPF) can replace synthetic fibres, making these natural products environmentally friendly (Yahya and Sheng Chin, 2017). SPF is strong and stiff, exhibiting exceptional structural properties, which make it suitable for construction materials (Hrabĕl et al., 2018). Its quality (long-lasting and seawater resistant) also makes it a potential reinforcement for polymer composites (Imraan et al., 2023). Alkali-treated SPF has flame resistance, making it suitable for motorcycle components (Sherwani et al., 2021). SPF can be used in making bricks, as a constituent in vehicle body fibres and concrete fibres (Azhar et al., 2022), and for producing MFC (Micro Fibrillated Cellulose) as a nucleating agent in Polypropylene (PP) composite applications (Yuanita et al., 2017).

Diversifying palm sugar products by enhancing skills and improving production equipment can significantly increase palm farmers' income and make the products more suitable for consumers. For instance, producing liquid sugar instead of solid sugar reduces production costs, as the process is shorter. However, modifying the process to prevent foam formation, which can lower sugar quality, is necessary. This can be achieved by adding lime (CaO) with an evaporation temperature of 70 °C (Nursafuan et al., 2016) or adding candlenut seeds and coconut oil (Santika et al., 2023).

Palm sap from *A. pinnata* can also be utilized to produce medicinal alcohol or bioethanol for bioenergy through fermentation (Kismurtono, 2012; Maliza et al., 2021). To enhance its potential for bioenergy production, the following strategies may be considered:

i. Technological advancements. Implementing sophisticated processing technologies to speed up the conversion of sugar palm biomass into biofuels, boosting efficiency, and reducing processing difficulties (Sanyang et al., 2016).
ii. Market development strategies. Developing solid market strategies, strengthening distribution networks, and improving the economic feasibility of sugar palm bioenergy products to overcome commercialization challenges and gain market acceptance (Imraan et al., 2023).
iii. Optimization techniques. Focusing on research and development to optimize bioethanol production from palm sap, such as enhancing Saccharomyces cerevisiae as an inoculum, can improve output efficiency and overall biofuel generation from *A. pinnata* (Ansar et al., 2021b).
iv. Sustainable practices. Implementing sustainable cultivation practices for sugar palm to mitigate environmental impacts, preserve biodiversity, and ensure ecosystem resilience is crucial for the long-term viability and acceptance of sugar palm bioenergy production (Elbersen et al., 2010).
v. Novel pretreatment methods. Exploring novel pretreatment procedures for sugar palm fibers to improve their characteristics and suitability for bioenergy applications will streamline the manufacturing process and enhance overall efficiency (Imraan et al., 2023).

By applying these strategies, stakeholders in *A. pinnata* bioenergy production can address processing challenges, commercialization barriers, optimization requirements, environmental impact concerns, and pretreatment demands. These solutions can help unlock the full potential of sugar palm as a sustainable and efficient bioenergy source while overcoming current limitations in its exploitation for renewable energy generation.

7.3. Business model and marketing strategy for A. pinnata development

The business model of *A. pinnata* in Indonesia primarily operates through traditional, small-scale, and segmented marketing channels (Fathurrohman et al., 2022; Masitah and Suwianto, 2023). These channels are typically managed independently or by farmer groups, often without formalized structures, leading to inefficiencies and limited market reach (Makkarennu et al., 2019). Customer segmentation primarily targets the mass market within local communities, with procurement relying heavily on middlemen. This reliance on intermediaries often results in reduced profit margins for farmers while increasing end-consumer prices. The key value propositions of *A. pinnata* products revolve around affordability and preservative-free, appealing to health-conscious consumers who prefer natural sweeteners. Distribution channels are largely indirect, involving intermediaries who facilitate the sale of raw and processed *A. pinnata* products to nearby markets. However, some direct sales occur through local markets, farmers' cooperatives, and small-scale processing units. Customer relationships are informal, built on personal trust and long-standing social networks rather than contractual agreements. To support production, partnerships are often established with *A. pinnata* tree landowners through profit-sharing agreements, which help secure raw materials while minimizing operational costs. The revenue model is primarily based on palm sugar sales, with minimal product diversification into high-value derivatives like palm flour or bioethanol. The cost structure remains low due to the use of naturally sources raw materials (e.g., palm sap and firewood) and reliance on family labor. Transportation costs being the primary cash expenditure, particularly in rural areas with poor infrastructure.

Recent studies suggest that two key marketing strategies can enhance the *A. pinnata* industry's sustainability and economic viability. First is developing marketing networks through partnerships and enhancing product value through diversification (Purbaningsih et al., 2022; Simamora et al., 2021; Suliyanto et al., 2019). Partnerships between farmer groups and larger corporations can facilitate value chain integration, improving competitiveness and enabling market access, including exports (Simbolon et al., 2022; Yani et al., 2022). The second is to seek government support to reduce production costs and enhance market stability (Makkarennu and Rahmadani, 2021). Government intervention is essential to lower production costs and stabilize pricing, particularly for smallholder farmers who struggle with fluctuating market conditions. Support in the form of subsidies, infrastructure improvements, and regulatory frameworks can optimize the supply chain and increase profitability for producers.

One of the critical indicators used to assess the effectiveness of marketing channels is farmer share, which reflects the proportion of final selling price retained by producers (Bappenas, 2021; Kotler et al., 2022). Studies show that for palm sugar, the farmer share ranges widely from 34 % to 100 %, depending on the involvement intermediaries and the complexity of the supply chains (Mokuna et al., 2017; Sakban et al., 2017). In contrast, for other processed *A. pinnata* products, such as palm flour, farmer share is significantly higher at 78 % (Suminar et al., 2019). However, there is no direct correlation between the supply chain and farmer share. This variation arises due to disparities in consumer-end pricing, regional market differences and the bargaining power of producers (Mokuna et al., 2017; Prihantini et al., 2022).

Expanding business scale and improving market access are critical to enhancing economic efficiency. Post-harvest processing technologies and improved tapping method can increase production yields, reduce waste, and optimize revenue streams (Purbaningsih et al., 2022; Suliyanto et al., 2019). Farmer group cooperatives play a vital role in facilitation inter-regional trade by building and developing business partnerships with other stakeholders, such as large agents (middlemen) and the government. Information sharing between entities can improve business growth, particularly when it comes to harvesting and cultivation technology and product diversity (Astuti Wisudayati and Charity Hidayat, 2023; Fitriwati et al., 2023). A well-structures collaboration among stakeholders – including regulatory bodies, financial institutions, and exporters- can accelerate market development and establish a more stable and competitive industry framework (Simamora et al., 2021).

Despite the traditional nature of *A. pinnata* marketing, emerging opportunities in digital and e-commerce can revolutionize distribution models to open new markets both domestically and internationally. Online marketplaces, direct-to-consumer sales, and influence-driven marketing can help farmers bypass intermediaries, leading to shorter supply chains and higher profit margins (Mirza et al., 2022). Farmers who handle packaging functions have shorter marketing channels compared to those who sell palm sugar directly to consumers or juice to palm sugar producers, as they sell directly to end consumers (Hidayat et al., 2017; Yanti et al., 2019). Establishing an online presence through social media networks and e-commerce platforms can facilitate direct-to-consumer sales and enable *A. pinnata* products to reach consumers beyond local communities. Additionally, fostering partnerships with retailers, wholesalers, and foodservice providers can help penetrate mainstream markets and expand product availability. Collaborating with these stakeholders to develop innovative product formulations and packaging can enhance the appeal of *A. pinnata* products to a broader consumer base. Expanding export market share is more effective when done collectively, as it requires meeting strong foundational criteria. Additionally, government support is necessary to provide market intelligence, product standardization regulations, and assistance with facilities and infrastructure (Mulyani et al., 2024). Investment in research and development to improve cultivation and processing methods is also crucial for scalability and efficiency.

To effectively develop *A. pinnata* products, a comprehensive marketing strategy is imperative. Processed *A. pinnata* products, such as palm sugar or biofuel, appeal to consumers seeking healthier or environmentally friendly lifestyles (Oktoyoki et al., 2021; Sanyang et al., 2016). For food products, the strategy should capitalize on the growing consumer interest in natural and organic products while addressing the unique attributes and challenges of the *A. pinnata* industry. Raising awareness about the health benefits and versatility of *A. pinnata* products is essential, particularly its potential to yield sugar with a low glycemic index (approximately 40) (Haagen and Lantican, 2014). This can be achieved through targeted marketing campaigns highlighting its low glycemic index, suitability for diabetic individuals, and its role in traditional Indonesian cuisine and beverages. Collaborating with health professionals and influencers can amplify this message and reach a wider audience.

Furthermore, leveraging the increasing demand for biofuels presents an opportunity to expand the market for *A. pinnata*-derived ethanol (Fig. 5). Positioning *A. pinnata* as a sustainable alternative to traditional biofuel sources can attract environmentally conscious consumers and foster partnerships with government initiatives aimed at reducing carbon emissions. Palm-based ethanol production offers a strategic advantage as palm trees thrive in equatorial regions, often coinciding with areas inhabited by marginalized populations. Redirecting revenues from bioethanol consumption in wealthier nations to these regions could have significant social benefits. The increasing global demand for biofuels, especially bioethanol and biodiesel, stems from mandates in many countries requiring their blending with gasoline or diesel to reduce oil import expenses and mitigate greenhouse gas emissions from the transportation sector.

The *A. pinnata* industry faces several challenges. One significant challenge is the reliance on traditional cultivation and processing methods, which may limit scalability and efficiency. Fluctuating weather patterns and environmental degradation pose risks to palm tree health and productivity. Additionally, competition from alternative sweeteners and imported sugar substitutes presents a challenge to the market expansion of *A. pinnata* products. Embracing sustainable practices not only aligns with consumer preferences but also ensures the long-term viability of the *A. pinnata* industry amidst environmental challenges.

A multifaceted marketing strategy that emphasizes health benefits, sustainability, and innovation is key to driving the development and market expansion of *A. pinnata* products. By capitalizing on market trends, leveraging strategic partnerships, and embracing technological advancements, the *A. pinnata* industry can realize its full potential and establish itself as a prominent player in the natural products market.

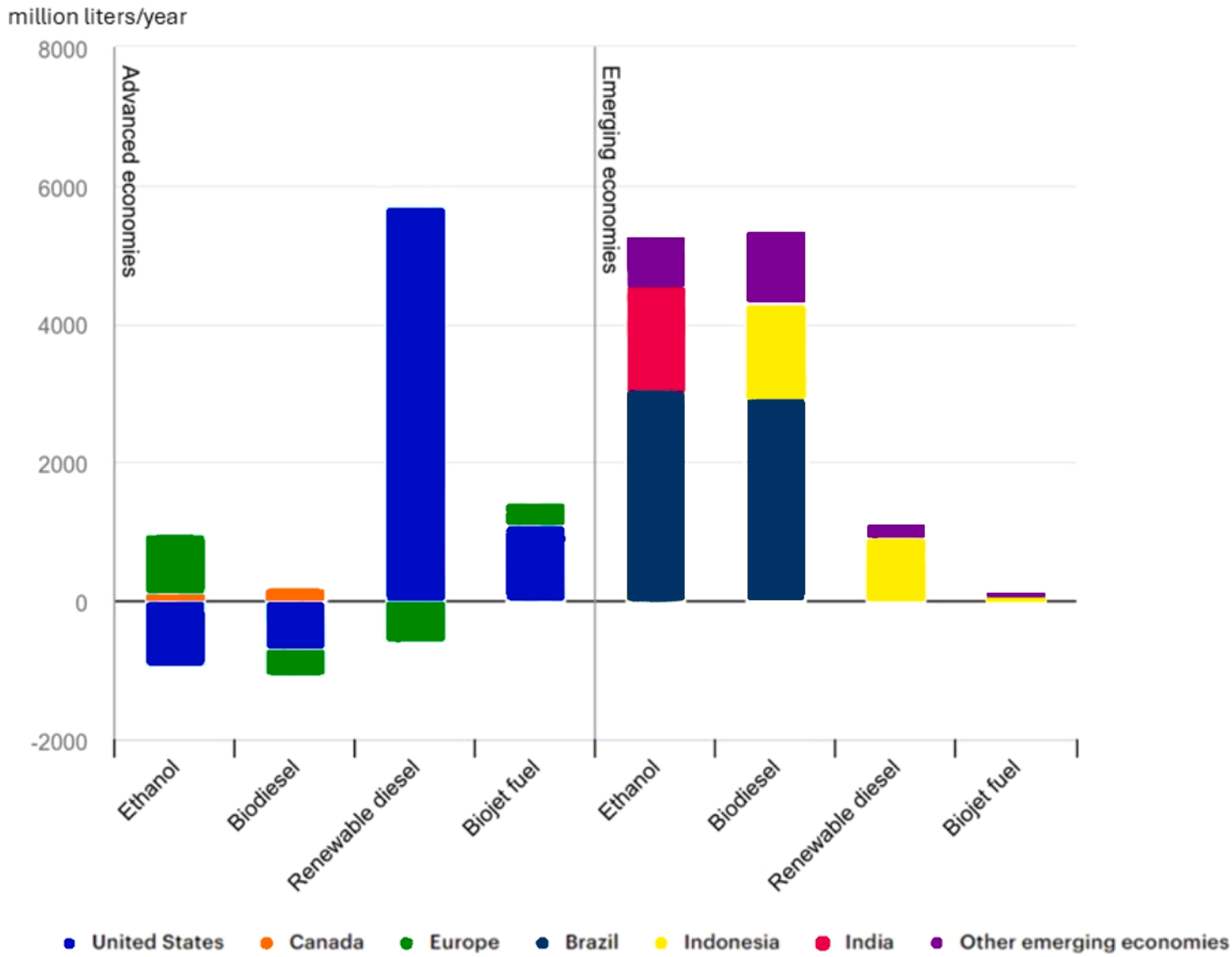

Fig. 5. Biofuel demand growth by fuel and region, 2022–2024.
Source: IEA (2023).

8. Conclusion

Arenga pinnata a native species of Indonesia, possesses high economic value and potential as a source of food, energy, and water conservation. The sap of *A. pinnata* is crucial for producing palm sugar, which boasts superior characteristics compared to cane sugar and can help meet domestic sugar demand. Additionally, the sap holds potential for bioethanol production with high oil yields. The population of *A. pinnata* also significantly contributes to water conservation, as its roots and stems can store large amounts of water. However, several challenges must be addressed to effectively develop this species. These challenges include declining populations due to forest and land conversion, a lack of cultivation, and limited knowledge and skills among farmers regarding maintaining and expanding its population, product diversification, production processes, and marketing. To promote the development of *A. pinnata*, several strategies can be implemented:1) Increasing farmers' knowledge and skills in cultivating the species, 2) Optimizing the production process and product value chain development of palm sugar and other products, 3) Fostering collaboration between stakeholders, especially the government, through policies that support farmers in developing and marketing their products. Implementing these strategies is expected to enhance the productivity of *A. pinnata*, improve farmer welfare, and provide environmental benefits. Consequently, *A. pinnata* can become a superior commodity for food, energy, and land-water security in Indonesia.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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