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Review Article

Ramie Fibers from Agroforestry System as Sustainable Materials for Functional Textiles: A Review

Manggar Arum Aristri[1,2], Wahyu Hidayat[3], Apri Heri Iswanto[4], Muhammad Adly Rahandi Lubis[1,*]

[1] Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong, Indonesia,
[2] Department of Forest Management, Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Indonesia
[3] Department of Forestry, Faculty of Agriculture, University of Lampung, Bandar Lampung, Indonesia
[4] Department of Forest Products Technology, Faculty of Forestry, Universitas Sumatera Utara, Padang Bulan, Indonesia
[*] Corresponding Author. E-mail address: muha142@brin.go.id

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ABSTRACT

Agroforestry system is a form of integrated land use involving forestry and agriculture, which is expected to help overcome the problems of increasing demand for agricultural land, decreasing environmental quality and poverty rates, and resulting in increasingly complex global issues. This system includes a combination of forestry crops with agricultural crops or other plants that can grow together on the same land. The application of agroforestry can improve agricultural welfare, overcome the environmental crisis and poverty, and maintain the sustainability of natural resource conservation. Ramie (*Boehmeria nivea*) fiber is an interesting plant to cultivate using an agroforestry system. It is easy to cultivate, positively impacts the environment, and has many application benefits because it is known as a strong and long-lasting fiber. On the other hand, the textile industry in Indonesia still predominantly uses cotton fiber which has low productivity, so the value of cotton imports increases yearly. Given the increasing demand for environmentally friendly and sustainable textiles, researchers and industry stakeholders are looking for other materials that provide functionality and environmental advantages. Ramie fiber is a type of natural fiber with advantages compared to other natural fibers, such as tensile strength, mechanics, and cellulose content, which has similar characteristics to cotton so that ramie can be applied as a functional textile material to replace cotton. This review paper aims to provide an in-depth overview of all ramie fiber properties, methods, and applications for functional textiles. This article highlights the environmental benefits of ramie fiber and its potential to encourage a more sustainable textile industry, citing various sources.

1. Introduction

Due to increasingly limited land availability in forest fringe areas, this has resulted in the widespread planting of various types of trees on the same land among farmers. However, converting natural forests into agricultural land can cause many problems in the form of erosion, decreased soil fertility, extinction of flora and fauna, flooding, drought, and global environmental change. Therefore, agroforestry emerged as a new science in forestry and agriculture. Agroforestry combines forestry science and agronomy, which combines agricultural forestry and forest conservation. Agroforestry is expected to be useful for preventing the expansion of degraded land, conserving forest resources, improving the quality of agriculture, and perfecting silvicultural intensification and diversification. It is hoped that the existence of this agroforestry system can improve farmers' welfare, conserve natural resources, and empower local communities through community-based forest management so that it can become a promising model for sustainable resource production and management. Ramie (*Boehmeria nivea*) fiber is an interesting type of plant to consider when implementing an agroforestry system because it has many benefits. Ramie is known as a strong and durable fiber. Using ramie fiber in an agroforestry system can control soil erosion because ramie roots have dense characteristics that help prevent erosion and are suitable for sloping areas. In addition, ramie fiber can provide habitat and support greater biodiversity in agroforestry systems. Ramie plants can also be planted in rows between other plants or trees, thereby maximizing space and efficiency in land use. The strong nature of ramie fiber and its good durability make ramie a profitable crop for textile production (Mitra et al. 2021; Rehman et al. 2019).

The development of the textile industry began thousands of years ago and will always evolve along with the times and adapt to human needs. Textile materials in ancient civilizations, including linen, cotton, and silk, were excellent materials and formed cultural identities in global trade. As time went by, the textile industry began to introduce wool, and synthetic fibers began to be used. However, along with the development of science and human concern about the environmental impacts caused, the development of textiles in the current century has begun to use sustainable and innovative materials. This is also motivated by the fact that conventional textiles have several problems, especially large environmental impacts, relatively high production costs, dangerous production materials, and sustainability is not given proper attention due to the use of scarce resources (Islam et al. 2022). Synthetic fibers in the textile industry harm the environment due to the processes and chemicals used in their manufacture, so ecological and social aspects need to be used to ensure cultural or economic impacts and that the ecosystem remains well maintained (Adams and Frost 2008). As knowledge and technology meet increasing market demands, the global environmental impact due to industrial activities becomes very important because it can cause a greenhouse effect and reduce green areas. Therefore, to maintain the existence of a textile industry and answer several challenges to improve the environment, we encourage innovation and new opportunities in the textile industry to become a more sustainable industry and pay attention to environmental aspects by utilizing natural fibers as an alternative. In Indonesia, natural fibers are currently dominated by cotton fiber, but the low productivity of cotton hampers its sustainability and forces the industry to import cotton.

An alternative way to reduce the high cost of cotton imports is to look for substitute materials for cotton fiber. One type of natural fiber that has the potential to be developed as a substitute for cotton is ramie fiber. Ramie is a herbaceous plant that can support an agroforestry system where the cultivation technique is very easy. This fiber has a relatively high cellulose content, so the fiber's strength is very good and can be applied as a material functional textile (Lubis et al. 2024). Ramie is a perennial plant grown extensively, particularly in Asian countries, and has been utilized as a fiber crop for over 4000 years. Ramie fiber is regarded as one of the longest and strongest fine textile fibers (Luan et al. 2018). Ramie fibers, noted for their durability, strength, and natural sheen, are a potential alternative to cotton as a traditional/conventional textile material, commonly used despite low productivity, especially in Indonesia.

Ramie fiber has been a cotton substitute in Indonesian textiles since the Dutch colonial era (Purwati 2010). In Indonesia, cotton fiber remains the primary source of natural cellulose fiber for textile production. However, the demand for cotton fiber is inversely proportional to its availability, causing an increase in the value of imports every year, which reached USD 2.448 billion per year in 2014–2018 (Suparno 2020). In Indonesia, currently, the most widely used natural fiber is cotton, while the area of cotton plantations in Indonesia is around 11,287 ha, with a total production of 2,558 tons (Suparno 2020). This data is not commensurate with the magnitude of domestic consumption needs. Domestic cotton productivity can only meet less than 0.1% of domestic cotton needs, and the supply shortage is overcome by importing cotton (Wright and Meylinah 2015). The supply of local raw materials is unlikely to meet domestic cotton needs, and there are better solutions than cotton cultivation to overcome dependence on this raw material. Cotton is challenging to cultivate in Indonesia because it requires high production costs, significant agronomic risks, a lack of quality seed varieties, and is prone to leafhopper pest attacks. The productivity data for cotton plants in Indonesia in 2020 experienced a decline, which was only around 240 kg/ha, and in 2021, it only reached 193 kg/ha (Fauziah et al. 2023). Therefore, it is hoped that Indonesia will have other natural resources producing cellulose fiber as an alternative to dependence on imported cotton fiber. One of the natural fibers that has potential is ramie fiber. This review article discusses the exploration of ramie fiber as a sustainable material used as a functional textile material. It also discusses the quality of ramie fiber, how it is processed from ramie plants into fiber, and its uses.

2. Ramie Fiber Properties

2.1. History, Morphology, and Cultivation Ramie Fiber

Ramie fiber is a natural or lignocellulosic fiber that has become increasingly popular over the centuries to reduce the value of cotton imports due to its low productivity. Ramie fiber can be said to be the oldest natural textile fiber and has premium quality. Ramie fiber has been used in the textile industry for over 6,000 years in China and South Asia. Having been grown in China for centuries, and in the period 5,000–3,300 BC in Egypt, this fiber was used as material for making mummy cloth. In addition, before cotton was introduced around 1,300 AD, ramie fiber had been one of the main crops for making cloth in the East. Therefore, this fiber was known in ancient Egypt and was usually called Chinese grass. Ramie fiber is a natural fiber obtained from the tree's inner bark, producing fibers with fine, long, and strong characteristics (Chen et al. 2020; Jose et al. 2016). The morphological form of the ramie plant is in the form of several tall stems measuring 0.9–2.44 m with two to four branches from the lower stem. Ramie has simple, heart-shaped leaves with serrated leaf edges (**Fig. 1**). Ramie plants have small flowers and are usually green, greenish-yellow, or pink. There are two different varieties of *Bohmeria nivea*, namely var. *Nivea*, commonly known as China grass and cultivated in subtropical areas, is characterized by a bright green color and soft white hairs on the lower surface. The second variety is var. *tenacissima Miq.* (rhea) which is usually cultivated in tropical climates with a distinctive morphological shape of leaves smaller than var. *nivea* and green color (Kochhar 2018).

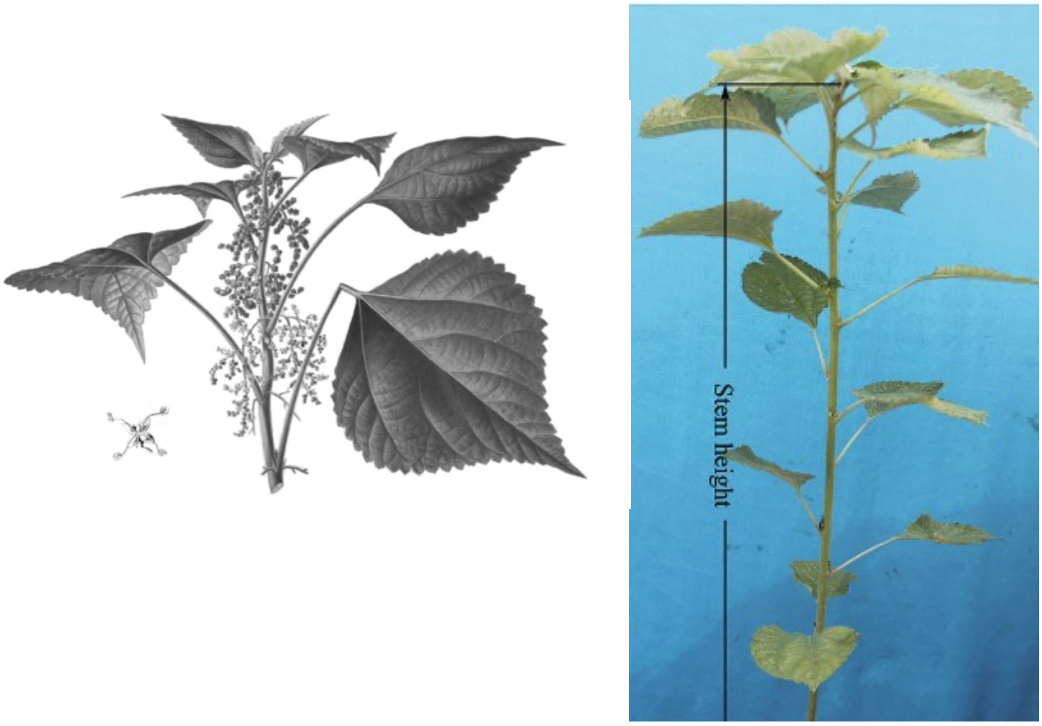


Fig. 1. Morphological of ramie plants (Du et al. 2015; Xu et al. 2019).

Fiber bundles formed from several fiber mother cells and bound by sap as an adhesive will form connections 90–180 cm long. In the ramie processing process, this sap needs to be processed (degumming) to separate the fibers from each other. Ramie's absorbency is 4% higher compared to cotton. Ramie fiber contains the main component in cellulose, which causes its high strength, but ramie fiber has low elasticity, is slippery, and is too stiff to spin. Ramie is a long fiber category with an average length of 120–150 mm and a fiber diameter of 40–60 microns, while cotton is only 20–38 mm and 14–16 microns. Ramie fiber can be used as an alternative to cotton because the cellulose content is similar to cotton, which is around 72–92% (Habibie et al. 2021). Ramie fiber is a plant that produces the longest and strongest unicellular fibers. Ramie fiber cells originate from the procambium and are arranged in several layers in the inner skin. Ramie fiber is suitable for textile purposes and can be mixed with other natural and synthetic fibers because of its excellent quality, strength, and durability. It can even be used as a bulletproof clothing material. The cellulose content and polymerization level of ramie fiber are high, so ramie fiber is relatively more resistant to fungal and bacterial degradation (Mitra et al. 2013). Ramie fiber has distinctive growth and development. Ramie plants can be harvested at 60–90 days, and the shoots that grow from the rhizomes of the first-generation plants or ratoons (second-generation plants) can be harvested again within two months. The third generation of ramie plants is the most stable in terms of fiber yield quantity and quality. However, ramie fiber is a type of plant that is very dependent on water availability. Differences in rainfall, season, and planting time can affect the growth rate and quality of the fiber produced. Apart from that, the soil type and fertilizer content are also factors that play an essential role in the growth and development of fiber, especially the content of macronutrients in nitrogen and potassium. Potassium can improve quality by reducing the diameter of the ramie fiber and tightening the fiber arrangement in the bark so that the amount of fiber produced is more significant with better fiber fineness (Subandi 2012).

Even though cotton fiber is widely used in the textile industry, cotton production is challenging because cotton plants are very susceptible to pests/diseases and require a specific biophysical environment. However, ramie has high adaptability, and nutrient and water supply significantly impact plant construction and yield (Ullah et al. 2016). Soil nitrogen and water are usually the most important factors influencing ramie growth, and large amounts of N and water are required. To maximize ramie yield, up to 280 kg/hm^2 of N would be used (Ullah et al. 2017), and under N-deficit conditions, fiber yield could be reduced by more than 30% (Ullah et al. 2016). Drought reduced ramie's fiber yield, stem length, diameter, and bark thickness by 26.7%, 23.5%, 17.7%, and 19.7%, respectively, compared to well-watered plants (Chen et al. 2020). The production and development of ramie fiber can be comprehensively developed through increasing cultivation, mastering processing technology, and diversifying final products. Therefore, ramie fiber can be an alternative producer of other cellulose fibers, especially as raw materials for functional textiles, which will be discussed in this review article.

3. Physical and Mechanical Properties

The ramie plant is known as China grass and belongs to the stem fibers that produce fiber from the bark. Ramie fiber has characteristics similar to cotton, with several advantages, such as longer fibers, greater fiber strength, and more excellent water absorption. Ramie fiber has higher strength than other natural fibers, including cotton, wool, silk, linen, bamboo, jute, hemp, and others, making it appropriate for composite reinforcement in various sectors. Compared to other natural fibers, namely ramie fiber, some advantages of this fiber are lightweight, high tensile strength, water absorption, antibacterial activity, and good air permeability (Li et al. 2016). In addition, this fiber also has a smooth appearance, high mechanical strength, and good water absorption capacity (Segovia et al. 2021). Therefore, considering these advantages, ramie fiber can be used as a high-quality textile material for garments, industrial packaging, vehicle accessories, fiber-reinforced composites, and various other possible applications. Based on previous research, ramie fiber has a strand length of up to 90 cm, with the longest individual cell being 40 cm, which is 7 to 13 times longer than cotton seed trichomes. Besides that, ramie fiber has the highest cross-sectional area among all the felt fibers. From tree bark amounting to 5.639 × 103 μm^2. Apart from that, ramie fiber is a fiber that has superior durability, tensile strength, fiber cell length, fineness, and color compared to other natural textile fibers. **Table 1** shows that the ultimate fiber cell length of flax is around 20–25 mm with an ultimate fiber cell width of around 15–80 μm, the L/B ratio of 3500/1, the cell wall thickness of 9–16 μm, the gravimetric fineness of 0.4–0.8 tex and the tenacity of ramie filament fiber of 40–65 g/tex, showing a higher figure than cotton, jute, and flax (Banerjee et al. 2015). However, ramie fiber is coarser and has lower stretchability than cotton fiber. Banerjee et al. (2015) also stated that the fineness of ramie fiber (0.8 tex) is next to cotton (0.2 tex), followed by jute (4.5 tex), mesta (5.5 tex), flax (6.0 tex), sun hemp (17 tex), and the finest is sisal (35 tex).

Ramie fiber is compatible with all synthetic and natural types, making it easy to mix with any fiber. Ramie fiber has the highest strength compared to cotton and jute, and the tensile strength value is shown in **Table 1**. According to Banerjee et al. (2015), a higher L/B ratio value indicates better fiber quality and referring to **Table 1** shows that ramie is better than cotton. In addition, the tensile strength of ramie fiber before and after degumming will be different. Degummed ramie generally exhibits lower tensile strength than undegummed ramie. This is because the degumming process removes the ramie fiber's latex component so that the fiber's tenacity will decrease over time and the high concentration of chemicals used during degumming. The degumming process makes ramie fibers more crystalline (Banerjee et al. 2015).

Table 1. The comparison of the physical-mechanical characteristics and chemical composition of natural textile fibers (Banerjee et al. 2015; Karimah et al. 2021)

Properties	Ramie	Cotton	Jute	Flax
Ultimate fiber length (L, mm)	20–25	16–52	0.8–6	26–65
Ultimate fiber cell breadth (B, μm)	15–80	15–20	5–25	10–35
Ratio of L/B	3500	2500	110	1700
Filament tenacity (g/tex)	40–65	30–35	30–45	45–55
Equilibrium moisture content (%)	15	8.8	9	12
Tensile strength (MPa)	400–1000	200-800	393–900	1500
Modulus of elasticity (GPa)	44–128	5.5–13	10–55	27.6
α-cellulose	86.9	88–96	61	80
B-cellulose	5	-	-	-
Hemicellulose	3.9	-	15.9	4.4
Lignin	0.5	-	13.5	5.5
Equilibrium Moisture Content (%)	15	8.8	9	12

4. Chemical Composition of Ramie Fiber

The strength of ramie fiber is due to several chemical compositions, especially cellulose. Apart from that, ramie fiber also has gummy substances, especially sugars, which bind the fibers into bundles and can increase their stiffness properties. The presence of this gummy material can pose challenges when using ramie fiber for textile production. Ramie fiber is a type of unicellular cellulose and contains the highest cellulose or polysaccharide $(C_6H_{10}O_5)_n$ among other types of bast fiber. Ramie fiber is also superior because it has strong properties and high durability, can be combined with all types of natural and artificial fibers, and is smooth and shiny. Ramie fiber has 6x higher strength than cotton, 2x superior to flax, and almost the same as silk. The density of ramie fiber is around 1.5–1.55 g/cm^3, with tensile strength varying between 400–1,600 MPa. The high cellulose content causes the structure of ramie fiber to be very crystalline and is closely related to its mechanical properties (Hasan et al. 2022). The characteristics of ramie fiber are easily identified through its thick walls, absence of twists, roughness, and ribbed surface, and resistance to attack by bacteria, fungi, insects, rot, sunlight, and mild alkalis (Debeli et al. 2018; Dey et al. 2017). Although the wetting strength of ramie fiber is relatively good, it has poor elasticity, abrasion resistance, and poor wrinkle recovery. Therefore, degumming is very important after the extraction process. However, the application of alkali and strong acids can eliminate the strength of the fiber due to cellulose hydrolysis. Ramie fiber, after going through the degumming process, makes it better than cotton. Aristri et al. (2023a) show that natural flax fiber shows several typical absorption peaks at 1424 cm^{-1} (aromatic vibrations), C-O ring stretch in lignin, and 1161 cm^{-1} (C-O-C asymmetric stretch of cellulose I and II). Meanwhile, at wave number 1377 cm^{-1}, it is aliphatic C-H stretching of cellulose and hemicellulose and at 1026 cm^{-1}, it is C-O-C stretching of cellulose, hemicellulose, and lignin. The thermal decomposition of ramie fiber reaches 275°C, and weight loss is caused by the evaporation of water and volatile substances such as low molecular weight fats and waxes. The weight loss that occurs at temperatures of 290–380°C is caused by cellulose degradation, and at temperatures of 280–500°C is lignin degradation (Aristri et al. 2023a; b).

Ramie fibers possess unique characteristics that make them suitable for functional textiles. They exhibit high tensile strength, exceptional breathability, and good moisture-wicking properties. Ramie fibers are also known for their resistance to microbial growth and excellent dyeability, allowing for the creation of vibrant and long-lasting textiles. The chemical content of ramie fiber consists of alpha-cellulose, hemicellulose, and pectin bound to Ca^{2+} ions, along with other minor constituents such as inorganic materials, nitrogen, fat and lignin, pigments, and lignin. Ramie fiber cellulose microfibrils are embedded in a soft matrix, namely pectin, hemicellulose, and lignin, as an important contribution to fiber strength. Ramie has the highest cellulose: hemicellulose ratio among other fibers, and Ramie also produces the highest crystallinity and stiffness of cellulose. The hemicellulose content of ramie fiber is higher than that of other non-cellulose components. The gum content in ramie consists of galactose, mannose arabinose, rhamnose, and xylose and can be used as an adhesive in making particle boards. Ramie fiber has the highest cross-sectional area of all tree bark fibers, making it durable and strong. In addition, ramie fiber has high fiber length, fineness, and L/B ratio, indicating superior quality compared to cotton (Banerjee et al. 2015). A comparison of the quality of ramie fiber with other textile fibers, including physical-mechanical properties and chemical composition, can be seen in **Table 1**.

These characteristics and ramie fiber’s long history in the textile industry make it one of the most widely used raw materials for textile applications. However, ramie fibers have several drawbacks, such as low crease resistance and trouble dyeing. These restrictions have hampered the widespread use of ramie fiber, particularly when compared to synthetic fibers with superior crease-resistance and dyeing capabilities. Ramie fiber has enormous potential for advancement and development in the textile industry. Therefore, it is vital to research and solve the constraints associated with ramie fibers, such as low crease resistance and dyeing difficulty (Wang et al. 2020). Researchers and industry professionals have addressed these constraints to improve ramie fibers’ crease resistance and dyeability. Chemical alterations, such as crosslinking or adding crease-resistant chemicals, and mechanical treatments, such as heat setting and mechanical stretching, are examples of these techniques. These approaches have demonstrated good results in enhancing the crease resistance of ramie fibers, broadening their use in the textile industry (Wang et al. 2020).

5. Processing Techniques of Ramie Fiber

This section explores various processing techniques involved in the production of ramie fibers. It covers the stages of retting, decortication, and degumming (**Fig. 2**), which are crucial for obtaining high-quality fibers. Additionally, this review article discusses mechanical and chemical treatments to enhance the fiber’s performance and improve its functional attributes. Ramie fiber comes from the stem’s inner skin tissue, and the ramie plant’s skin cannot be removed from the wood tissue inside just by going through a simple retting process, as is commonly used on flax, ramie, or jute. The outer bark must be scraped first in ramie fiber, usually done using a decortication machine. Decortication can remove the outer bark, central heartwood, and some parts of the gum and wax layer of tree bark, which is done mechanically. The decortication machine, usually called a decorticator, consists of a beating plate and a drum equipped with blades. Operator efficiency and plant conditions can affect the yield or quality of the decortization performed. Stalks that are dry after harvesting cannot be decorticated properly, so the decortication process should be completed on the day of harvest, and if any remains have not been decorated, the stems must be kept moist by sprinkling with water until decortication is complete. Using self-decorticator machines can reduce the costs of transporting unwanted plant material to the ground (Rana et al. 2014). Fibrous materials extracted after washing must be immediately dried or sapped to prevent mold growth on the fibers. Ramie fiber cannot be processed like other stem fibers due to the pectin content, which makes it difficult to remove compared to the pectin contained in other fibers. The extracted fiber contains 25–30% gum. Therefore, washing the fiber after the decortication process can help to remove water-soluble gum, resulting in a reduction in the dry weight of the fiber of up to 8% (Cheng et al. 2020). The rubber content in the fiber can make the fiber stiff and brittle, but it can also prevent the entry of water and other chemicals into the fiber. Therefore, before further fiber processing is carried out, it is necessary to remove the gum contained, or what is usually called degumming.

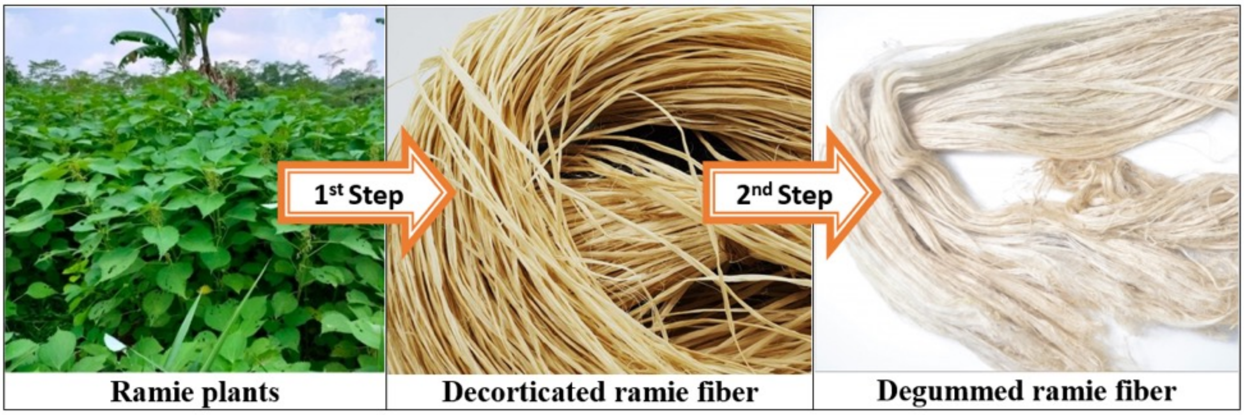


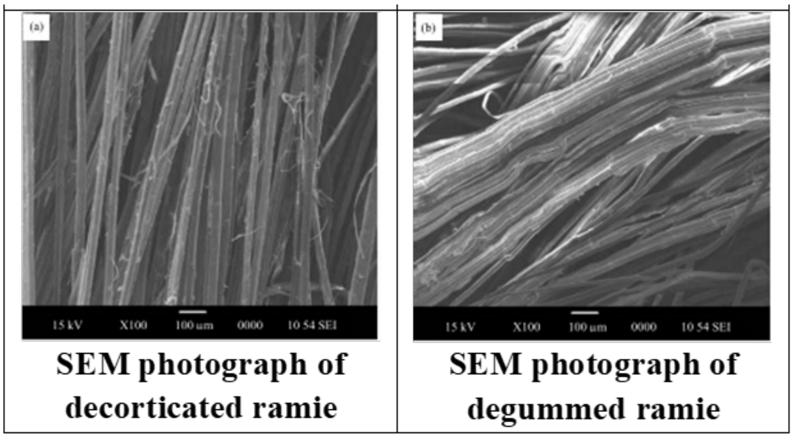
Fig. 2. Primary step of ramie's processing.

Degumming can be done chemically (using hydrogen peroxide or sodium hydroxide (Li and Yu 2015), or enzymatically (Chandra et al. 2020; Chiliveri et al. 2016), or with the help of microbes (Ramakanth et al. 2014). Mao et al. (2019) stated that chemical or microbiological processes can degum ramie. The most common chemical degumming process is alkali-cooking NaOH, which involves soaking the decorticated ramie in sulfuric acid, boiling it in an alkaline solution with surfactants and washing it in water. Each type of degumming process used has advantages and disadvantages (Mao et al. 2019). Cheng et al. (2020) stated that chemical degumming requires an intricate engineering system, which is carried out according to the principle that in alkali, inorganic acid, or oxidant conditions, the cellulose and gum (lignin, pectin, and hemicelluloses) in ramie fiber degraded to varied degrees. Chemical degumming works by hydrolyzing or oxidizing differences between cellulose and impurities in specific chemical conditions to remove gum materials gradually or simultaneously. This process is combined with the idea that refined ramie fiber's mechanical and physical performance properties should be minimized. In general, cellulose cannot readily hydrolyze in a high-concentration alkali solution, although pectin and hemicellulose (mostly mannan and xylan) can hydrolyze (Cheng et al. 2020). Liu et al. (2012) found that this approach causes significant environmental impact, excessive energy consumption, high manufacturing costs, and fiber degradation. Chemical degumming is categorized into modern and traditional, based on the chemicals used by Liu et al. (2012). Chemical concentration, temperature, duration, and pressure impact the degumming process.

According to Jose et al. (2016), the approach should ensure that the solution is evenly distributed throughout the fiber.

The old chemical degumming technique involved immersing the decorticated ramie ribbon in a hot alkaline solution, either under pressure or not. In the traditional chemical degumming method, the decorated ramie ribbon was immersed in a concentrated hot alkaline solution, either under high pressure or not. Gum and cellulose fibers were separated using chemical, physical, and mechanical processes, including scouring and washing. Generally, chemical degumming was carried out at more than 96°C for two hours using a 1% sodium hydroxide (NaOH) solution, including a wetting agent. Treatment with 0.5% sodium sulfate (Na_2SO_4) was then applied in succession.

Similarly, pectic materials were dissolved in aqueous alkaline solutions (NaOH, Na_2SO_4, or their mixes), and the degummed ramie fibers were further bleached at a high temperature using chlorine dioxide (ClO_2) or hydrogen peroxide (H_2O_2). Because the cellulose component of ramie fiber is highly sensitive to alkaline solutions, faults in the degumming process might degrade fiber quality (Cheng et al. 2020). The way to reduce the potential of fiber damage is to add acetic acid to remove excess alkali from the fiber. The separated ramie cells are known as 'filasse' and are completely white in appearance. Degumming and bleaching have the effect of changing the chemical content of ramie fiber while also making the fiber's visual surface cleaner, and Jose et al. (2016) confirm this statement by the SEM results in **Fig. 3**. However, it takes a lot of NaOH reagents under high temperatures and high-pressure conditions to perform traditional chemical degumming for ramie, making it an extremely expensive and energy-intensive process. Furthermore, much wastewater was produced during traditional chemical degumming, which cannot be discharged immediately due to the excessive chemical oxygen demand (COD). The cost of wastewater treatment makes conventional chemical degumming far more expensive, restricting the method's widespread application (Cheng et al. 2020).



SEM photograph of decorticated ramie

SEM photograph of degummed ramie

Fig. 3. Morphological of ramie after degummed process (Jose et al. 2016).

To improve hemicellulose removal from ramie materials, additional reagents, including pentasarbate, 1.8-dihydroxyanthraquinone, surfactants, and sodium percarbonate ($2Na_2CO_3 . 3H_2O_2$) can now be added to the modern chemical degumming process by the development of degumming additives. Pectin, hemicellulose, and lignin polysaccharides are all hydrolyzed and oxidized by H_2O_2 in an alkali environment to produce oligosaccharides soluble in water. In the alkali conditions, H_2O_2 can oxidize nearly all -OH in cellulose macromolecules, reducing their strength and hydrophilicity. This study examines the effectiveness of urea peroxide as an oxidant in ramie gum removal. The analysis revealed that fiber strength decreased when the amount of urea peroxide increased. There is a linear correlation between urea peroxide concentration and fiber strength. The maximum fiber strength is attained at 95°C and 3 hours under the provided circumstances. Therefore, reducing agents with low standard electrode prospects, such as potassium borohydride (KBH_4) and sodium borohydride ($NaBH_4$), have to be added to the oxidation procedure of ramie degumming to prevent damage to oxidant cellulose. In wastewater treatment, Fenton's reagent (H_2O_2 + iron catalyst) was employed to break down organic molecules and oxidize contaminants. Iron (II) sulfate is a common catalyst. It is demonstrated that Fenton's reagent is a potential oxidizing substance for degumming ramie material. This process is carried out under low pH conditions, resulting in a good degumming effect. Compared to alkali oxidation, a contemporary degumming method using Fenton's reagent can reduce gum residue in ramie material while boosting cellulose in processed fibers. Fibers degummed with Fenton's reagent exhibited greater toughness, density, and breaking elongation than fibers degummed with alkali oxidation (Cheng et al. 2020).

The $NaOH/H_2SO_4/H_2O_2/NaCO_3$ chemical degumming process generates high-quality fibers in a short period (up to 48 hours) but comes at a significant expense due to waste disposal. The dew degumming process takes 3–6 weeks, results in uneven fiber quality, and can reduce fiber strength. The cold water degumming procedure yields high-quality fiber but requires 1–2 weeks and can result in stinky organic waste from fermentation. Although the hot water degumming technique delivers clean and homogenous fiber quality in 3–5 days, it also causes significant contamination. The enzyme degumming process is relatively short, around 2–24 hours, and does not result in fiber damage, but the costs required are very high. Apart from that, mechanical degumming takes only 2–3 days and a maximum of 10 days with coarse fiber quality. The degumming process, with the help of ultrasonic waves, produces fiber quality only suitable for technical textiles and non-textile applications, while steam explosive degumming can produce fibers with high fine quality and fiber properties comparable to cotton (Novarini and Sukardan 2015; Subash and Muthiah 2021).

Meanwhile, due to several shortcomings of the chemical degumming method, which generates waste and requires a lot of energy and money, there have been several advancements in the bio-degumming method, which uses microorganisms (bacterial cultures, fungi, and enzymes) to remove sap from ramie fiber and produce quality fiber. However, each microorganism has advantages and disadvantages. For example, when bacterial or fungal cultures are used in the bio-degumming process, ramie fiber does not undergo a flawless degumming process, which takes time and results in poor fiber quality (Subash and Muthiah 2021). On the other hand, a degumming method uses enzymes to speed up the degumming process and improve the quality of the fiber generated; however, the costs are quite high due to the rarity of the enzymes utilized. Consequently, a "biochemical degumming" technique was developed, combining chemical and biological processes. Combining these procedures is expected to produce high-quality fiber while lowering costs, energy usage, and waste during the degumming procedure. Mao et al. (2019) invented a biochemical fiber degumming process involving a consortium of microorganisms, especially developed for degumming ramie fiber, that could remove ramie fiber from gum without harming the fiber and uses ramie sap as a carbon and energy source. The gum content on the fiber surface was assessed using a Fluorescence Microscope (FLSM), with support from SEM, to see the fiber surface after degumming. The fiber results obtained through the biochemical degumming process were then evaluated using RAMCD407 to see the separation and surface of the fiber (Mao et al. 2019).

Through color emission, a fluorescent microscope (FLSM) can detect gum content on fiber surfaces and pectin, xylan, and lignin concentrations in ramie fibers. The color emission in numbers 1 and 2 of **Fig. 4b** indicates the presence of lignin (red), xylan (indigo), or pectin particles (orange). Mao et al. (2019) observed variations in the materials of raw ramie fiber that had not been degummed (**Fig. 4a**). When analyzed by applying FLSM, it showed that the layer of raw ramie fiber consisted of a lot of xylan matrix content, as well as a small quantity of pectin and lignin material that was distributed unevenly. The majority of the gum contained in the fiber after undergoing the bio-degumming process has been eliminated, save for some xylan content, and the findings are displayed in **Fig. 4c** and **4d**, which reveal the presence of indigo color emission resulting from FLSM analysis and verified by the SEM results in **Fig. 4e** indicates that the fiber surface still contains a little quantity of gum, as indicated by the arrow in the figure. The combination of bio-degumming and alkali treatment with 0.2% NaOH results in a smoother, whiter fiber surface (**Fig. 4f**, **Fig. 4g**, and **Fig. 4h**). According to the final results of research conducted by Mao et al. (2019) the combination of bio-degumming with alkali treatment resulted in a reduction in residual gum in the fiber of around 2.84% compared to those without alkali treatment. The results of combining bio-degumming with alkali treatment did not affect the fiber's strength because the ramie fiber's quality remained good and met spinning conditions.

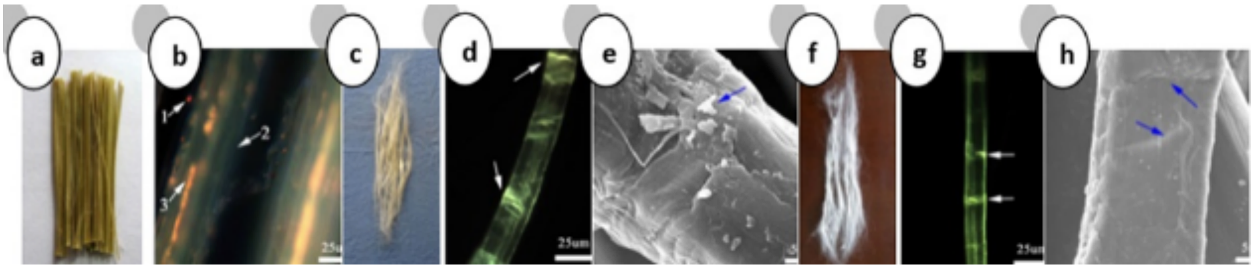


Fig. 4. Visual characterization of degummed ramie fiber process (a) decorticated ramie fiber; (b) FLSM gum distribution on decorticated ramie fiber surface; (c) bio-degummed ramie without alkali treatment; (d) FLSM gum distribution on bio-degummed ramie fiber surface; (e) SEM picture of gum contained on bio-degummed ramie fiber surface; (f) bio-degummed ramie followed by alkali treatment; (g) FLSM gum distribution on bio-degummed ramie followed by alkali treatment; (h) SEM picture of gum contained on bio-degummed ramie followed by alkali treatment (Mao et al. 2019).

The degumming process can remove some of the sap and reduce the weight of the fiber by around 25% so that the fiber's ductility, wet strength, and extensibility can increase. The degumming process can also make the fiber more crystalline because the width of the crystallite increases (Cui et al. 2018). Usually, when the fiber first enters the factory and is applied as a coarse product, it has greenish-yellow to yellowish-white stripes. However, if ramie fiber is to be spun into yarn for fine fabrics, the factory must remove the gum from the fiber. Good fiber, when it first arrives at the factory, contains around 10–15% latex, whereas if the quality of the fiber is poor, it contains around 20–30%, so this fiber must be extracted further. Ramie fiber production in the current era is carried out on a commercial scale. Before being spun, the fibers are differentiated into types, starting from long fibers (fibers with a criterion of 60% of the total weight of the material being sapped) and medium and short fibers. Long fibers are spun separately, while medium fibers can be spun alone or with short fibers. The spinning process requires fibers free from gum, wax, and pectin to be soft and clean, but the strength and other textile properties remain the same. There are two types of spinning: dry spinning (sap-free fiber) and wet spinning, which requires white resin (Suriani et al. 2021). As a result, the length of ramie fiber usually varies, so it is necessary to cut it into a uniform size. Mixing ramie fiber with natural and synthetic fibers in certain proportions can produce better quality. The tensile strength of the jute/flax blend (50/50) in dry and wet conditions was better when compared to 100% jute (Kuang et al. 2017). Ramie fiber is often used to mix with other fiber types because of its strength, absorbency, luster, and good coloring affinity. Long fiber types are usually used for spinning, while short fibers are used for making paper, composites, and other products.

6. Environmental Benefits

Ramie fiber cultivation may be said to be sustainable and has various positive environmental consequences. Ramie fiber is harvested every 60 days by cutting the bark of mature trees and still protecting the roots because the system for harvesting ramie fiber is continuous so that the ramie plants that have been harvested can grow again every 60-day cycle, this cycle can be repeated for eight years (Cheng et al. 2020). Ramie fiber is considered environmentally friendly because it is a type of fiber plant that is unlike other conventional plants. This plant can contribute as a carbon absorbent, save energy, and reduce non-renewable resources. Additionally, ramie is a carbon absorber since it can assist in absorbing CO_2. Apart from that, bast fiber plants also have a fairly good tolerance to heavy metal stress. However, no recent data has been reported on how much carbon can be absorbed by ramie plants. This is because the potential for carbon that can be absorbed and stored by the soil in these plants is influenced by several factors, such as soil type, climate, and management practices (Rehman et al. 2019). Ramie plants can absorb heavy metals from the soil and provide soil cleansing. Aside from that, the ramie plant can help maintain a strong soil structure and protect the soil from water runoff due to its deep roots (at least three feet underground). Unlike other industrial plants, Ramie plants can enrich the soil by producing mature compost when the leaves fall to the ground throughout the growing season.

Compared to cotton, ramie fiber production is more efficient because ramie can produce 250% more fiber (Rana et al. 2014). Ramie also has a wide range of industrial applications, including medical, construction, car doors, animal feed, animal bedding, hydrocarbon absorbers, household products, paper, biodegradable plastic, and textiles. Ramie fibers are highly sustainable due to their minimal environmental impact. Biomaterials such as ramie fiber have received great attention from researchers because of their renewable and environmentally friendly nature, and ramie fiber has better ozone layer depletion than other fibers. The *Boehmeria nivea* plant is known for its low water and pesticide requirements, making ramie cultivation less resource-intensive than other fiber crops. The fiber’s biodegradability further contributes to reducing textile waste and environmental pollution. Ramie cultivation can provide ecological benefits in the form of land conservation. Ramie plants developed on critical land can increase the volume of groundwater to store water reserves for the dry season, and critical land can be turned into productive land in just a short period of around 5–6 months (Purwati 2010).

The development of a conservation agricultural system can be carried out by planting ramie to maintain the biological function of the soil so that soil organic matter can increase so that it can sustainably reduce the amount of carbon gas in the atmosphere significantly and play an important role in reducing greenhouse gas emissions from the sector. However, the ramie fiber production process, which includes degumming to spinning, can contribute to environmental impacts and cause pollution. However, there is still potential for improvement in ramie fiber production techniques by optimizing the reduction of chemical consumption during the degumming process. Another environmental benefit is that ramie fiber can be degraded naturally, reducing the energy required for product disposal. Cultivating, harvesting, and extracting ramie fiber contributes to freshwater eutrophication, ozone depletion, and ecotoxicity (Dong et al. 2018). Apart from this, ramie fiber has many environmental benefits, such as its ability to save water during cultivation. Ramie fiber can also protect the soil, remove heavy metals, act as a carbon absorber, and produce more fiber than cotton, so ramie fiber is suitable for various applications in the textile industry (Rana et al. 2014).

7. Future Prospect of Ramie in Functional Textile

Ramie fiber is being more widely employed in a variety of industrial applications. Ramie fiber is most commonly used in the following industries: building, textiles, binding ropes, geotextiles, paper, packaging, furniture, electricity, banknote production, and pipe manufacturing (Mahir et al. 2019). This section highlights the diverse applications of ramie fibers in functional textiles. Indonesia is the second largest importer of cotton fiber in the world, with demand for raw materials in the textile industry increasing every year and increasing the number of cotton imports. It is difficult to increase local cotton production due to its susceptibility to pests and diseases and the need for certain conditions in its cultivation, thus opening up opportunities for ramie fiber as a substitute for cotton in textiles. This ramie plant grows well in Indonesia, a country that produces fiber used in textiles. The relatively easy and simple process of cultivating ramie is one of the main reasons for the large opportunities for cultivating ramie. The quality of ramie fiber in Indonesia can also compete with fiber from other countries, thus giving the textile industry a superior image to play a role in encouraging the rural economy. Ramie fiber reinforcement for composite panels can increase their technological and economic value. In addition, the global market demand for ramie fiber is much higher than the current supply from China, Brazil, and the Philippines, thus opening up great opportunities to develop ramie fiber as a raw textile material. Ramie fabrics are widely utilized in sportswear, outdoor clothing, and other performance-driven apparel due to their breathability, moisture management, and UV resistance. Moreover, incorporating ramie fibers in home textiles, such as bed linens and upholstery, enhances comfort and durability.

Among the various advantages of ramie fiber, there is a weakness in this fiber, namely that the fiber is not resistant to heat or fire. By looking at Indonesia's potential in producing ramie fiber as an alternative to cotton, ramie fiber has the prospect of continuing to be developed to overcome some of its weaknesses. Due to its low fire resistance, several studies have been conducted, including modifying ramie fibers using the impregnation method. The impregnation material developed to increase its heat resistance is bio-polyurethane based on lignin and tannin from isocyanate to non-isocyanate. Lignin-based polyurethane resin with low viscosity has been proven to improve its thermal and mechanical properties due to forming a urethane bond between the fiber and the impregnating material. This research showed that thermal stability increased by 6% and mechanical properties increased by 100% in ramie fibers impregnated using LPU-ethyl acetate for 30 minutes compared to control ramie (Lubis et al. 2022). Apart from that, impregnation was also carried out using non-isocyanate lignin-based bio-polyurethane, which can improve the fiber's mechanical properties and increase its weight. Longer impregnation times produce better weight gain values and better flax properties, but using dimethyl carbonate and hexamethylenetetramine instead of isocyanate results in relatively low heat resistance (Raditya et al. 2023). Aristri et al. (2023b) found that using tannin-based non-isocyanate bio-polyurethane to impregnate ramie fiber increases mechanical properties and opens up new opportunities for its use as a textile raw material.

8. Challenges and Future Directions

Ramie is a fiber that could be used in textile manufacture instead of cotton. Ramie production is particularly popular because of its high productivity and ability to be produced in tropical, subtropical, and temperate environments and metal-contaminated sites. Ramie growing can also lessen reliance on imported fiber and provide an alternate application for textile fiber (Rehman et al. 2019). Research and development methods must be undertaken to support the cultivation of ramie fiber with high productivity and quality, which may be used in various industrial sectors, particularly the textile industry.

Ramie plants may grow in various climates, but producing high-quality, profitable ramie plants presents numerous problems. Soil conditions such as sandy loam soil with good drainage, high nutrition, consistent high temperatures, moisture, and reasonably evenly distributed rainfall (not less than 112 cm per year) must be examined. Furthermore, because the ramie plant drains the soil, proper fertilizer must be used after harvest to promote bud production. Weeding ramie plants is only necessary in the early stages of growth (Kochhar 2018). Apart from that, though the potential of using ramie fibers seems great, some problems need to be solved first: high energy consumption and water use to process them. The research additionally delves into the continuous research and development attempts to enhance ramie fibers' mechanical properties and functionality in reaction to textile industry demands that are constantly changing.

9. Conclusions

The agroforestry system is an integrated land use that combines agricultural and forestry crops on the same land. This system can include several studies from an ecological and economic perspective. Ecologically, the productivity of agroforestry land is higher. Trees in agroforestry systems can also absorb carbon from the atmosphere and help reduce soil erosion. Economically, this system can provide benefits for farmers in increasing their income because it utilizes land previously considered unproductive. Ramie plants have advantages over fiber plants, such as cotton and jute. Ramie is a plant that supports agroforestry systems, is the easiest to cultivate, has high productivity, and has fiber quality similar to cotton, so that it can be an alternative to cotton used in the textile industry. Ramie fiber has advantages compared to other fibers, such as high tensile strength, high mechanical strength, lightweight, and water absorption. Apart from that, ramie fiber also contains high levels of cellulose, similar to cotton. Ramie can be harvested every 60 days by cutting the stems, passing them through a decorticator machine to produce coarse fiber, and degumming to produce ready-spun fiber. Considering the above, ramie fibers could be an advantageous sustainable replacement candidate for shaping functional textiles. Their special properties, eco-friendly culture, and biodegradability make them promising materials for a healthier textile industry. However, further research and technological advances are needed to improve processing methods and fiber properties. Therefore, with more persistence and effort put into it, ramie can meet the challenges ahead and play a role in the fabric sector that is sustainable and efficient.

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