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Sustainability Value Chain Analysis of Environmentally Friendly Natural Rubber Productivity: A Case Study

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Abstract

Natural rubber is a major internationally traded commodity that contributes substantially to producer-country economies through employment and export revenue, with key processed products including Standard Indonesian Rubber (SIR), Ribbed Smoked Sheet (RSS), and concentrated latex (centrifuge latex). This study maps and analyzes productivity along the natural rubber (NR) supply chain and formulates strategies to improve environmentally friendly productivity to support the sustainability of state-owned enterprises. Priority strategies were identified using the Analytic Hierarchy Process (AHP), and their performance was assessed using the Green Productivity Index (GPI) and visualized through the Green Value Stream (GVS). Results show that upstream cultivation achieved a higher GPI (3.84) than downstream processing, including RSS (0.38) and SIR (0.16). Upstream priorities to increase GPI include semi-intensive cultivation and replanting (0.42), reuse of cultivation waste (0.30), and substitution with organic pesticides (0.28), while downstream priorities include process optimization (0.36), wastewater reuse (0.29), raw material control (0.20), and raw material substitution (0.15). Overall, sustainable NR cultivation and production at PTPN 1 Regional 2 can be strengthened through consistent implementation and strong commitment across integrated economic, environmental, social, and governance dimensions.

Keywords: green productivity; green value stream; natural rubber; sustainability; supply chain

1. Introduction

Natural rubber is a key plantation commodity in international trade and can be processed into a wide range of industrial products. Since 1900, global consumption of rubber—both synthetic and natural—has continued to increase at an average rate of 5.8% per year [1]. In Indonesia, natural rubber production has fluctuated in recent years. Output reached approximately 2.88 million tons in 2020 and increased to 3.12 million tons in 2021. Production rose slightly again to around 3.14 million tons in 2022, but declined to approximately 2.44 million tons in 2023 due to factors such as climate variability, land conversion, and the spread of Pestalotiopsis leaf fall disease that adversely affected rubber stands. In 2024, production gradually recovered to around 2.6 million tons, supported by productivity improvement efforts and reduced disease incidence [2].

Compared with other major rubber-producing countries, Indonesia's yield per hectare remains relatively low. This gap is largely attributed to aging rubber trees and limited investment capacity among smallholders, which constrain field rehabilitation and reduce harvesting performance. In contrast, Thailand, Vietnam, and Malaysia report higher productivity levels, with yields of 1,800

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kg/ha/year, 1,720 kg/ha/year, and 1,510 kg/ha/year, respectively, while Indonesia produces about 1,080 kg/ha/year [3]. These conditions highlight the need for integrated interventions that improve productivity while addressing environmental and sustainability concerns across the supply chain.

Existing studies on natural rubber have predominantly focused on upstream supply and farm-level practices. Research has addressed nursery and seedling management [4–9]. While several studies have examined production systems and supply chains—such as rubberwood utilization [10] and environmental impacts associated with rubber production [11,12]—relatively few have integrated productivity analysis with environmental performance and long-term sustainability outcomes. Notably, Arifin (2005) emphasized the importance of linking productivity improvement with environmental management, including the introduction of improved rubber varieties and land-use practices aligned with sustainable natural resource governance [13]. In addition, climate-related challenges have underscored the need for climate-adaptive clones to sustain production under global climate change [14], and intercropping systems have been shown to enhance drought resilience in rubber trees [15]. At the supply-chain level, Peramune & Afs (2007) mapped the overall flow from Indonesian natural rubber producers to end consumers in both domestic and international markets [16].

Beyond technical and agronomic dimensions, the expansion of rubber plantations in Southeast Asia has raised concerns regarding social and environmental implications [1,17], as well as political and economic drivers shaping land-use change [18,19]. These dynamics reflect broader Triple Bottom Line (TBL) challenges—economic, social, and environmental—associated with natural rubber development [3,20,21]. In response, frameworks such as Sustainable Natural Rubber Development (SNRD) and Sustainable Agricultural Development (SAD) have been proposed to balance TBL priorities through integrated consideration of environmental, economic, social, and governance dimensions [22]. Evidence from Negash et al. (2021) further indicates that technical support plays a critical role in reducing economic and social risks in natural rubber development, and that environmental and economic sustainability are closely interconnected [23]. Key priorities for improving smallholder sustainability include value addition, quality improvement, capital investment, marketing platforms, alternative income sources, openness to change, and efficient material use.

Value chain analysis provides a comprehensive view of production from upstream to downstream activities—covering seed and planting material provision, cultivation, maintenance, harvesting, processing, and distribution—where each stage influences final product quality and value creation. Effective value chain management aims to enhance efficiency, raise productivity, and strengthen system sustainability. In the context of environmentally friendly rubber production, green practices may include adoption of green technologies, improved waste management, and sustainable farming methods, which can be assessed through indicators such as low-carbon technology implementation, water management, and renewable energy use. Environmentally responsible practices are also increasingly guided by international standards and platforms, including the International Organization of Standardization (ISO), the Global Organic Latex Standard (GOLS), and the Global Platform for Sustainable Natural Rubber (GPSNR), which support organizations in adopting and verifying sustainability-oriented practices.

In Indonesia, the natural rubber supply chain comprises suppliers, distributors, processors, and marketers. Suppliers include smallholders, private estates, government-owned plantations, and natural rubber importers. Major processed natural rubber (NR) products include Standard Indonesian Rubber (SIR), Ribbed Smoked Sheet (RSS), concentrated latex (centrifuge latex), and crepe rubber (brown crepe and white crepe). Prior research has applied sustainability-oriented supply chain assessment using the Green Productivity Index (GPI) in private natural rubber plantations in Indonesia focusing on value chain analysis and identifying factors influencing efficiency and sustainability [24]. Similar work on smallholder rubber value chains reported that (1) the agricultural productivity of the Restu Farmer Business Group declined over one year, (2) the Green Productivity

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Index value was 3.6, and (3) key issues were associated with the use of non-environmentally friendly supporting materials [25].

To complement studies conducted in private and smallholder plantations, further investigation is needed on state-owned plantations, specifically PTPN I Regional 2. Therefore, this study examines the natural rubber value chain and sustainability performance in PTPN I Regional 2 using the Green Productivity Index (GPI), the Green Value Stream (GVS), and the Analytic Hierarchy Process (AHP) as the core methodological approach. The study aims to assess natural rubber management holistically through a sustainability lens by providing an in-depth understanding of upstream-to-downstream process flows, including key actors, activities, and linkages across stages within the supply chain.

2. Materials and Methods

2.1. Study Area and System Boundary

PTPN I Regional 2 is a state-owned natural rubber plantation and processing operator in West Java, Indonesia, managing 12,119.28 ha. The company produces concentrated latex (on a special-order basis), Ribbed Smoked Sheet (RSS), and Standard Indonesian Rubber (SIR). This study applies a cradle-to-factory-gate boundary that includes (i) upstream cultivation (field maintenance and harvesting), (ii) downstream processing (RSS and SIR production within the factory system), and (iii) internal logistics and transport from estates to processing units as represented in the Green Value Stream (GVS). Nursery and seedling operations were excluded because they were not conducted during the study period.

A mixed-methods design was used. Quantitatively, material flow analysis and GVS mapping were applied to characterize resource use, wastes, and emissions along the supply chain and to quantify environmentally friendly productivity (green productivity). Improvement scenarios were then prioritized using the Analytic Hierarchy Process (AHP). Qualitatively, interviews were conducted to contextualize operational practices and interpret sustainability drivers across environmental, economic, social, and governance dimensions. Social and governance evidence was additionally collected through a structured questionnaire administered to employees across job levels (Manager, Assistant Head, Assistant Afdeling, Mandor 1, Mandor Sadap, and tappers). The sample size was calculated using the Frank Lynch formula (population N = 2,449), yielding n = 95.2, which was rounded to 95 respondents. Surveys were completed during plantation and factory visits after production activities ended.

Functional unit and time basis. All calculations were performed on a monthly operational basis using production and resource-use records for the period 2024. Energy and material flows were recorded in their original operational units (kWh, m^3, kg, km) and converted to carbon-equivalent metrics (tCO_2e) using documented emission factors. Daily records were normalized to monthly totals using the number of operating days.

2.2. Green Value Stream (GVS) and Material Flow Analysis

Value chain analysis was conducted by developing a baseline Green Value Stream (GVS) to map current flows of materials, energy, water, wastes, and emissions across the natural rubber system. The upstream boundary includes field maintenance and harvesting; nursery/seedling activities were excluded because PTPN I Regional 2 has not conducted nursery operations since 2014. The downstream boundary covers RSS and SIR processing. RSS process mapping includes raw material reception, dilution and coagulation, milling, smoking, sorting, packaging, labeling, and shipment to the estate warehouse. SIR process mapping includes raw material reception/sorting, dry rubber content determination, milling, drying, final sorting/handling, labeling, and shipment to the estate warehouse.

Data were obtained from three sources: (i) direct field and factory observations to document operational practices and identify loss points, (ii) company operational records on production

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volumes and resource consumption, and (iii) expert interviews with relevant stakeholders (academics, practitioners, and government officials) to validate process descriptions and confirm key assumptions. Using the GVS framework, seven categories of "green waste" were identified and quantified: energy, water, material losses, non-reusable waste, transportation, emissions, and biodiversity impacts.

GVS calculations were compiled on a monthly basis to ensure consistent aggregation across heterogeneous activities. Inputs and outputs were recorded in operational units—electricity (kWh), water (m^3), materials and solid waste (kg), transportation (km), emissions (tCO_2/day), and biodiversity impact (ha)—and then converted to annualized carbon-equivalent reporting (tCO_2/year). Electricity-related emissions were calculated using an emission factor of 0.84 (Jamali standard), and diesel fuel emissions were calculated using an emission factor of 2.68.

2.3. Green Productivity Index (GPI)

Green Productivity Index (GPI) was computed by integrating economic performance and environmental performance, following the green productivity framework [22]. The index is defined as:

$$\text{Green Productivity Index (GPI)} = \frac{Economic\ Indicator}{Environmental\ Indicator}, \quad (1)$$

The economic indicator reflects the relationship between output value and production cost:

$$\text{Economic Indicator} = \frac{Revenue}{Total\ Cost}, \quad (2)$$

where Revenue is the total sales value of product output within the analysis period, and Total Cost includes all relevant production costs required to generate the corresponding output (e.g., labor, inputs, utilities, maintenance, fuel/transport, and processing costs) within the same period.

The environmental indicator was derived from the Environmental Sustainability Index (ESI) approach, aggregating multiple environmental impacts into a composite Environmental Impact (EI) score [26]. For cultivation (upstream), the EI formulation is:

$$EI = 0.375\ GWG + 0.25\ WG + 0.125\ SWG + 0.25\ LWG, \quad (3)$$

For downstream processing, the EI formulation is:

$$EI = 0.17\ SWG + 0.5\ GWG + 0.33\ WC, \quad (4)$$

where GWG represents gaseous waste generation (e.g., process-related emissions), WG wastewater generation, SWG solid waste generation, LWG unused land/land burden, and WC water consumption. In this study, EI was operationalized using measured or recorded indicators including air quality and air pollution reduction, greenhouse emissions, biodiversity impacts, water consumption, water quality, material/solid consumption reduction, and land area. All indicator calculations were aligned to the defined boundary and time basis, and were converted or normalized to a consistent EI unit prior to aggregation.

2.4. Green Value Stream Mapping (GVSM) and Green Waste Sources

Green Value Stream Mapping (GVSM) extends conventional value stream mapping (VSM) by focusing on environmental waste and quantifying impacts such as energy consumption, raw material losses, process waste, water consumption, transportation burden, gaseous emissions, and biodiversity effects [27,28]. In the context of green productivity, GVSM functions as an eco-mapping tool. GVSM identifies seven primary sources of green waste: (1) energy (electricity and fuel use during production), (2) water (total water use during production), (3) material (residual materials that can still be reused), (4) waste (residual outputs that cannot be reused), (5) transportation (fuel use and travel distance), (6) emissions (outputs associated with energy use, typically greenhouse gases such as CO_2 and methane), and (7) biodiversity (land area directly affected by degradation of flora, fauna, and other organisms) [29].

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GVS calculations were conducted on a monthly basis to facilitate the estimation of energy use and waste generation across all activities in both upstream and downstream stages. Estimation of energy sources and waste generation was based on the sampled plantation area, production output, number of tappers, types and quantities of inputs used, and the types of vehicles and machinery utilized. All waste streams in the GVS were converted and reported as tons of CO_2 per year (tCO_2/year). Input data were recorded in their original units—electricity (kWh), water (m^3), materials (kg), solid waste (kg), transportation (km), emissions (tCO_2/day), and biodiversity impacts (ha)—and subsequently converted where needed. For example, electricity consumption (kWh) was multiplied by an emission factor of 0.84 (Jamali standard), and diesel fuel (L) was multiplied by an emission factor of 2.68 [30].

2.5. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was used to prioritize improvement strategies for upstream cultivation and downstream processing. The AHP hierarchy consisted of five levels: (1) focus, (2) factors, (3) actors, (4) objectives, and (5) alternatives. Pairwise comparisons were conducted using the Saaty fundamental scale (1–9), where 1 indicates equal importance and 9 indicates extreme importance of one element over another.

Respondents and data collection. AHP judgments were elicited through interviews with selected key persons (stakeholders) and domain experts involved in natural rubber cultivation and processing, including internal operational roles and external stakeholders (academics, practitioners, and government representatives). For the upstream hierarchy, stakeholder groups considered include government, board of directors, estate management, tappers, and universities/research institutions. For the downstream hierarchy, stakeholder groups include board of directors, government, universities/research institutions, and downstream industry. A structured interview guide was used to support AHP elicitation.

Pairwise matrix construction. In accordance with the AHP calculation appendices, entries in the pairwise comparison matrices were constructed based on the relative priority weights provided by key persons; when the relative importance value was <1, its reciprocal (1/value) was used to populate the comparison matrix. Full calculation tables for upstream and downstream AHP are provided in the Supplementary Materials.

Consistency assessment. For each pairwise comparison matrix, the maximum eigenvalue (λmax) was used to compute the Consistency Index (CI) and Consistency Ratio (CR):

$$\mathrm{CI} = \frac{\lambda max - n}{n - 1}, \tag{5}$$

$$\mathrm{CR} = \frac{CI}{RI} \tag{6}$$

where n is the matrix size and RI is the random index. A matrix was considered acceptable when CR < 0.10. Consistency evaluation tables are reported in the Supplementary Materials. For example, the downstream "factor" matrix (n = 6) yields CR ≈ 0.021, and the governance-dimension matrix (n = 5) yields CR ≈ 0.007, both below the acceptance threshold.

2.5. Social and Governance Assessment

Social and governance dimensions were assessed using a structured questionnaire administered to employees and operational stakeholders at PTPN I Regional 2. The respondent population was N = 2,449, and the sample size was determined using the Frank Lynch formula, resulting in n = 95 respondents. Respondents represented multiple job levels (e.g., Manager, Assistant Head, Assistant Afdeling, Mandor 1, Mandor Sadap, and tappers). The questionnaire included items covering worker welfare, education and health support, labor–management relations, community empowerment, monitoring and evaluation, accountability and transparency, sustainability principles, and regulatory compliance. Responses were measured using a Likert scale range 1–9, and results were

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summarized as percentage satisfaction for each indicator. The full questionnaire instrument and tabulated survey results are provided in the Supplementary Materials.

3. Results and Discussion

3.1. Green Productivity Index

Improving productivity while strengthening environmental management is essential for enhancing firm performance and competitiveness. The implementation of Green Productivity supports simultaneous improvements in operational productivity and environmental performance [31]. In this study, Green Productivity is treated as a strategic approach to increase productivity and reduce environmental impacts while contributing to broader socio-economic outcomes, and it is used to assess the future sustainability of PTPN I Regional 2.

The GPI was calculated for each product stream (latex, RSS, and SIR) based on two components: an economic indicator and an environmental indicator [26]. The GPI results show that upstream natural rubber cultivation achieved a GPI of approximately 3,83, derived from an economic indicator of 4,47 and an environmental indicator of 1,16. This pattern indicates that the economic performance of upstream operations is stronger than the environmental component in the cultivation stage. Upstream processes also exhibit higher GPI values than downstream processing, where RSS records a GPI of 0,38 and SIR ranges around 0,15–0,16 (Figure 1). The relatively low GPI values in downstream processing reflect higher environmental burdens, which increase the denominator of the index and suppress overall GPI. This finding is consistent with evidence from private plantations showing higher upstream GPI compared with downstream GPI [24]. In that study, the upstream GPI was 1,95, while research in smallholder plantations (Kelompok Usahatani Restu) reported an upstream GPI of 3,60.

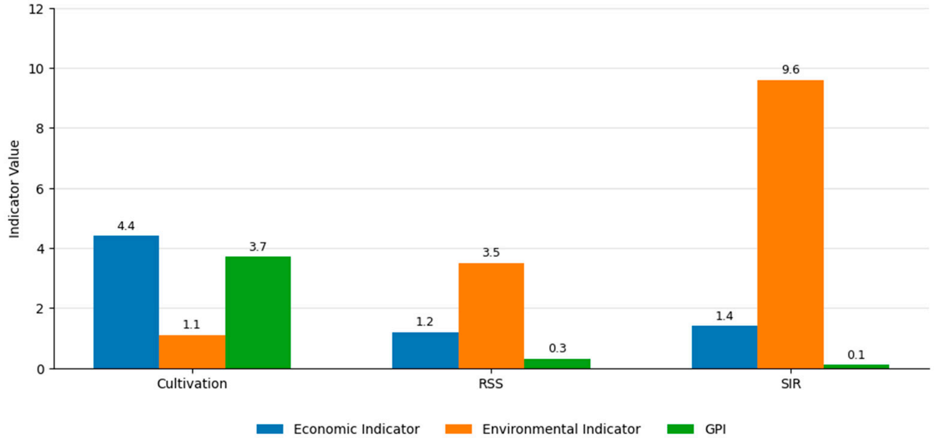

Figure 1. Economic indicator, environmental indicator, and GPI for natural rubber cultivation and production processing at PTPN I Regional 2.

At present, PTPN I Regional 2 maintains two main products RSS and SIR while concentrated latex is produced only for special orders. Although the GPI values for RSS and SIR are lower than those for latex, the decision to prioritize RSS and SIR is driven by market stability and demand certainty. Consistent procurement volumes from downstream industries and product specifications that meet globally accepted standards make RSS and SIR economically strategic. This pattern is widely observed in the rubber industry because RSS and SIR remain major feedstocks for tires, gloves, and polymer-based manufacturing, supporting relatively stable demand despite price fluctuations [32]. In addition, the predictability of sales value supports operational continuity: RSS and SIR prices are reported in the range of Rp 30.000–Rp 40.000/kg, and are projected to reach Rp 43.000/kg in 2024. From an operational economics perspective, cash-flow stability is critical to cover fixed and variable costs, asset maintenance, and payroll obligations [33] Accordingly, sustained

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demand for RSS–SIR functions as an important buffer for enterprise sustainability in a competitive global market.

3.2. Upstream and Downstream Green Value Stream (GVS)

Green Value Stream (GVS) analysis was applied to identify energy and material consumption and waste generation across upstream and downstream processes. At the upstream (cultivation) stage, routine maintenance activities generate 1.993 kg/month of waste, while herbicide and stimulant use reaches 2.507 kg/month; transportation activities contribute emissions of 0,058 ton CO_2/day. This distribution is consistent with previous research, which highlights that large-scale plantation systems often generate substantial carbon footprints during maintenance and raw-material transport [34–36].

At the downstream stage, RSS processing requires 1.281 kWh of electricity, 287 m³ of water, and 15.601 kg of chemicals per month, and generates 5.006 kg/month of solid waste. The most electricity-intensive step is milling, consuming 1.267 kWh/month. Smoking operations require 228 m³/month of firewood, producing CO_2 emissions of 0,036 ton/day and ash waste of 5 tons/month. This pattern aligns with previous research, which identifies drying and smoking as major emission hotspots in natural rubber processing [37,38]. In comparison, SIR production requires 468 kWh/month of electricity and 862 m³/month of water, and consumes 1.552 liters of diesel, generating 0,14 ton CO_2/day. Water consumption is notably higher in SIR processing than in RSS, making water efficiency a key priority for subsequent improvement efforts.

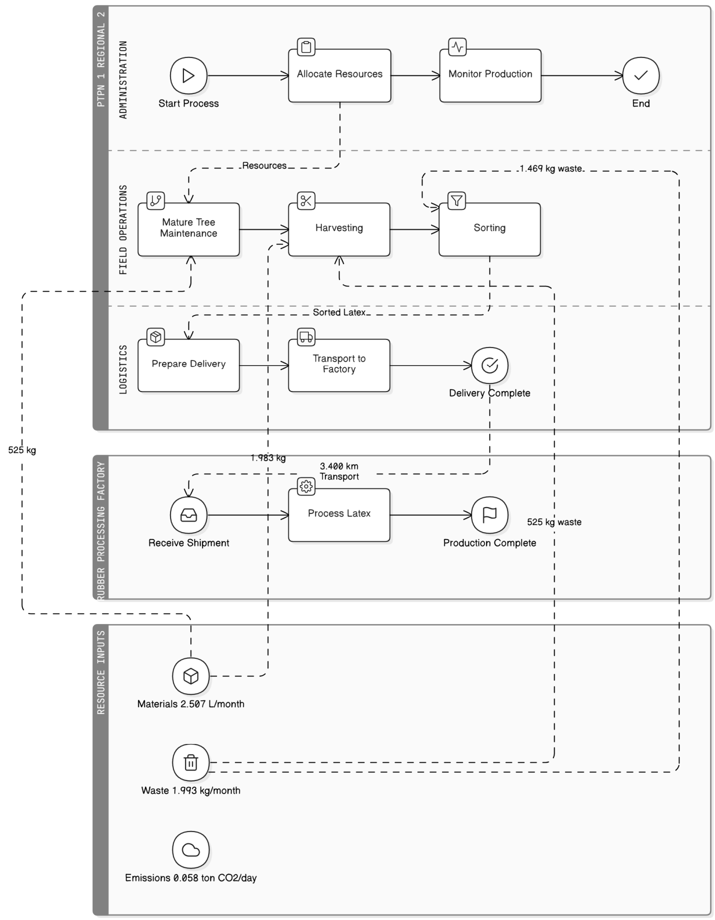

Figure 2. Identification of energy use and waste generation in the upstream natural rubber cultivation process.

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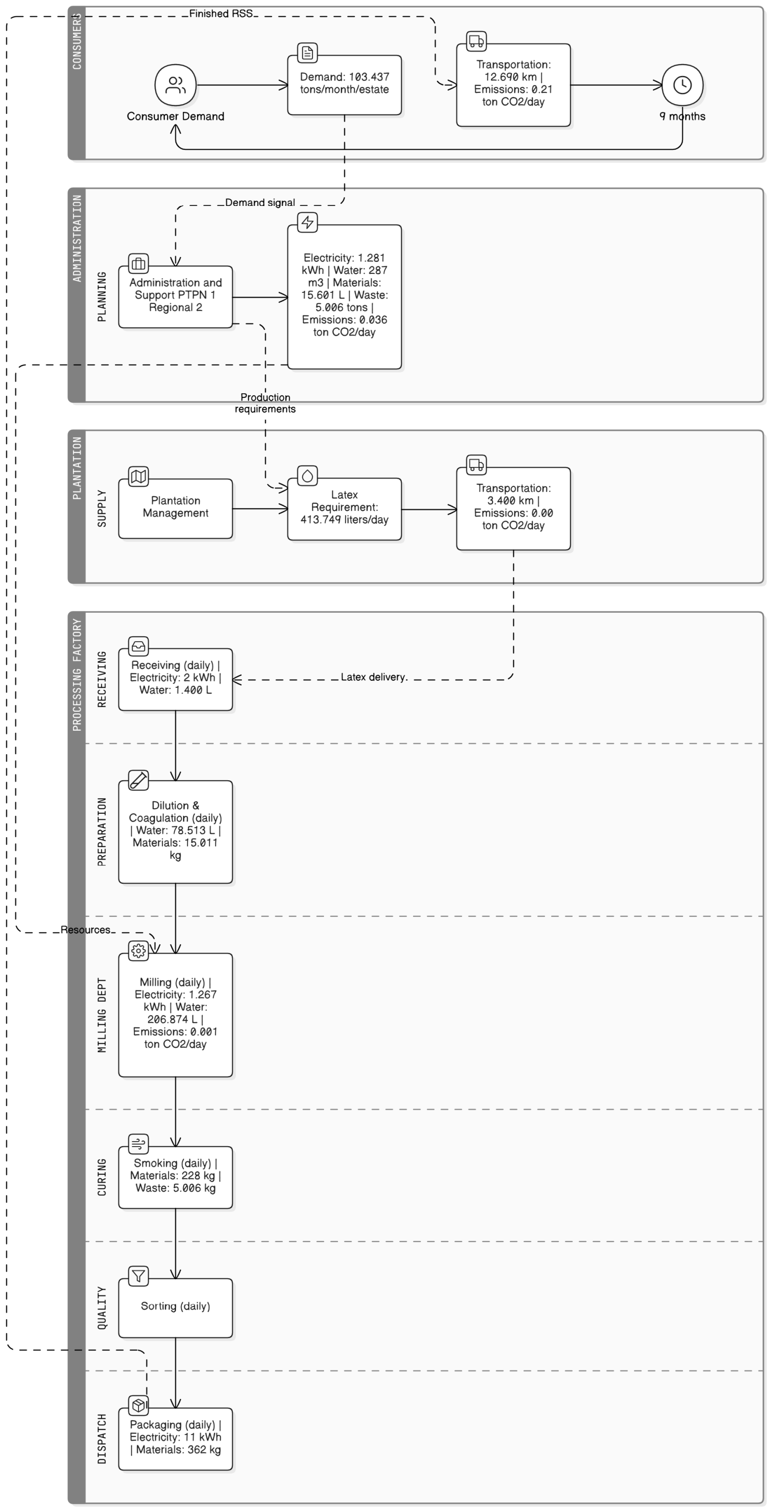

Figure 3. Identification of energy use and waste generation in the RSS production process.

The RSS production chain includes raw material reception, dilution and latex coagulation, milling, smoking, sorting, and packaging. Across these stages, electricity demand is dominated by milling (1.267 kWh/month), while water is used primarily for soaking and milling, totaling 206 m³/month. Smoking relies on firewood (228 m³/month), generating 5 tons of ash and CO_2 emissions of 0,036 ton/day. Chemical inputs are concentrated in dilution and coagulation (15.601 kg/month).

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Although sorting and packaging require less energy than milling or smoking, they still contribute to solid waste through packaging residues and unused latex. Overall, downstream RSS production generates substantial environmental loads through resource consumption (energy, water, materials) and outputs (solid waste, wastewater, and emissions).

For SIR processing, producing 34,4 tons of dry rubber requires 468 kWh/month of electricity and 862 m³/month of water (Figure 4), indicating that SIR processing is more water-intensive than electricity-intensive. Diesel use (1.552 liters) adds to environmental burdens by producing 0,14 ton CO_2/day, primarily associated with fossil-fuel use during processing activities—especially drying, which is among the most energy-intensive units.

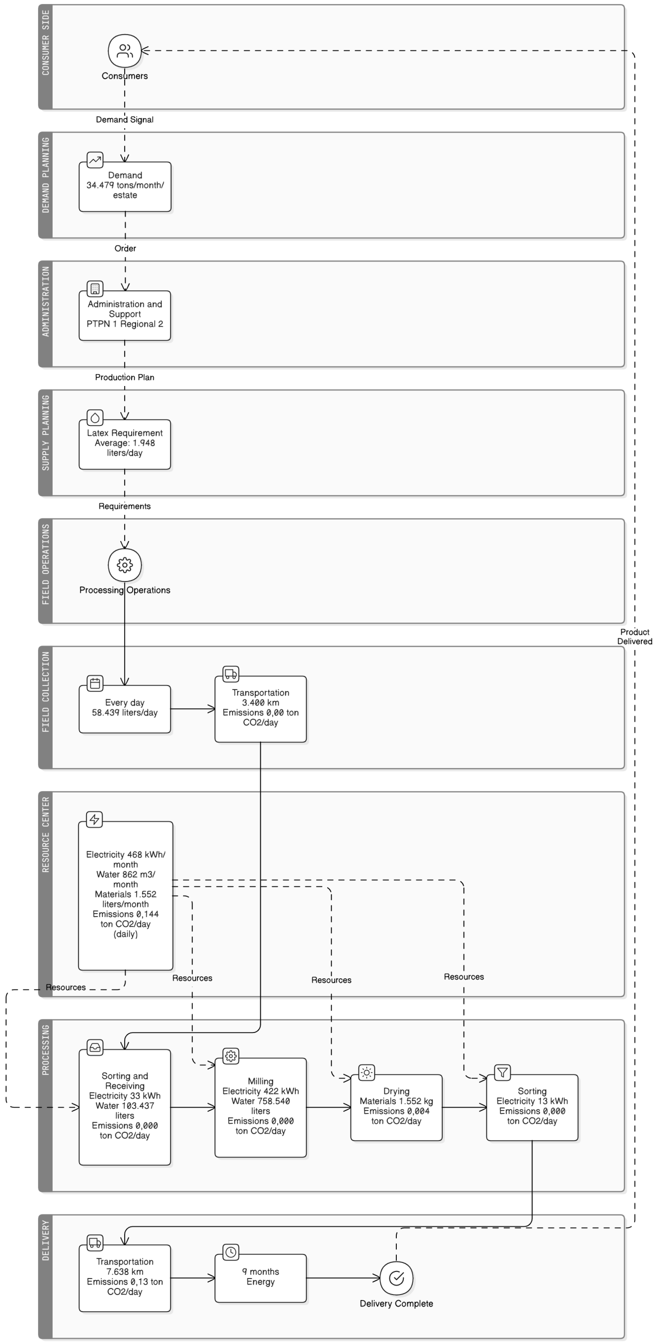

Figure 4. Identification of energy use and waste generation in the SIR production process.

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3.3. Future Green Productivity Index (GPI)

Projections for upstream and downstream management indicate that the GPI can increase over time. Because the environmental indicator strongly influences GPI (as a divisor in the assessment), environmental improvements are central to strengthening sustainability. Key measures include wastewater reuse in production processes and substitution of raw materials and fuels with more environmentally friendly options, such as organic fuels or cleaner energy sources that reduce emissions.

The analysis indicates that GPI improvements across production lines can be achieved through: (1) wastewater reuse, (2) shifting energy sources to low-carbon fuels, (3) adopting organic-based chemicals, and (4) optimizing production processes. These strategies align with Cleaner Production principles and the Circular Economy approach, where resource efficiency and waste reduction directly improve environmental performance [39,40]. Under the projection scenario, GPI increases from 3,84 to 7,24 for cultivation, from 0,38 to 0,63 for RSS, and from 0,16 to 0,26 for SIR. These gains are driven by reductions in the environmental indicator through lower water consumption, emissions, and solid waste, as summarized in Table 1. These results suggest that improved environmental quality can also reduce operational costs and enhance international competitiveness, particularly as global markets increasingly demand low-emission products [41,42]

Table 1. Comparison of current and projected GPI values and indicators.

Process	Current GPI	Projected GPI	Current Economic Indicator	Projected Economic Indicator	Current Environmental Indicator	Projected Environmental Indicator
Upstream	3,84	7,24	4,47	4,30	1,17	0,59
RSS	0,38	0,63	1,40	1,40	3,67	2,23
SIR	0,16	0,26	1,51	1,67	9,75	6,45

3.4. Green Productivity Improvement Strategies in Upstream and Downstream Operations

3.4.1. Upstream (Cultivation) Strategies

AHP-based evaluation of productivity and sustainability strategies indicates that field-level operations are the most influential drivers of performance. Within the “factor” criteria, tapper competence has the highest weight (0,37), followed by optimal utilization of rubber trees (0,24) and plantation maintenance (0,15). Infrastructure, transportation–communication, and technology/policy factors each fall below 0,08. This confirms that rubber productivity is strongly shaped by the technical skills of tappers. As noted by Francis et al., (2022), improper tapping techniques reduce latex yield and accelerate bark damage, highlighting training, safe stimulant use, and routine supervision as priority interventions [43].

For the “actor” criteria, tappers again receive the highest weight (0,39), followed by assistant heads (0,24) and managers (0,16). External actors such as universities and government primarily support innovation and regulation, but their direct contribution to production outcomes is relatively smaller, reinforcing the importance of strengthening human capacity at the field level. For the “goal” criteria, increasing latex production is the main priority (0,51), followed by increasing income (0,34) and reducing environmental impacts (0,15). Although yield improvement remains central, inclusion of environmental objectives indicates a clear sustainability orientation.

Among alternatives, semi-intensive practices and replanting have the highest priority (0,42), followed by converting waste into organic fertilizer (0,30) and substituting chemical pesticides (0,28). Together, these strategies can raise productivity while reducing ecological pressures through improved input efficiency, reduced chemical residues, and better soil health. Overall, the AHP results provide a rational basis for prioritizing productivity strategies that are economically relevant and environmentally aligned.

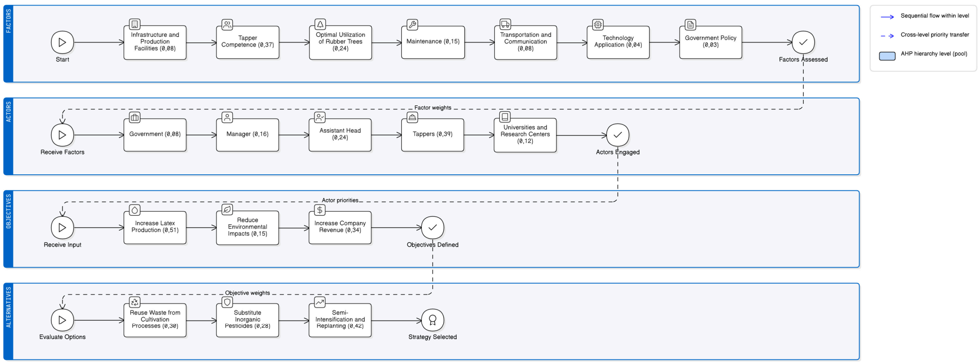

Figure 5. AHP structure for improving upstream natural rubber cultivation productivity at PTPN I Regional 2 Downstream (Processing) Strategies.

3.4.2. Downstream (Processing) Strategies

AHP for downstream processing considered four criteria: factors, actors, goals, and alternatives. Under the "factor" criteria, raw material characteristics carry the highest weight (0,31), indicating that dry rubber content, purity, and quality stability strongly affect processing efficiency and final product quality for both RSS and SIR. The next most influential factor is selling price (0,22), which is sensitive to global market fluctuations; therefore, competitiveness requires value-added diversification and cost efficiency. Production costs (0,18) and human resource competence (0,12) also have substantial influence, particularly through energy and auxiliary material use, machine maintenance, and technical capacity. Market demand and environmental policy each have weights of 0,08, shaping production direction and compliance with emissions and waste regulations.

For the "actor" criteria, the board of directors has the highest weight (0,44) due to authority over investment decisions, machinery modernization, and quality policy. Downstream industry partners (0,28) play a strategic role in supply integration, while universities/research centers (0,14) provide innovation and process technology. Government (0,13) acts as regulator and provider of environmental incentives. Under the "goal" criteria, increasing company profit dominates (0,77), while environmental impact reduction remains important (0,23) through waste management, emissions reduction, and adoption of environmentally friendly technologies.

Regarding alternatives, process optimization (0,36) and wastewater reuse (0,36) are prioritized, followed by raw material control (0,20) and raw material substitution (≤0,08). Process optimization and wastewater reuse are prioritized because they deliver efficiency gains while supporting sustainability standards. Implemented jointly, these strategies enable simultaneous productivity improvement, resource savings, and environmental burden reduction, strengthening long-term sustainability in downstream natural rubber processing.

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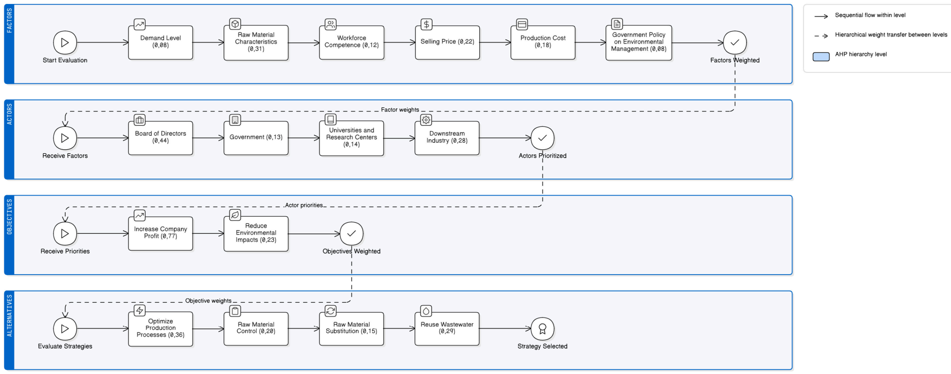

Figure 6. AHP structure for improving downstream natural rubber processing productivity at PTPN I Regional 2.

3.5. Future Green Value Stream and Integrated Sustainability Performance

An overall increase in the Green Productivity Index (GPI) of 3,69 reflects the effectiveness of sustainability strategies across upstream and downstream operations at PTPN I Regional 2. A rising GPI indicates that productivity improvements are accompanied by reductions in environmental impacts, consistent with cleaner production and resource efficiency principles [44]. In upstream cultivation, two primary levers drive environmental improvement: substitution of hazardous inputs and operational efficiency.

Replacing synthetic herbicides with organic alternatives reduces agrochemical residues. Organic, biodegradable inputs can lower soil contamination, preserve microbial quality, and reduce risks of water pollution. This is consistent with Dewi et al. (2024), who reported that environmentally friendly pesticides reduce heavy metal residues and mitigate soil structural degradation without reducing weed-control effectiveness [45]. Beyond biophysical benefits, this substitution increases sustainability value across the latex production chain.

Operationally, improving internal plantation logistics contributes to lower carbon footprints. Repositioning work areas (hanca) and shortening transport distances reduce fuel consumption and CO_2 emissions from operational vehicles. Because transport is a major emissions contributor within plantation commodity supply chains [46], logistics efficiency is instrumental for achieving low-carbon plantation performance, while also reducing operating costs and supporting financial sustainability.

In downstream operations, GPI increases are primarily driven by reduced water use and the adoption of water recycling in RSS and SIR processing. Given the high water demand for washing and purification, recycling industrial wastewater through filtration, reverse osmosis, ultrafiltration, or layered aeration-pond systems can reduce freshwater consumption by up to 33%. This provides dual benefits: lowering water procurement costs and reducing the volume of wastewater requiring treatment. These practices align with the 3R principle (reduce, reuse, recycle) in green manufacturing [47,48]. Recycled water can be reused for equipment washing or irrigation of non-productive areas, enabling a more efficient closed water loop and strengthening environmental performance—particularly for RSS, where downstream GPI initially lagged behind upstream performance.

For SIR, the main energy strategy is substituting diesel with Compressed Natural Gas (CNG) for drying operations. CNG offers lower carbon and particulate emissions, improved thermal efficiency, and potential reductions in operational costs, consistent with broader decarbonization practices in bio-material-based industries [49]. Combined with water recycling in non-critical process stages, these interventions reduce resource intensity and wastewater generation. Together, they reduce the environmental indicator by 3,29 for SIR, indicating substantial improvements in energy and water performance.

Sustainability performance at PTPN I Regional 2 was assessed using both quantitative and qualitative indicators, including GPI, Green Value Stream (GVS), social indicators, and governance.

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Upstream GPI (3,83) indicates high productivity with relatively low environmental burden, while downstream performance (RSS 0,38; SIR 0,15) remains the primary improvement focus through input substitution, energy efficiency, and life cycle costing aligned with ISO 14051. Based on AHP, environmental priorities are ranked as follows: waste management (0,40), water resource management (0,25), environmentally friendly herbicide use (0,17), biodiversity conservation (0,11), and carbon-emission reduction (0,08). This prioritization is consistent with UNEP – Sustainable Production Guidelines, which emphasize water and energy efficiency as major determinants of green productivity.

From the social perspective, the company emphasizes worker welfare, industrial relations, community empowerment, and capacity building. Employee satisfaction exceeds 74% for each indicator and reaches 85,26% for welfare. Implementation of UMSP, health facilities, education support, and technical tapping training reflects corporate social responsibility practices aligned with World Bank Social Responsibility Standards. Governance performance focuses on accountability, transparency, stakeholder participation, and regulatory compliance. Good Corporate Governance (GCG) implementation refers to PER-02/MBU/03/2023 and is supported by certifications including ISO 9001:2015, ISO 17025:2017, Halal, SMK3, and SNI. AHP weights across dimensions are: economy (0,36), environment (0,28), social (0,22), and governance (0,15), indicating that productivity improvements should be reinforced by environmental protection, social welfare, and credible governance.

Overall, the observed GPI increase of 3,69 indicates that input substitution, energy efficiency, water recycling, and decarbonization can reduce environmental impacts without compromising production performance. Through an integrated economic–environmental–social–governance approach, natural rubber production can become more efficient, competitive, and sustainable over the long term.

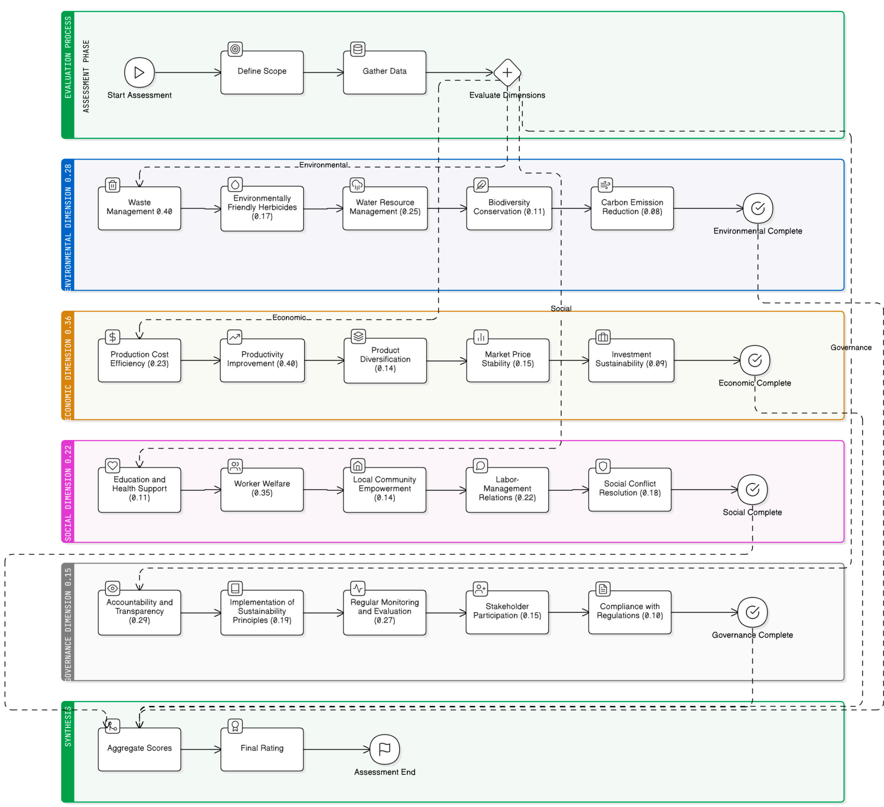

Figure 10. AHP structure for sustainability of natural rubber cultivation and production processes.

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4. Conclusion

The strategy implemented by PTPN I Regional 2 demonstrates that productivity gains can be achieved alongside reductions in environmental impacts. Using the AHP framework, combined with process innovation, fuel substitution, and improved efficiency in water use and waste management, the company substantially increased its GPI values. This approach is consistent with the principles of Sustainable Production and the Circular Economy, as well as international standards guiding environmental management in the natural rubber industry. In contrast to studies in private plantations that primarily assess economic–environmental dimensions, this study also incorporates social and governance dimensions, offering a more comprehensive and contemporary sustainability assessment.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. 1. Interview guide; 2. Social/governance questionnaire instrument; 3. Full AHP calculation matrices; 4. Tabulated social/governance survey results.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
EI	Environmental Impact
ESI	Environmental Sustainability Index
GCG	Good Corporate Governance
GOLS	Global Organic Latex Standard
GPI	Green Productivity Index
GPSNR	Global Platform for Sustainable Natural Rubber
GVSM	Green Value Stream Mapping
GVS	Green Value Stream
GWG	Gaseous Waste Generation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRSG	International Rubber Study Group

 doi:10.20944/preprints202603.1586.v1

ISO	International Organization for Standardization
km	kilometer
kg	kilogram
kg/ha/year	kilograms per hectare per year
kWh	kilowatt-hour
L	liter
LWG	Land Waste / Unused Land
m^3 (m3)	cubic meter
NR	Natural Rubber
OECD	Organisation for Economic Co-operation and Development
PER-02/MBU/03/2023	Regulation/Decree code
PTPN I	PT Perkebunan Nusantara I
PTPN I Regional 2	PT Perkebunan Nusantara I, Regional 2
Rp	Indonesian Rupiah
RSS	Ribbed Smoked Sheet
SAD	Sustainable Agricultural Development
SIR	Standard Indonesian Rubber
SNRD	Sustainable Natural Rubber Development
SWG	Solid Waste Generation
t (ton) / tons	metric ton
tCO_2/day	tons of CO_2 per day
tCO_2/year	tons of CO_2 per year
TBL	Triple Bottom Line
UNEP	United Nations Environment Programme
UMSP	Not defined in the text
VSM	Value Stream Mapping
WC	Water Consumption
WG	Wastewater Generation
3R	Reduce, Reuse, Recycle

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