SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Rubber plantations in tropical landscapes: agronomic systems, environmental impacts, and evidence-based management recommendations

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ARTICLE INFO

Keywords:
Biosystem monoculture
Deforestation
Environment
Ecosystem functions
Hevea Brasiliensis

Article history
Submitted: 2025-04-17
Revised: 2025-05-20
Accepted: 2025-09-22
Available online: 2025-10-28
Published regularly: December 2025

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ABSTRACT

While Natural Rubber (NR) supports global supply chains, rapid expansion in South and Southeast Asia has noticeable effects on biodiversity, hydrology, and the carbon balance. This review synthesizes the economic importance, environmental challenges, commercial applications, and ecological impacts of rubber production and plantation expansion. Furthermore, the study combines high-resolution deforestation attribution (Sentinel-2/Landsat), Eddy-Covariance (EC) comparisons of plantations and nearby tropical forests, and models that include a rubber-specific Plant Functional Type (PFT). In addition, conversion from forest to rubber consistently simplifies habitats, decreases species richness and functional diversity, reduces ecosystem carbon storage, raises peak flows and sediment export, and lowers baseflow. Conversely, replacing annual cropland can increase above-ground biomass and provide partial carbon gains. As such, results depend systematically on prior land use, monsoon intensity and rainfall patterns, elevation, and management practices (monoculture versus diversified agroforestry). The study recommends directing new planting onto already cleared land through spatial planning and reliable traceability, as well as adopting diversified rubber agroforestry and soil- and water-conserving methods. This includes explicitly integrating rubber within zero-deforestation policies and results-based carbon payments. In line with this, rubber-specific modeling and open flux datasets should support climate-risk assessments and monitoring. Overall, focused governance and agroforestry strategies can balance ecological trade-offs while maintaining production, aligning natural-rubber supply with verifiable climate and biodiversity safeguards.

How to Cite: Ali, F. M. H., Zaibon, S. b., Uddin, M. K., Abubakar, A., & Haque, S. (2025). Rubber plantations in tropical landscapes: agronomic systems, environmental impacts, and evidence-based management recommendations. Sains Tanah Journal of Soil Science and Agroclimatology, 22(2), 337-348. https://doi.org/10.20961/stjssa.v22i2.101146

1. INTRODUCTION

Natural Rubber (NR) originates from *Hevea brasiliensis*, a species native to the Amazonian rainforest, and was first documented in 1823 (Nair, 2021). By the late nineteenth century, the nascent plantation industry in Southeast Asia underwent its first major expansion, establishing the foundations of a sector that now spans production, trade, and processing across many countries. Today, numerous nations occupy multiple roles along an integrated global rubber value chain, simultaneously producing, exporting, and importing, reflecting deep market interdependence (van Noordwijk et al., 2020). Alongside NR, Synthetic Rubber (SR) has become indispensable to modern manufacturing. SR is produced by polymerizing monomers derived from oil or natural gas (Kawahara et al., 2022). Notably, current estimates place annual global demand for NR at approximately 6.5 million tonnes sourced through tapping (Nair, 2021).

A pivotal agronomic inflection point occurred in the early 1950s, when vegetative propagation by budding became standard practice. Since 1951, the use of green or brown budding (using scions onto selected rootstocks) has driven the rapid dissemination of high-yielding clonal material in plantations. Moreover, it has a reported success rate of 90% to 100% under appropriate stock selection and seasonal conditions (Tongtape, 2022). In essence, this shift accelerated gains in stand uniformity, tappable girth development, and overall productivity.

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v22i2.101146

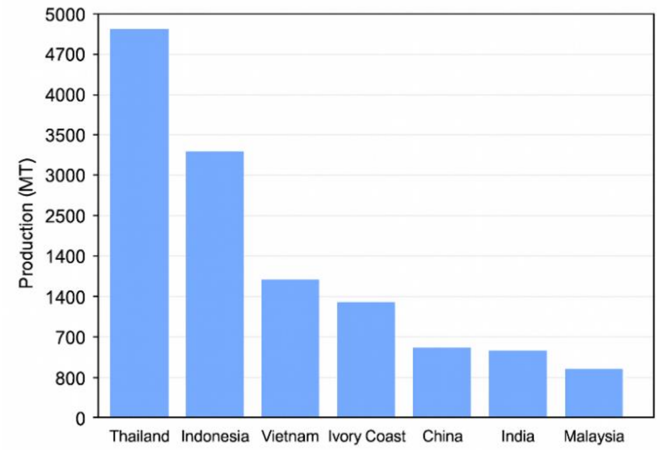

Figure 1. Top eight countries in rubber production for 2022 (adapted from Rohayzi et al. (2023).

Historically, the geographic diffusion of rubber followed distinct phases. *H. brasiliensis* grew wild in Amazonian forests and came under global scrutiny during the Industrial Revolution (Suryanarayanan & Azevedo, 2023). Between 1860 and 1913, reliance on a few Amazonian magnates for supply fostered exploitative extraction systems, including the enslavement of Indigenous peoples (Chiarelli et al., 2018). In the early twentieth century, colonial introductions to South Asia led to widespread farmer adoption and the emergence of extensive agroforestry systems based on unselected seedlings, so-called “jungle rubber” (Byerlee, 2014; Joshi et al., 2002). Following this, policy shifts in the 1950s to 1960s, particularly in Malaysia and Thailand, promoted the replacement of jungle rubber with clonal monocultures to raise yields and standardize quality (Ali et al., 2021). Subsequently, in the new millennium, a pronounced price boom catalyzed rapid land conversion to rubber across continental Southeast Asia (Liu et al., 2018), with expansion into marginal environments contributing to documented impacts on biodiversity, soils, and hydrology. Figure 1 illustrates the annual rubber production in 2022, providing context for the sector’s current scale.

Key challenges for the rubber sector span supply security, material quality, industrial performance, and sustainability. Specifically, projected supply shortfalls, driven by expanding global demand and disease-induced losses, underscore the need to diversify rubber sources. This includes the development of alternate rubber-producing crops and disease-resilient planting material (Cornish & Cherian, 2021). In line with this, variability in natural raw rubber properties across clones, seasons, and processing streams constrains downstream manufacturing, motivating the definition of robust, process-relevant physicochemical criteria for quality control (Gohet et al., 2013; Liu et al., 2018; Panklang et al., 2022; Sugebo et al., 2022). At the same time, the tire industry faces stringent performance and sustainability targets, lower Carbon Dioxide (CO_2) emissions, improved tread wear, and extended service life, requiring consistent material inputs and traceable, lower-impact supply (Olthuis, 2020). On the cultivation side, persistent sustainability concerns, low and volatile prices, food insecurity, land expropriation, deforestation, and loss of biodiversity and ecosystem services can be mitigated through smallholder-centered production systems. It can also be addressed through enforced safeguards on large-scale concessions and landscape-level planning (Kenney-Lazar et al., 2018).

This review is necessary since evidence on rubber’s climate and ecological impacts remains fragmented across disciplines, with baselines and counterfactuals being inconsistently defined. This includes the fact that policymakers, standard setters, and supply-chain actors lack an integrated synthesis that links biophysical outcomes to socio-economic realities and governance levers. Accordingly, we pursue four objectives: (i) review the economic and strategic significance of rubber production within global value chains; (ii) synthesise environmental issues associated with plantation establishment and manufacturing; (iii) clarify the commercial utilisation of latex from the lower trunk alongside secondary timber uses (e.g., firewood, pegs); and (iv) evaluate the ecological implications of rubber expansion with emphasis on soils, carbon, hydrology, biodiversity, and livelihoods.

Furthermore, we explicitly assess negative externalities, including soil degradation and loss of topsoil's physicochemical properties following forest conversion, land-use reconfiguration, and water-resource stress (e.g., reduced monthly runoff); as well as broader landscape and livelihood risks, while identifying contexts and management choices under which these impacts are attenuated or reversible. Notably, advancing sustainable development in rubber-producing countries and along value chains requires a comparative analysis of production models (monoculture versus agroforestry), incentive structures, and enabling policies. In particular, two methodological gaps motivate this synthesis. First, mapping rubber under persistent cloud cover and within complex vegetation mosaics remains a challenging task. However, while many studies focus on distinguishing rubber from natural forest, they insufficiently address confusion with other tropical tree crops and mixed tree systems (Ali et al., 2022). Second, long-term evidence on repeated rotations is limited, impeding attribution of soil change to stand age, deforestation history, and prolonged cultivation. Concurrently, available data indicate that these factors can jointly degrade topsoil properties and soil organic carbon (Panklang et al., 2022).

Our contribution is to integrate rubber’s dual role in carbon sequestration and environmental impact across tropical landscapes, balancing potential benefits for smallholders with exposure to commodity-price and climate risks. We foreground water- and carbon-pathway mechanisms, plant-soil water uptake, and water-use efficiency across agroforestry configurations. This includes their modulation of fluxes, highlighting the emerging role of artificial-intelligence-enabled monitoring in improving mapping, attribution, and management. Collectively, these elements advance understanding of the distribution, impacts, carbon storage, water use, and production dynamics of rubber plantations in the region, providing a decision-oriented rationale and evidence base for policy, certification, and investment.

2. Rubber

A rubber stand follows a well-defined demographic trajectory: an immature phase of approximately five to seven years until first tapping, a peak-yield period from ~10 to 20 years, and senescence at ~25 to 30 years that typically triggers replanting (Nair, 2021). Meanwhile, estate- and landscape-level continuity of output is achieved through staggered replanting, often referred to as "time-series planting," which sequences new and restored blocks to accommodate this biological lag. Operationally, the end of the immature stage is defined by a threshold stem size. For example, when about 50% of trees reach 50 cm girth at 1 m height. Accordingly, maintaining soil fertility during establishment is a primary constraint across both traditional and non-traditional growing regions (Nair, 2021). At the same time, long production cycles in rural settings can progressively deplete site fertility if exports in latex and biomass are not balanced by replenishment (Yamin et al., 2023).

Yield is governed by a coupled set of site and management factors: soil organic carbon and nutrient status (macro- and microelements) (Michael, 2020), planting window and pit geometry, balanced fertilization, and pest-disease control. While a minority of farmers still rely on seedling-derived local clones, most regions have transitioned to superior clonal material. Nevertheless, suboptimal implementation of clone-specific recommendations, stock-scion choice, density, and tapping systems remains a common cause of low productivity (Afrizon et al., 2021). Maximizing output, therefore, requires (i) adoption of high-yielding clones, (ii) deliberate adjustment of clonal composition at the garden scale, and (iii) alignment of spacing and stand design with the target agroecosystem. Note that deviations from recommended practice can depress productivity by as much as ~60%.

Latex, or Natural Rubber Membrane (NRM), is an aqueous colloid in which rubber particles are dispersed within serum phases and stabilized by interfacial biopolymers. Fresh latex typically contains ~30 to 45% rubber by weight, with the remainder partitioned into B- and C-serum fractions enriched in soluble carbohydrates, proteins, lipids, and ions (Fig. 2B). At the particle scale, a protein-phospholipid corona (often described by a double-layer or membrane model) forms an inner phospholipid layer with adsorbed proteins outward (Fig. 2D), conferring electrostatic and steric stabilisation that governs colloidal behaviour, coagulation kinetics, and downstream processing performance (Guerra et al., 2021). Correspondingly, this nanoscale architecture links plantation physiology to material properties, underscoring why site nutrition and health management translate directly into latex quality and industrial consistency.

Following an immature phase of ~6 years, latex can be harvested for 20 to 30 years in monoculture systems via periodic bark tapping. Specifically, ethylene stimulation (e.g., ethephon) has delivered substantial labor and land productivity gains by enabling reduced tapping frequency while sustaining flow, with yield increases reported up to ~78%. By contrast, nutrient management is typically a weaker short-term lever for latex output. In addition, across trials, fertilization effects on production are modest, on the order of +5% to +10%, and highly site-dependent (Gohet et al., 2013). Refer to Table 1 for representative recent, open-access studies that contextualize yield drivers, environmental trade-offs, and advances in monitoring.

3. Fertilization

Table 2 synthesizes fertilizer guidance for immature rubber by combining the classical per-tree nutrient benchmarks, as reported by Warren-Thomas et al. (2018). This is in addition to open-access national schedules that specify mixture grades, split timings, and soil-group adjustments for Sri Lanka and India (Pradeep et al., 2022; RRISL, 2016). In brief, the updated recommendations extend beyond single "average" rates; instead, they operationalize Integrated Nutrient Management (INM) through phenology-aligned split applications, targeted N-P-K-Mg ratios, and soil conservation practices, measures that are increasingly crucial under longer dry spells, heat waves, and more intense rainfall in rubber-growing regions (Vrignon-Brenas et al., 2019; Warren-Thomas et al., 2018).

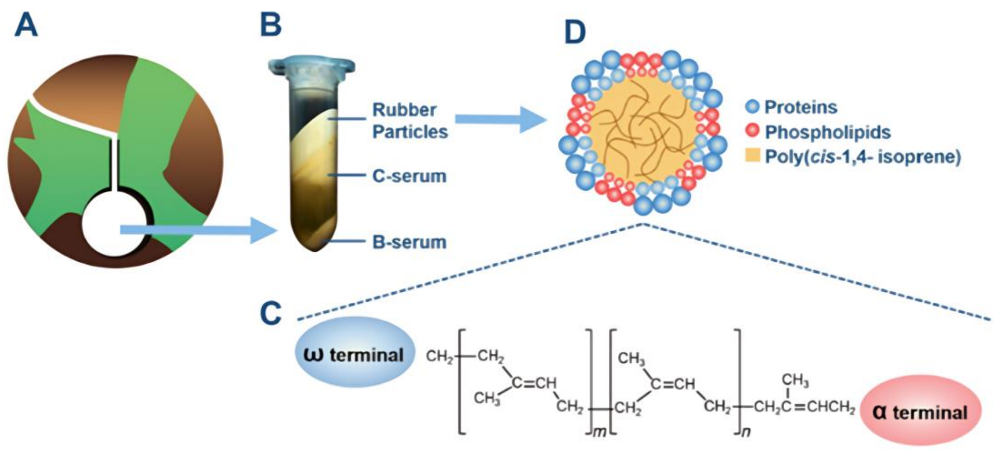

Figure 2. Natural Rubber Membrane (NRM) particle composition and structure. (A) Tapping of H. brasiliensis yields latex from the bark. (B) Post-harvest fractionation separates a cream layer enriched in rubber particles (upper), a C-serum (middle), and a B-serum (lower), representing distinct soluble phases. (C) Rubber particles consist primarily of poly(cis-1,4-isoprene) macromolecules. (D) Particle ultrastructure follows a phospholipid-protein interfacial model in which an inner phospholipid layer is coated by adsorbed proteins, conferring electrostatic and steric stabilization (adapted from Guerra et al. (2021)).

Table 1. Key studies on rubber's environmental impacts and policy implications.

Region/scope	Study focus	Land-use baseline/comparison	Methods/data	Ecological metrics	Key findings	Management/policy implications	Ref.
SE Asia	Deforestation risk & carbon payments	Forest → rubber; oil palm competition	Scenario modeling: economic break-even	Forest loss, CO_2	Carbon prices needed to deter forest conversion often exceed prevailing market rates.	Link payments to realistic opportunity costs; zero-deforestation pledges.	Warren-Thomas et al. (2018)
SE Asia (10 m maps)	High-resolution mapping of rubber & associated deforestation	Region-wide	Sentinel-2/Landsat, cloud computing	Deforestation attribution	Rubber-related forest loss is substantially underestimated in policy inventories.	Include rubber in deforestation regulations; target hotspots.	Wang et al. (2023)
Hainan, China	Sentinel-2 phenology for rubber mapping	Rubber vs. other tree crops/forest	Multi-temporal composites; RF classifier	Mapping accuracy (PA/UA/F1)	Phenology-based composites robustly separate rubber into complex mosaics.	Operational monitoring pipelines for compliance/traceability.	Ali et al. (2022)
Global modelling	New rubber PFT in CLM5	Plantations vs. forest PFTs	Land-surface model augmentation; flux validation	LAI, NEP, ET	Rubber-specific PFT improves carbon and water flux estimation.	Use rubber-aware LSMs for climate-risk planning.	Ali et al. (2022)
Xishuangbanna	Climate change & plantation expansion effects on ET_o	Multi-decadal land-use change	Trend analysis, climate drivers	Reference ET, hydroclimate	Expansion and warming increase water demand; drought sensitivity also rises.	Integrate irrigation/water planning into expansion policies.	Ling et al. (2022)
Monsoonal tropics	Water-Use Efficiency (WUE) seasonality	Rubber plantations	EC; flux partitioning	WUE, H_2O/CO_2 fluxes	Firm seasonal WUE shifts under monsoon vs. drought conditions.	Time tapping/stimulation with hydro-climate windows.	Guo et al. (2023)
Greater Mekong	Plant diversity patterns across the rubber	Cross-country comparisons	Extensive ground surveys; multivariate stats	Alpha/beta diversity	Diversity varies with intensity; Laos > China/Myanmar/Cambodia.	Promote less intensive, agroforestry-like management.	Lan et al. (2022)
Hainan, China	Post-rubber restoration trajectories	Decommissioned plantations	Vegetation & soil surveys across succession	Understory diversity, soil C, N, P	Understory recovers faster than soils within 3-7 years.	Pair plantation reforestation with soil recovery measures.	Du et al. (2024)
Xishuangbanna	Landscape ecological security (1996-2030)	Forest → rubber/tea; urbanisation	Landsat, SVM, Fragstats, grey models	Fragmentation, vulnerability	Rubber expansion correlated with lower landscape security classes.	Spatial planning to curb rubber in high-risk zones.	Zhang et al. (2023)
Thailand & Cambodia	Plantation hydrology & ET	Rubber plantations (eddy sites)	EC, met data	ET, deep water access	High annual ET: deep water use sustains rapid refoliation.	Safeguard catchments; assess water budgets prior to expansion.	Giambelluca et al. (2016)
Hainan	Long-term carbon flux & extremes	20-year-old plantation	2010-2022 EC time series	NEP, GPP/Reco; phenology	Rubber acts as a net sink; fluxes are modulated by radiation, heat, and extremes.	Manage for heat/drought resilience to stabilize sinks.	Yang et al. (2023)
Global	Aridity/ET datasets for land modeling	Cross-biome	Gridded climate/ET products	PET/ET_o indices	Provides vetted drivers for rubber water-stress assessment.	Use consistent climate drivers in plantation planning.	Zomer et al. (2022)

To be continued ...

Region/scope	Study focus	Land-use baseline/comparison	Methods/data	Ecological metrics	Key findings	Management/policy implications	Ref.
SE Asia	Primary forest → rubber: ecological losses	Primary forest baselines	Synthesis/policy mini review	Carbon, nutrients, water, and biodiversity	1.8 Mha primary forest converted (2001-2021) with cascading losses.	Prioritize protections; avoid primary-forest siting.	Wang and Zhang (2025)

Table 2. Traditional and updated fertilizer schemes for immature rubber (g tree^{-1} yr^{-1} unless noted).

Country/region	Stage (yrs)	Fertilizer grade (N-P_2O_5-K_2O-MgO)	Annual schedule (g mixture tree^{-1} yr^{-1})	Cumulative mixture (yrs shown) (g tree^{-1})	Cumulative nutrients (g tree^{-1} over yrs shown) N / P_2O_5 / K_2O / MgO	Notes (timing/soil group)	Ref.
Sri Lanka (legacy baseline)	Immature (typical)	-	-	-	433 / 578 / 311 / 100	Single average values historically reported	Watson (1998) via Vrignon-Brenas et al. (2019)
Thailand (legacy baseline)		-	-	-	556 / 600 / 489 / 111		
Indonesia (legacy baseline)		-	-	-	644 / 687 / 293 / 111		
Malaysia (legacy baseline)		-	-	-	500 / 556 / 378 / 111		
India (legacy baseline)		-	-	-	444 / 444 / 258 / 47		
Liberia (legacy baseline)		-	-	-	500 / 500 / 556 / 444		
Ghana (legacy baseline)		-	-	-	422 / 422 / 578 / 422		
Sri Lanka (updated; urea-based; Soil Groups I & III)	Y1-Y4 (pre-tapping)	15-15-7-0 (R/U)	Y1: 275; Y2: 550; Y3: 800; Y4: 800	2,425	364 / 364 / 170 / 0	Split applications; avoid co-applying dolomite with urea	RRISL (2016)
Sri Lanka (updated; SA-based; Soil Groups I & III)		9-12-4-2 (R/SA)	Y1: 450; Y2: 900; Y3: 1,350; Y4: 1,350	4,050	365 / 486 / 162 / 81	Split applications: Mg supplied in a mix	
Sri Lanka (updated; SA-based; Soil Group II)		9-11-11-0 (R/SA)	Y1: 375; Y2: 750; Y3: 1,125; Y4: 1,125	3,375	304 / 371 / 371 / 0	High-Mg soil; no Mg addition	
India (Kerala & most regions; Mg deficient)		10-10-4-1.5 (NPKMg)	Y1: 225; Y2: 450+450; Y3: 550+550; Y4: 450+450	3,125	313 / 313 / 125 / 47	Apply in Sep-Oct & Mar-Apr splits; pit manuring at planting	Pradeep et al. (2022)
India (Mg-rich regions: TN/NE/Karnataka/Goa)		12-12-6-0 (NPK)	Y1: 190; Y2: 380+380; Y3: 480+480; Y4: 380+380	2,670	320 / 320 / 160 / 0	Same timing; omit Mg on high-Mg soils	

Notes: (i) Legacy rows present per-tree nutrient totals historically reported for “immature” stands; updated rows present mixture schedules and the derived cumulative nutrients for Y1-Y4 to enable direct comparison. (ii) Country updates beyond Sri Lanka and India were not located with per-tree specificity; where available, literature confirms national recommendations exist (e.g., Thailand RRIT, Malaysia MRB) but does not provide open, per-tree schedules; these remain listed as legacy baselines.

INM principles for young stands are consistent across sources: (i) couple organic inputs (mulches, manures, legume cover-crop residues) with mineral fertilizers to synchronize supply with crop demand in time and space; (ii) retain residues and manage groundcover to curb erosion; and (iii) adjust dose and timing to stand age, soil status, and weather windows (RRISL, 2016; Vrignon-Brenas et al., 2019). Functionally, N supports canopy development and latex biosynthesis (via sucrose supply), and P promotes rooting and energy metabolism. Meanwhile, K underpins stomatal control and water-use efficiency under drought, while Mg sustains chlorophyll and carbon fixation; where soils are deficient, micronutrients such as B and Zn prevent avoidable yield penalties (Vrignon-Brenas et al., 2019). Consistent with these roles, the national schedules in Table 2 emphasize split N and K around leaf flush and early growth, and, on acidic soils, liming to maintain base saturation; the Rubber Research Institute of Sri Lanka (RRISL) further notes to avoid co-applying urea and dolomite (RRISL, 2016; Vrignon-Brenas et al., 2019).

From a sustainability perspective, fertilization policy interacts with environmental risks. Frontier rubber expansion has been associated with biodiversity loss, soil-carbon decline, altered hydrology, and erosion (Kenney-Lazar et al., 2018; Panklang et al., 2022). Within existing plantations, however, improving nutrient-use efficiency via INM can reduce mineral requirements, limit runoff and nitrous-oxide risks, and stabilize yields. Such approaches moderate footprints at a given production level (Vrignon-Brenas et al., 2019). Conversely, prolonged "low-input" regimes risk nutrient mining, since N, P, K, and base cations are exported in latex and biomass as stands age (Liu et al., 2018).

Evidence on soil organic matter trajectories remains mixed. That is, some sites demonstrate depletion, whereas others do not. This highlights landscape and management heterogeneity and the need for long-term, rotation-scale trials that control for prior land use, stand age, and climate (Tanaka et al., 2009; Vrignon-Brenas et al., 2019).

Operationally, diagnostics and stimulation choices complement nutrition. Specifically, leaf and latex diagnostics can detect emerging deficiencies before yield loss. At the same time, ethylene stimulation (e.g., ethephon) often delivers larger short-term yield and labor gains than fertilizer alone, with fertilization effects on latex output typically modest (+5-10%) and site-dependent (Gohet et al., 2013). Under climate variability, actionable priorities include: (i) phenology- and weather-informed split dosing (e.g., pre-flush N and K; post-stress recovery applications); (ii) emphasizing K and Mg on drought-prone sites; (iii) integrating leguminous cover crops to fix N and enhance moisture; and (iv) maintaining soil pH and base saturation via liming where appropriate (RRISL, 2016; Tanaka et al., 2009; Vrignon-Brenas et al., 2019).

4. Biochemistry and biodiversity of latex production

Latex is an aqueous colloid comprising rubber and non-rubber fractions, carbohydrates, proteins, lipids, inorganic ions, and suspended particulates (Wang et al., 2023). Rubber particles typically constitute ~50% of latex volume and are generally spherical (occasionally ovoid or pyriform). As such, they remain stably dispersed due to an adsorbed protein-phospholipid interfacial layer that imparts a net negative charge (zeta potential), providing electrostatic/steric stabilization of the colloid (Marques et al., 2024).

Rubber biosynthesis initiates with acetyl-CoA and proceeds through the formation and polymerization of Isopentenyl Pyrophosphate (IPP), catalyzed by rubber transferase complexes located on particle surfaces. Furthermore, plantation productivity hinges on the clone's capacity to regenerate latex between successive tappings. Key biochemical determinants of regeneration include Total Solid Content (TSC), thiols, Inorganic Phosphate, Magnesium, and sucrose. Simultaneously, the sucrose conversion efficiency, rubber produced per unit sucrose in latex, serves as an integrative proxy for metabolic control over carbon allocation to polyisoprene (Baidoo et al., 2022).

Demand for NR, principally for tire manufacture, has driven the expansion of *H. brasiliensis* plantations across Southeast Asia and tropical Africa. In 2016, the global rubber area reached 11.4 million hectares (MHa) (FAO, 2018). Expansion has often entailed forest conversion, resulting in biodiversity loss, increased carbon emissions, and broader environmental degradation. Contemporary estates, whether smallholdings or agro-industrial blocks, frequently adopt monocultures of high-yielding clones at ~400 to 550 stems ha^{-1} under active management. Meanwhile, ~0.81 Mha of low-intensity "jungle rubber" agroforestry remains, mainly in Indonesia, retaining a forest-like structure with mixed planted and wild trees across age classes (Warren-Thomas et al., 2018).

Trade-offs between production, biodiversity, and ecosystem function are well-documented (Warren-Thomas et al., 2018). Monocultures commonly deliver nearly double the latex yields of jungle-rubber agroforests, with simpler agroforestry systems (fewer non-rubber species, clonal, even-aged stands) approaching monoculture yields. Nevertheless, evidence from other land-use systems suggests non-linear relationships between livelihoods and biodiversity, implying scope to make rubber landscapes more wildlife-compatible without sacrificing output through targeted design and management (Pradeep et al., 2022).

Biodiversity responses also depend on stand structure and landscape context. For example, agroforests with higher richness and density of non-rubber trees provide greater food resources (notably fruits) and better habitat for forest specialists (Pradeep et al., 2022). In Sumatra, structurally diverse jungle rubber supports rare frugivorous birds, multiple endangered species, and additional forest specialists. At the same time, increased canopy complexity and a developed understory can shift assemblages, especially among ectotherms. Additionally, empirical studies have reported that enhancing understory height and density can increase species richness for birds and butterflies. Conversely, in Thailand, monocultures retaining vegetated understories host more bird species than understory-poor stands. At the same time, in Brazil, plantations with 10 to 20-year understories supported additional butterfly species and more closely resembled nearby forest fragments than densely weed-free plantations (Cambui et al., 2017). Critically, responses operate across scales: on-farm diversity is shaped by within-stand management and the surrounding landscape matrix, as well as connectivity.

5. Rubber yield management

5.1. Cropping systems and intercropping

Rubber can be cultivated under diverse management contexts by accommodating multiple cropping patterns. On smallholdings established on newly cleared land, intercropping with short-duration food crops (e.g., rice, maize, cassava, banana) during the first two to three years is traditional. It can also provide a bridge income until canopy closure. However, early systems relied on hand slashing to suppress weeds with minimal additional inputs (Watson, 1998). When appropriately designed, matching crop phenology, spacing, and residue management, intercropping does not compromise rubber growth and can improve early cash flow and soil cover (van Noordwijk et al., 2020). In addition, to avoid resource competition, intercrops should be maintained at safe distances from young trees, and since some intercrops require tillage, intercropping is best restricted to level to gently sloping terrain to minimize erosion (Punnoose et al., 2000).

5.2. Establishment of cover crops

Creeping legumes are the preferred establishment cover since they fix nitrogen, grow rapidly, tolerate shade and intermittent drought, and compete weakly with young Hevea for nutrients. Species widely used include *Pueraria phaseoloides*, *Mucuna bracteata*, *Calopogonium mucunoides*, and *Centrosema pubescens* (Dilipkumar et al., 2020). Accordingly, legume covers reduce N fertilizer needs, limit soil erosion, especially on slopes, and lower weeding costs. It also increases soil moisture retention and contributes organic matter, accelerating the transition to tappable girth (Dilipkumar et al., 2020).

5.3. Weed management and intercropping integration

Historically, weed control in young plantings relied on manual strip weeding; herbicides were applied sparingly, typically in the dry season. Current recommendations emphasize Integrated Weed Management (IWM) that combines cover crops, targeted pre-emergent herbicides (soil-applied) and post-emergent herbicides (foliar-applied), and cultural measures (e.g., mulching, residue retention) to maintain a competitive yet non-injurious understory (Adnan & Wang, 2024). During the immature stage, rubber performs best as a row monoculture with legume cover in the interrows. At the same time, carefully selected intercrops can be grown in wider interspaces until canopy closure (van Noordwijk et al., 2020), plant legumes in alternate interrows or designated strips to sustain cover while preventing overlap with intercrops. Thus, maintaining clear buffers around tree bases reduces competition for water and nutrients (Punnoose et al., 2000).

5.4. Irrigation

Although rubber is typically rain-fed, supplemental irrigation can be decisive in non-traditional or drought-prone areas. Trials suggest that summer irrigation accelerates growth and can shorten immaturity by 6 to 12 months (Vrignon-Brenas et al., 2019). In nurseries, irrigation improves seedling and polybag plant quality by stabilizing moisture during critical establishment windows. In regions with cool, dry winters (e.g., parts of north-eastern India), strategic irrigation mitigates low-temperature stress and dry-season deficits. Where water is limiting, supplying up to 50% of crop Evapotranspiration (ET) demand at key phenophases has reduced the immature period from ~10 to ~6 years (Vijayakumar et al., 1998). Hence, designing irrigation for rubber should follow deficit-irrigation principles, align with local water budgets, and consider landscape hydrology (Rahayu et al., 2021).

5.5. Diseases and pests

Disease pressure is influenced by climate, site history, and management practices. Important leaf diseases include *Phytophthora* spp. (secondary leaf fall), *Oidium heveae* (powdery mildew), *Colletotrichum gloeosporioides* (anthracnose), and *Corynespora cassiicola* (Corynespora leaf fall) (Syed Sagaff et al., 2022). Notably, epidemics of Corynespora have prompted significant clone policy changes (e.g., withdrawal of RRIC 103 in Sri Lanka), and concerns have been raised for widely planted clones such as RRII 105 and RRIM 600 in parts of southern India (Liyanage et al., 2020; RRII, 1998). The most severe rubber disease globally is South American Leaf Blight (SALB; Microcyclus ulei), which devastates stands in the Neotropics and represents a quarantine threat to Asia. Nonetheless, breeding and selecting SALB-resistant materials remain strategic priorities (Nair, 2021). Other notable pathogens include pink disease (*Corticium salmonicolor*), affecting stems/branches of three to seven-year-old trees; black stripe on tapping panels (often associated with *Phytophthora*); and root diseases such as white root rot (*Rigidoporus lignosus*) and brown root rot (*Phellinus noxius*) (Liyanage et al., 2020; Nair, 2021).

Although rubber is comparatively resilient to many insect pests, termites, cockchafers, mites, and thrips can cause economic damage in young stands. In response, surveillance and Integrated Pest Management (IPM), including sanitation, biological control, and targeted, threshold-based insecticide use, are recommended (Liyanage et al., 2020). Across all disease and pest risks, clone choice, nursery hygiene, balanced nutrition, canopy aeration, and tapping discipline are first-line defenses that reduce inoculum pressure and stress predisposition (Nair, 2021).

6. Deforestation: nature and causes

Across Southeast Asia, conversion of natural forests to industrial crop plantations, predominantly oil palm (*Elaeis guineensis*) and rubber (*H. brasiliensis*), has dominated recent land-use changes (Margono et al., 2014). Specifically, Indonesia is a core hotspot, with FAO (2018) identifying the country as the world's second-largest producer of NR. This includes official estate statistics reporting ~3.6 MHa under rubber and annual output on around 3 million tonnes (Directorate General of Estate Crops, 2017; FAO, 2018). Furthermore, historical pathways helped enable this trajectory: rubber seedlings were transferred by Malaysian plantation workers and artisans to Sumatra in the late nineteenth century (Joshi et al., 2002). Today, Sumatra and Kalimantan together account for ~95% of national production (Directorate General of Estate Crops, 2017; Warren-Thomas et al., 2018).

Forest conversion has typically proceeded in stages, from mixed forest systems into "jungle rubber" agroforestry and subsequently into clonal monoculture plantations, eroding structural and compositional complexity (Nguyen et al., 2020; Panklang et al., 2022; Wang et al., 2022; Warren-Thomas et al., 2018). As such, the expansion of industrial crops (oil palm and rubber) has been a leading proximate driver of regional deforestation. In Sumatra alone, approximately half of the forest cover was lost between 1985 and 2007 (Margono et al., 2014). These shifts from natural or semi-natural ecosystems to simplified agricultural landscapes have well-documented environmental consequences. Among them are increased carbon emissions and biodiversity loss, accelerated soil erosion and nutrient depletion, and deterioration of water quality and watershed function (Margono et al., 2014; Panklang et al., 2022; Sugebo et al., 2022). Collectively, these patterns underscore the need for policies that steer any unavoidable expansion toward already-cleared lands while safeguarding remaining primary and high-integrity secondary forests.

7. Future of rubber

To extend beyond generalities, we distill actionable priorities grounded in evidence on carbon and water fluxes, land use change, nutrition, disease, and supply chain governance, drawing on studies such as Warren-Thomas et al. (2018), Vrignon-Brenas et al. (2019), Ali et al. (2022), Ali et al. (2022),Wang et al. (2022), and Wang et al. (2023).

First, climate-robust genetics and physiology are essential. The aim is to deliver clones that tolerate heat and drought and that reduce the risk of tapping panel dryness without penalizing yield. However, this requires multi-environment testing across rainfall and temperature gradients, common nurseries with harmonized phenotyping of latex flow, total solids content, water-use efficiency, and canopy temperature, and the coupling of marker-assisted and omics selection with rigorous stress screening (Gautam et al., 2024). Essentially, a practical ambition by 2030 is to achieve a yield gain of at least 10% with equal or lower nitrogen inputs and a reduction of tapping panel dryness incidence to one-fifth in high-risk sites. In line with this, promising mechanisms include latex metabonomics and particle-interface biology that link nutrition to material quality, as well as stress priming to delay the onset of the disorder (Guerra et al., 2021).

Second, accounting for carbon and water must be rubber-specific. The objective is to narrow uncertainty in Net Ecosystem Productivity (NEP) and ET under climatic extremes. The research portfolio should expand Eddy-Covariance (EC) arrays into undersampled regions, operate paired forest and rubber sites, and implement throughfall-exclusion experiments. Additionally, a dedicated rubber Plant Functional Type (PFT) in CLM5 should be calibrated and validated against fluxes and leaf area phenology to reduce model bias for NEP and ET to less than 10%, with open flux datasets released for intercomparison (Ali et al., 2022; Wang et al., 2022).

Third, land-use governance must internalize opportunity costs. The goal is to curb forest-to-rubber conversion while protecting the incomes of smallholder farmers. The literature reveals that rubber-related deforestation is both substantial and undercounted and that carbon prices required to deter conversion often exceed market rates (Wang et al., 2023; Warren-Thomas et al., 2018). Therefore, policy should integrate rubber into zero-deforestation rules, deploy results-based payments tied to realistic opportunity costs, and steer any new planting to already-cleared land identified with Sentinel-2 phenology mapping. In particular, a credible milestone is at least a 30% reduction in deforestation per tonne of NR by 2030 in mapped hotspots.

Fourth, agronomy must become water-secure as reference evapotranspiration rises. The goal is to stabilize the yield with reduced water usage. Hence, trials should factorially combine INM with legume cover and deficit irrigation at half of the crop water demand on drought-prone sites, while timing the use of ethephon and tapping into favorable hydro-climate windows. In addition, success would be reflected in a ten to 15% gain in water-use efficiency and a 5 to 10% improvement in yield stability during dry spells without higher nitrogen loads (Gohet et al., 2013; Huang et al., 2022; Vrignon-Brenas et al., 2019).

Fifth, the functions of soil across rotations require clarity. The aim is to define the conditions under which soils degrade or recover through successive plantings. Correspondingly, longitudinal trials need to control for prior land use and stand age and should quantify soil organic carbon fractions, Pi pools, base saturation, and erosion. At the same time, management should maintain or increase soil organic carbon by at least 0.2 tonnes of carbon per hectare per year using residue retention, liming on acid soils, and cover crops (Panklang et al., 2022; Tanaka et al., 2009).

Sixth, disease risk must be managed at the landscape scale. The priority is to reduce risks from Corynespora and SALB while minimizing the use of blanket fungicides. This calls for cloning by climate risk models, audits of nursery hygiene, diversified clone portfolios, and surveillance networks for early warning. Specifically, a practical benchmark is a 30% reduction in days lost to disease-related tapping interruptions within five years in districts with high incidence (Liyanage et al., 2020; Nair, 2021).

Seventh, circular materials and longer product lifetimes can satisfy demand without extensive resource use. The sector should scale up recycling, extend tire lifetimes, and add value to rubberwood via improved processing, while evaluating latex-timber ideotypes where appropriate. For instance, a realistic goal is a 20% increase in recycled NR content or lifetime-adjusted material efficiency in priority product segments by 2030 (Hanieh, 2021; Mahyudin et al., 2023).

Eighth, open data and traceable supply are prerequisites for verifiable compliance and cumulative science. Accordingly, establishing a Rubber Observatory with shared protocols for flux sites, plot metadata, and wall-to-wall maps would support research, certification, and policy. Consistent with this, certification systems should require traceability to plantation polygons.

In the near term, over the next one to three years, the community can deploy monitoring assets, close mapping gaps, and standardize trial protocols. Within a three- to seven-year timeframe, the first climate-robust clones can be released, and water-secure agronomy can be operational at scale. Conversely, in the long term, beyond seven years, rubber-aware Earth system modeling should be mainstreamed to inform investment and policy decisions. Overall, this agenda knits testable hypotheses and measurable outcomes to concrete levers in genetics, agronomy, hydrology, and governance, providing a tractable pathway to align NR supply with climate and biodiversity safeguards.

8. CONCLUSION

This review synthesizes evidence across agronomy, ecology, and value-chain studies, indicating that while rubber plantations contribute to livelihoods and industrial supply security, they generate trade-offs when expanded at the expense of forests. Compared to natural forest, forest-to-rubber conversion reduces ecosystem carbon storage, simplifies habitats, lowers species richness and functional diversity, increases peak flows and sediment export, and depresses baseflow. In particular, rubber plantations function as variable, relatively weak carbon sinks, with annual NEP sensitive to radiation, temperature, and moisture, as well as reduced during extremes. By contrast, cropland-to-rubber transitions can raise above-ground biomass and deliver partial carbon gains. Nevertheless, outcomes vary depending on prior land use, monsoon intensity, rainfall regime, elevation, soil type, stand age, and management intensity. Diversified agroforestry, vegetated understories, residue retention, and balanced N-P-K-Mg improve water regulation and nutrient-use efficiency; deep-water access and local hydrology modulate ET and drought response. Additionally, ethylene stimulation enhances labor productivity. However, it does not offset environmental externalities.

We recommend conserving remaining primary and high-quality secondary forests, and directing new plantings to already-cleared land through spatial planning and traceable supply chains. This includes mainstreaming diversified rubber agroforestry alongside water-secure INM (phenology-aligned splits, emphasis on K and Mg on drought-prone sites, legume covers, pH control, and context-specific deficit irrigation). Therefore, rubber should be explicitly incorporated into zero-deforestation policies and results-based carbon payments. Furthermore, continued support for open flux datasets and a rubber-specific PFT is essential for effective risk assessment and monitoring. Collectively, these measures can sustain production while ensuring that the natural-rubber supply aligns with verifiable climate and biodiversity safeguards.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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