

The Rubber Plant: Economic Importance, Environmental Challenges and Technological Advancement in Rubber Production and Processing

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ABSTRACT

Rubber (Hevea brasiliensis) plays a significant role in the global economy, serving as a raw material for numerous industries, including automotive, healthcare, and manufacturing industries. However, its production and processing come with both economic benefits and environmental challenges. This study examines the economic importance of environmental challenges and technological advancements in rubber production and processing. It explores the botanical characteristics, taxonomy, and chemical composition of the rubber plant, alongside an analysis of pests and diseases affecting rubber cultivation. The study further delves into the global economic impact of rubber production, with a focus on Africa and other rubber-producing regions. Additionally, it evaluates the environmental consequences of rubber cultivation, such as deforestation, pollution, and carbon emissions, while highlighting waste management strategies developed to mitigate these effects. Technological innovations, including precision agriculture, biotechnology, and sustainable processing techniques, are also discussed as key advancements shaping the rubber industry. The findings emphasize the need for sustainable practices to balance economic growth and environmental conservation in rubber production.

Keywords: Biotechnology, Rubber, Deforestation, Global Market, Carbon Emission.

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Introduction

Rubber is one of the most economically significant agricultural commodities found globally, serving as a raw material for various industries, including automobile, healthcare, and manufacturing industries [1]. The production and processing of rubber have contributed significantly to economic growth in many tropical regions, particularly in countries such as Thailand, China, Japan, the USA, the UK, Russia, Germany, Indonesia, Malaysia, Nigeria, and India [2]. However, rubber production and processing are affected by the increasing environmental and economic challenges that threaten their sustainability and profitability. Deforestation, soil degradation, water pollution, and climate change are among the key environmental issues affecting rubber plantations worldwide [2, 3]. At the same time, inefficient production methods and outdated processing techniques contribute to resource wastage and environmental degradation. De-

spite technological advancements, many rubber-producing regions still rely on traditional practices that are less efficient and more harmful to the environment.

In response, technological advancements in rubber production and processing have emerged to improve efficiency, reduce environmental impacts, and enhance sustainability [4]. The environmental challenges associated with rubber production primarily stem from land use changes, excessive water consumption, chemical pollution, and greenhouse gas emissions [5]. According to Fox and Castella, large-scale rubber plantations have contributed to deforestation in Southeast Asia, leading to biodiversity loss and soil degradation [3]. Furthermore, climate change poses a significant threat to rubber yield, as fluctuations in temperature and precipitation can affect tree growth and latex production [6]. These challenges necessitate the adoption of environ-

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mentally sustainable practices, such as precision agriculture, agroforestry, and organic farming, to mitigate adverse effects and ensure long-term production viability [7]. Technological advancements have played a crucial role in transforming the rubber industry, making production more sustainable and economically viable. Innovations such as genetic modification, automated tapping systems, and improved processing techniques have increased latex yield and reduced waste [1]. For instance, the use of ethylene stimulation has been proven to enhance latex flow and extend harvesting periods, thereby improving productivity [4]. Additionally, modern processing technologies, such as the use of bio-based coagulants and energy-efficient drying systems, have reduced environmental footprints while maintaining product quality [8].

The rubber industry is a major source of employment and income for millions of people, particularly in developing countries. However, unsustainable practices threaten the long-term viability of the sector. By examining the role of technology in overcoming environmental constraints, this study will contribute valuable knowledge to policymakers, industry stakeholders, and researchers. It will highlight sustainable solutions that can enhance production efficiency, reduce environmental footprints, and improve the livelihoods of those dependent on rubber farming. Furthermore, technological advancements are rapidly reshaping the global rubber industry, and understanding their economic impact is crucial for competitiveness. Automation, precision agriculture, and biotechnology are transforming rubber cultivation and processing, enabling producers to maximize yields while minimizing costs and environmental harm [1]. Therefore, this research seeks to investigate the economic implications of these environmental challenges and explore how technological advancements can mitigate their impact and enhance sustainability in rubber production and processing. The significance of this study lies in its potential to provide insights into the economic benefits of addressing environmental challenges in rubber production.

The Rubber Plant

The rubber plant (*Hevea brasiliensis*) is a member of the Euphorbiaceae family, known for its ability to produce latex, the primary raw material for natural rubber. Native to the Amazon rainforest, it is now extensively cultivated in tropical regions worldwide, including Southeast Asia, West Africa, and South America. The rubber tree is a fast-growing, deciduous species that can reach heights of up to 30–40 meters under natural conditions, though in plantations, it is usually maintained at 20–25 meters for ease of harvesting [1]. The tree has a straight trunk

with smooth, grayish bark that contains specialized laticifer cells responsible for latex production. The leaves of *H. brasiliensis* are trifoliate, with each leaflet being ovate-lanceolate in shape, measuring approximately 10–15 cm in length. These leaves are shed during dry seasons, followed by new growth with young reddish shoots. The flowers are small, pale yellow, and arranged in panicles, with the species exhibiting a monoecious flowering system where male and female flowers exist on the same tree [9]. The fruit of the rubber tree is a three-lobed capsule containing seeds that are large, brown, and speckled, resembling castor beans. These seeds are rich in oils and proteins and serve as a secondary economic product. The tree typically begins latex production between the fifth and seventh year of growth, reaching peak productivity around 10–15 years and continuing for up to 30 years before declining yield necessitates replanting [4].

Taxonomy of the Rubber Plant

The rubber plant (*Hevea brasiliensis* Muell. Arg.), belongs to the plant kingdom which includes all green plants capable of photosynthesis. The taxonomic classification of *H. brasiliensis* is as follows:

Kingdom: Plantae

Phylum: Angiosperms (Magnoliophyta)

Class: Eudicots

ORDER: Malpighiales

Family: Euphorbiaceae

Genus: *Hevea*

Species: *H. brasiliensis* (Muell. Arg.)

This classification places rubber within the Euphorbiaceae family, which includes various latex-producing plants. Among the *Hevea* species, *H. brasiliensis* is the most economically significant due to its superior latex yield and adaptability to plantation cultivation [7].

Physicochemical Profiling of the Rubber Plant

Proximate Composition

The rubber plant, particularly its seeds and latex, contains several nutritional and industrially relevant components. Rubber seed oil is a potential source of industrial and edible oil, though its high levels of unsaturated fatty acids make it susceptible to oxidation [8]. The proximate composition of rubber seeds has been analyzed and found to contain: moisture content (<8%), crude protein (<25%), crude fat (<50%), carbohydrates (<20%), ash (<5%), fiber (<10%) as shown in Table 1. A comparative analysis of the proximate composition of the seeds, leaves, and latex of the rubber plant was also shown in Table 1 below.

Table 1: The Nutrient Composition of Rubber Plant

| Nutrient | Rubber Plant Composition | | | Significance |
|----------------|--------------------------|--------------|--------------|------------------------------------|
| | Seeds (%) | Leaves (%) | Latex (%) | |
| Moisture | 6.35 ± 1.15 | 67.5 ± 7.50 | 57.50 ± 7.50 | • Affects storage stability |
| Crude protein | 20.00 ± 3.00 | 10.00 ± 2.00 | 3.00 ± 1.00 | • Important for nutrition (seeds) |
| Crude fat | 41.50 ± 4.50 | 3.50 ± 1.50 | 1.00 ± 0.50 | • Source of oil (seeds) and energy |
| Crude fiber | 4.50 ± 1.50 | 14.00 ± 4.00 | <1.0 | • Aids digestion in animal feed |
| Ash (minerals) | 3.25 ± 0.75 | 7.50 ± 1.50 | 2.00 ± 1.00 | • Indicates mineral content |
| Carbohydrate | 20.00 ± 5.00 | 42.5 ± 7.50 | 25.00 ± 5.00 | • Energy source |
| Rubber content | 0.00 ± 0.00 | 0.00 ± 0.00 | 35.00 ± 5.00 | • Important for rubber production |

Phytochemical Composition

The rubber plant contains various bioactive compounds, including: alkaloids which is widely Known for its antimicrobial properties, flavonoids which act as antioxidants and contribute to plant defense, phenolic compounds that provide resistance against pests and diseases, tannins that help protect the plant from herbivores i.e., overgrazing, and saponins which contribute to antifungal and antibacterial activities (Table 2). These phytochemicals enhance the plant's defense mechanisms and have potential medicinal and industrial applications [10].

Table 2: The Phytochemical Composition of Rubber Plant

| S/N | Phytochemical | Presence in plant parts | Biological/industrial significance |
|-----|---------------|-------------------------|---|
| 1 | Alkaloids | Leaves, bark, latex | <ul style="list-style-type: none"> Antimicrobial Antifungal properties |
| 2 | Flavonoids | Leaves seeds | <ul style="list-style-type: none"> Antioxidant Anti-inflammatory UV light shield |
| 3 | Tannins | Bark, leave | <ul style="list-style-type: none"> Astringent properties Used in leather tanning |
| 4 | Saponins | Latex, seeds | <ul style="list-style-type: none"> Foam formation Surfactant in industry, Medicinal benefits |
| 5 | Phenolics | Bark, leaves, seeds | <ul style="list-style-type: none"> Antioxidant Antimicrobial Used in pharmaceuticals |
| 6 | Steroids | Lates, bark | <ul style="list-style-type: none"> Precursor for medicinal steroid Plant defense |
| 7 | Terpenoids | Latex, bark | <ul style="list-style-type: none"> Aromatic compounds Antimicrobial Rubber biosynthesis |
| 8 | Glycosides | Seeds, bark | <ul style="list-style-type: none"> Cardio-active properties Antimicrobial potentials |

Mineral Composition

Rubber latex and seeds contain essential minerals such as: calcium (Ca) which is very important for cellular function and tree health, magnesium (Mg) which aids chlorophyll formation and enzyme activation, phosphorus (P) which is essential for energy transfer and root development, potassium (K) that regulates latex flow and overall plant metabolism; zinc (Zn), iron (Fe), and copper (Cu) that are actively involved in enzyme activity and resistance to diseases. The composition of minerals varies in the different parts of the rubber plant as shown in Fig 1 below. These minerals play critical roles in the growth, health, and productivity of rubber trees, influencing both latex yield and quality [1].

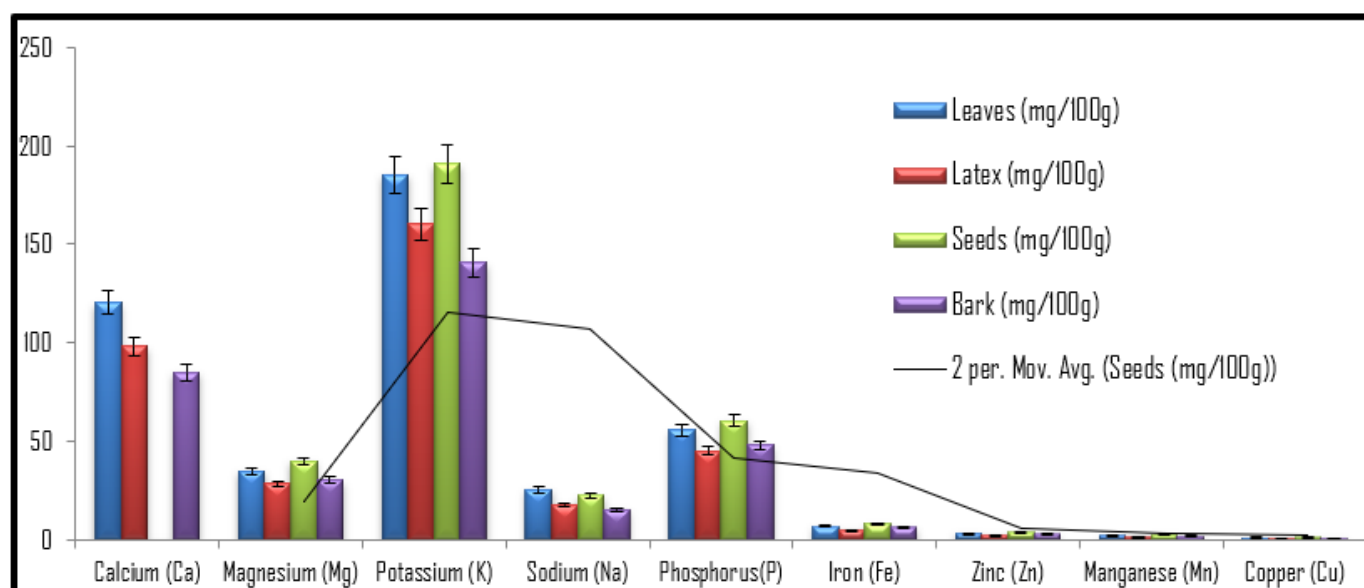


Figure 1: The mineral composition of rubber plant

Pests and Diseases of Rubber

Rubber plantations are susceptible to various pests and diseases that can significantly reduce yield and economic returns. The major pests and diseases affecting rubber trees include:

Common Rubber Tree Pests

- Termites (*Odontotermes* spp. and *Macrotermes* spp.): Damage roots and stems, weakening the tree structure.
- Mealybugs (*Planococcus citri*): Suck plant sap, leading to reduced growth vigor.
- Scale insects (*Coccus viridis*): Cause leaf yellowing and defoliation.
- Mites (*Tetranychus* spp.): Feed on leaves, causing chlorosis and reduced photosynthesis.
- Rodents and Wild Animals: Feed on bark and roots, causing physical damage.

Major Diseases of the Rubber Plant

- South American Leaf Blight (*Microcyclus ulei*) – A fungal disease that leads to leaf necrosis and defoliation, severely affecting plantations in South America.
- Powdery Mildew (*Oidium heveae*) – Causes white powdery spots on leaves, leading to premature defoliation.
- Phytophthora Leaf Fall and Black Stripe Disease (*Phytophthora* spp.) – Affects leaves, stems, and tapping panels, reducing latex yield.
- Root Rot (*Rigidoporus lignosus*) – Causes decay of the root system, leading to tree collapse.
- *Corynespora* Leaf Fall (*Corynespora cassiicola*) – Leads to severe leaf drop, reducing photosynthetic capacity.

These pests and diseases pose significant threats to rubber cultivation and require effective management strategies to minimize losses [5].

General Pest and Disease Management Strategy for Rubber Plants

The management of rubber pests and diseases requires an integrated approach that includes cultural, biological, and chemical control methods.

Cultural Control

- Proper spacing of trees to ensure adequate air circulation and reduce disease spread.
- Regular pruning and sanitation to remove infected leaves and branches.
- Use of resistant clones bred for disease tolerance.
- Crop rotation and intercropping to minimize pest buildup.

Biological Control

- Predatory insects and fungi such as *Beauveria bassiana* (entomopathogenic fungus) to control insect pests.
- Use of mycorrhizal fungi to enhance root health and resistance.

Chemical Control

- Fungicides such as copper-based compounds for leaf diseases.
- Insecticides applied in controlled doses to manage pest populations.
- Herbicides for weed control to minimize pest breeding sites.

Integrated Pest Management (IPM)

The integrated pest management strategy (IPM) combines multiple strategies, including monitoring pest populations, using biological controls, and applying pesticides only when necessary to reduce environmental impact while maintaining tree health and latex yield [1].

Economic Importance of Rubber

Rubber is one of the most vital raw materials in the global economy, primarily due to its wide range of applications in industries such as automotive, healthcare, manufacturing, and construction. As the foundation for the production of tires, rubber contributes to the transportation industry, enabling the movement of goods and people across the world. The global demand for rubber is largely driven by automotive production, where it is used for tires, seals, and gaskets [1]. Additionally, rubber finds use in medical products like gloves, catheters, and surgical devices, making it essential for the healthcare industry. Rubber cultivation and processing are critical to the economies of many tropical countries, particularly in Southeast Asia, West Africa, and South America. The cultivation of rubber provides direct and indirect employment to millions of people, from smallholder farmers to large plantation workers, and supports a substantial number of rural communities. For instance, Thailand, Indonesia, and Malaysia are major producers, and the sector is vital to their economies [2]. The value chain in rubber production—from cultivation and tapping to processing and manufacturing—supports a broad range of sectors, including agroforestry, logistics, and machinery manufacturing, contributing significantly to GDP and export revenues in producing countries.

Moreover, rubber contributes to trade, with the global rubber market valued at billions of dollars annually. According to the International Rubber Study Group (IRSG), the global rubber trade reached approximately \$39 billion in 2020, with natural rubber accounting for a substantial portion of this trade. This highlights the significant economic impact rubber has on global commerce and trade relations. The rubber sector's economic importance is further underscored by the growing demand for sustainable and environmentally responsible practices, which add a new dimension to its value in global markets [7].

Technological Advancement in Rubber Production

Technological advancements in rubber production have revolutionized the industry, improving efficiency, increasing yields, and reducing environmental impacts. One of the major technological innovations has been the development of high-yielding rubber clones through selective breeding and genetic modification. These clones are more resistant to diseases and pests, and they produce latex in higher quantities, thus improving the productivity of rubber plantations [1]. The introduction of precision agriculture techniques, such as automated tapping systems and sensors for monitoring soil moisture, temperature, and nutrient levels, has further enhanced rubber cultivation. These systems allow farmers to optimize resources and reduce costs while increasing yields [4]. Furthermore, the adoption of automated systems for processing latex, including efficient coagulation techniques and energy-saving drying technologies, has minimized waste and reduced energy consumption.

In addition, the rubber industry has seen advances in the development of bio-based materials and products. For example, bio-rubber, made from renewable plant sources, is emerging as an alternative to synthetic rubber in various applications [8]. The development of greener, more sustainable production processes, such as using bio-based coagulants for latex, has gained traction in response to environmental concerns, offering a promising future for eco-friendly rubber manufacturing. These technological advancements ensure that the rubber industry can continue to meet growing global demand while minimizing its environmental footprint.

Socioeconomic Impact of Rubber and Rubber Products

The rubber industry has significant socio-economic implications across the globe, particularly in both producing and consuming countries. The impact is especially pronounced in major rubber-producing nations in Africa, Asia, and Latin America, where rubber cultivation supports millions of livelihoods. Additionally, in industrialized economies where rubber is a crucial raw material, its availability and price fluctuations can influence key industries such as automotive, healthcare, and manufacturing. A comparative review of rubber production within some selected continents was provided below:

Rubber Production in Africa

Africa has a growing presence in the global rubber market, with key producers including Nigeria, Côte d'Ivoire, Ghana, Liberia, and Cameroon. These countries have favorable climatic conditions for rubber cultivation and are increasingly positioning themselves as significant contributors to the global rubber trade.

- **Nigeria:** Nigeria is one of the largest rubber producers in Africa, with the industry providing employment to thousands of smallholder farmers. The rubber sector has also attracted foreign investments, contributing to economic diversification and export earnings. However, challenges such as poor infrastructure, outdated processing technology, and deforestation continue to hinder its growth [10].
- **Côte d'Ivoire:** Côte d'Ivoire is Africa's largest producer of natural rubber, with production surpassing 950,000 metric tons in 2022. The rubber sector is a major employer, particularly in rural areas, where thousands of smallholder farmers cultivate rubber for export [11].
- **Liberia:** Liberia has a long history of rubber production, with major companies such as Firestone operating large plantations in the country. The sector plays a key role in the nation's economy, providing direct and indirect employment and contributing significantly to GDP [12].
- **Ghana and Cameroon:** Both Ghana and Cameroon have been expanding their rubber production capacities, focusing on improving processing infrastructure and increasing exports to global markets. The rubber sector in these countries has become an essential driver of rural development and poverty alleviation [11].

Rubber Production in Asia

Asia dominates global rubber production, with Thailand, Indonesia, Vietnam, India, and Malaysia leading the industry. Thailand and Indonesia alone account for over 60% of the world's natural rubber supply. The rubber sector in these countries plays

a critical role in employment generation, trade, and industrialization. Governments in these nations have implemented policies to modernize rubber production, improve sustainability, and enhance export revenues [13].

Rubber Production in Latin America

Brazil, the birthplace of the rubber tree (*Hevea brasiliensis*), remains a notable producer, although its share of the global rubber market has declined due to competition from Asia. Other Latin American countries, such as Colombia and Guatemala, are also involved in rubber production, mainly for regional consumption and export to North America [1].

Impact on Consumer Economies

In consumer economies like China, the United States, and European Union countries, rubber is a crucial raw material for industries such as automotive manufacturing, healthcare, and construction. China is the world's largest importer of natural rubber, driven by its extensive tire production industry. The United States and Europe also rely heavily on rubber for medical equipment, industrial machinery, and various consumer goods. Changes in rubber prices and supply chain disruptions can significantly impact these economies, influencing production costs and overall economic stability.

Environmental Challenges faced by Rubber Producers

While rubber is an essential commodity, its production and processing have significant environmental consequences. The large-scale expansion of rubber plantations has led to deforestation, loss of biodiversity, soil degradation, and increased greenhouse gas emissions. Additionally, the chemical-intensive nature of rubber processing poses risks to water quality and air pollution.

Deforestation and Biodiversity Loss

One of the most pressing environmental challenges linked to rubber cultivation is deforestation. In Southeast Asia, particularly in countries like Thailand, Indonesia, and Vietnam, large-scale conversion of tropical forests into rubber plantations has led to habitat destruction for endangered species such as orangutans, tigers, and elephants [3]. Similarly, in Africa, increasing rubber cultivation in Nigeria and Côte d'Ivoire has contributed to deforestation, threatening native flora and fauna [2].

Carbon Emissions and Climate Change

Rubber plantations contribute to carbon emissions, both through deforestation and land-use change. Clearing forests for rubber plantations releases stored carbon dioxide into the atmosphere, exacerbating climate change. Additionally, the industrial processing of rubber, which involves energy-intensive drying and vulcanization, contributes further to greenhouse gas emissions [6].

Soil Degradation and Water Pollution

The intensive cultivation of rubber trees depletes soil nutrients, leading to reduced land productivity over time. Additionally, rubber processing factories discharge chemical-laden wastewater into rivers and streams, polluting water bodies and affecting aquatic life. In some rubber-producing regions, the overuse of

fertilizers and pesticides has led to soil and water contamination, impacting both biodiversity and human health [5].

Waste Management Challenges

The disposal of rubber waste, particularly used tires, is another major environmental issue. Millions of tons of discarded rubber products, such as tires and gloves, accumulate in landfills, where they take centuries to degrade. The burning of waste rubber releases toxic gases, contributing to air pollution and respiratory diseases in nearby communities [4].

Solutions and Sustainable Practices

Efforts to mitigate the environmental impact of rubber production have led to the development of several sustainable practices:

1. **Agroforestry and Sustainable Rubber Farming:** Encouraging farmers to integrate rubber cultivation with other crops can help preserve biodiversity and maintain soil fertility. Agroforestry systems have been successfully implemented in countries like Thailand and Ghana [6].
2. **Eco-friendly Processing Techniques:** The use of bio-based coagulants instead of synthetic chemicals in latex processing reduces water pollution. Additionally, energy-efficient drying and processing technologies can help reduce emissions.
3. **Waste Recycling and Circular Economy:** Recycling used tires into materials for road construction, playground surfaces, and industrial applications has become a key strategy for reducing rubber waste. Countries like the United States and Germany have adopted advanced tire recycling programs to manage rubber waste effectively.
4. **Carbon Sequestration Initiatives:** Some rubber-producing companies are investing in reforestation and afforestation projects to offset carbon emissions from rubber plantations. Such initiatives are particularly active in Indonesia and Malaysia, where companies are working to restore degraded forests.

Waste Management Strategies for Rubber Processing Industries

The processing of rubber, particularly the latex coagulation and drying stages, generates significant waste that can contribute to environmental pollution if not properly managed. Rubber processing industries have developed several waste management strategies to mitigate the environmental impact of their operations.

- One common waste management strategy is the recycling of rubber products, including tires, which can be repurposed into new products such as rubber mats, road surfacing materials, and even new rubber products through the process of devulcanization [8]. This not only reduces the volume of waste sent to landfills but also conserves valuable raw materials and energy.
- Another strategy is the treatment and recycling of water used in rubber processing. Closed-loop water systems, which reuse water within the processing plant, help to reduce water consumption and minimize contamination of surrounding water sources. Additionally, the use of bio-based coagulants instead of synthetic chemicals in the latex coagulation process has reduced the environmental impact of waste generated by processing.

- The use of energy-efficient technologies in rubber processing plants also contributes to waste reduction. Solar energy, biogas production from rubber biomass, and the optimization of energy use during drying and coagulation are some of the innovations being implemented to minimize energy consumption and reduce emissions [4]. Furthermore, many companies are adopting sustainable practices that include reducing emissions from factories and improving the overall environmental performance of their operations.

In conclusion, the adoption of waste management strategies in the rubber processing industry is essential to ensuring that the sector remains environmentally sustainable while meeting global demand for rubber products. These strategies help reduce pollution, conserve resources, and support the broader goal of sustainable development in the rubber sector.

Conclusion

The economic importance of rubber production extends beyond the primary producers, influencing trade, employment, and industrial growth worldwide. Technological advancements have played a critical role in enhancing the efficiency of rubber cultivation and processing, leading to higher yields, improved quality, and more sustainable practices. However, rubber production is not without its challenges, particularly in terms of environmental impacts. Issues such as deforestation, water use, and pollution from rubber processing industries need urgent attention. While efforts have been made to mitigate these impacts through sustainable farming practices, waste management strategies, and the development of alternative materials, there is still much to be done to ensure that the rubber industry becomes more environmentally sustainable in the future. The global rubber industry, with its technological innovations and growing demand, continues to shape economies and societies in profound ways. As the world moves toward more eco-conscious practices, the future of rubber production will likely hinge on the balance between economic benefits and environmental stewardship. The integration of sustainable practices and waste management strategies within the rubber production process is crucial for mitigating the negative effects of the industry while ensuring its long-term viability.

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