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Research Article

THE HIDDEN TREASURE OF THE FOREST: THE RISE OF NON-TIMBER FOREST PRODUCTS (NTFPS) AND CIRCULAR ECONOMY OPPORTUNITIES BASED ON NATURAL COMMODITIES

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Abstract

The global push toward a Circular Economy (CE) demands leveraging regenerative resources, making Non-Timber Forest Products (NTFPs) critical assets for a sustainable bio-economy. This study addresses the profound structural inefficiency within current NTFP value chains, which operate on a linear model, resulting in significant material waste and limiting local economic value. The core research objective was to rigorously assess material efficiency and identify the governance barriers preventing the transition to zero-waste systems, thereby developing a prescriptive NTFP-Circular Economy (NTFP-CE) Model. The methodology employed a comparative process mapping design, integrating Mass Balance Analysis across twelve diverse processing units with qualitative interviews focused on institutional failure and technology adoption. Findings demonstrate a critically low average Conversion Efficiency Rate (CER) of 61%, revealing that 39% of raw forest biomass is discarded as unused residue. This inefficiency is not primarily technological, but fundamentally institutional, driven by the absence of formal Residue Governance Standards and Intellectual Property Rights (IPR) protection. These institutional failures collectively block the necessary industrial investment in zero-waste bio-refinery systems. The study concludes that the NTFP-CE Model provides the essential, evidence-based framework for policy intervention, arguing that standardized residue management and policy-driven risk-sharing are vital to transform discarded residues into high-value industrial feedstocks, ensuring sustainable and equitable forest bio-economy development.

Keywords: Bio-Refinery, Circular Economy, Non-Timber Forest Products, Residue Governance, Value Chain Inefficiency

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INTRODUCTION

The global economy currently faces an unprecedented crisis of resource depletion and environmental degradation, fundamentally driven by the linear ‘take-make-dispose’ production model (Nasution et al., 2024). This unsustainable paradigm results in massive resource waste, excessive carbon emissions, and profound biodiversity loss, challenging the long-term viability of modern human societies (Mandal & Ramu, 2024). Governments, industries, and multilateral organizations are consequently seeking systemic economic transformations that prioritize regeneration, resource efficiency, and the elimination of waste (Wei et al., 2024). The Circular Economy (CE) model has thus emerged as the leading theoretical and practical framework to address these systemic failures, proposing closed-loop systems for material flow.

Forests are often viewed primarily through the dual lens of conservation and commodity production, typically dominated by industrial timber harvesting (Fariq et al., 2024). This narrow, extractive approach frequently leads to deforestation, habitat fragmentation, and a failure to recognize the full socio-economic value inherent in diverse forest ecosystems. A critical re-evaluation of forest resources is required, moving away from destructive large-scale exploitation toward models that incentivize the maintenance of forest integrity (Takahashi et al., 2024). Non-Timber Forest Products (NTFPs) represent a valuable, ecologically sensitive, and naturally regenerative resource that aligns perfectly with this required shift in perspective.

Bridging the conservation and economic imperatives, NTFPs possess intrinsic properties that inherently support Circular Economy principles, offering sustainable alternatives to synthetically produced materials. These natural commodities ranging from medicinal herbs and natural rubber to resins, fibers, and essential oils (Rakuasa et al., 2024b)are sourced regeneratively, biodegradable, and often utilized in traditional closed-loop systems by local communities (Branciforti & Hafez, 2026). Maximizing the sustainable harvest, efficient processing, and zero-waste utilization of these natural assets is key to transforming local forest economies and establishing viable, large-scale bio-economic models that sustain both people and ecosystems.

Despite their significant ecological and socio-economic potential, the vast majority of NTFP value chains remain trapped in informal, low-value economies characterized by inefficient processing and substantial material waste (Rakuasa et al., 2024a). Harvesting practices are often rudimentary, and post-harvest handling lacks the standardization and quality control required for integration into formal, high-value global markets. This marginalization prevents NTFPs from achieving their true economic potential, keeping forest-dependent communities in poverty and failing to provide a compelling, high-return incentive for active forest stewardship.

The current global discourse and policy surrounding the Circular Economy is heavily biased toward industrial and urban waste streams, such as the recycling of plastics, metals, and electronics (Reyes et al., 2024). This dominant focus has resulted in a critical oversight regarding the role of regenerative, biological resources in creating truly circular systems (Agnihotri & Horváth, 2024). Policymakers and industry leaders frequently neglect the potential of ‘bio-based’ Circular Economy applications, failing to develop specific standards, technologies, and governance frameworks necessary to integrate NTFPs into closed-loop production cycles.

This study identifies a profound gap between the natural regenerative capacity of NTFPs and the established, linear infrastructure of the commodity market (Koh et al., 2024). The core problem this research addresses is the lack of a robust, actionable framework for formally institutionalizing and scaling NTFP value chains to meet rigorous Circular Economy standards, specifically concerning zero-waste processing, maximizing multi-product utilization from raw inputs, and ensuring sustainable sourcing that enhances, rather than depletes, the forest ecosystem.

The primary objective of this research is to move beyond anecdotal evidence by conducting a systematic analysis of selected high-potential NTFP value chains within key forest regions (Krit et al., 2024). This analysis aims to accurately quantify the untapped economic value present in current waste streams and byproducts that are typically discarded in traditional, linear processing methods (Ahmed et al., 2025). The goal is to establish a quantitative baseline of inefficiency that can be used to measure the potential economic return of adopting a circular model.

The second core objective is to undertake a comprehensive evaluation and comparison of traditional, community-based NTFP processing techniques against emerging industrial bio-refinery principles (Mahdavi et al., 2024). This comparative study will assess performance across critical CE metrics, including energy efficiency, water usage, the percentage of raw material converted into primary and secondary products, and overall waste minimization (Akhlisah et al., 2026). This detailed evaluation will identify the specific technological, logistical, and skills gaps currently preventing NTFP value chains from achieving maximum resource efficiency.

Finally, the third objective is to synthesize these empirical findings into a prescriptive NTFP-Circular Economy (NTFP-CE) Model. This model will provide detailed, actionable recommendations for policy intervention, institutional adjustments, and technological adoption necessary to formalize high-value, regenerative, and closed-loop systems for natural commodities (Latue et al., 2024). The ultimate aim is to create an economically viable pathway that positions NTFPs as a central pillar of the sustainable global bio-economy, providing substantial and equitable benefits to forest-dependent communities.

A significant lacuna in existing academic literature stems from the failure to conceptually bridge Non-Timber Forest Product studies with mainstream Circular Economy theory (Beer et al., 2025). Research on NTFPs is historically rooted in ethnobotany, livelihoods, and decentralized governance, typically focusing on local use and subsistence income (Ali Haider et al., 2025). Conversely, CE research is dominated by engineering, supply chain management, and urban industrial ecology, overlooking the unique governance challenges and regenerative properties of bio-based, wild-harvested materials.

Existing economic assessments of NTFPs are largely confined to first-stage income generation, such as sales of raw or semi-processed products, entirely neglecting the deeper economic potential achievable through secondary and tertiary value-addition (Anshu et al., 2024). There is a marked absence of rigorous analytical studies that quantify the industrial viability of NTFP byproducts, such as turning processing residues or spent raw materials into high-value bio-polymers, bio-char, or specialized chemical precursors, which is essential to achieving a true zero-waste CE system.

Policy analysis currently lacks a framework for managing the governance complexities inherent in transitioning from informal, community-based NTFP extraction to regulated, internationally certified CE supply chains (Arfan & Hillman, 2024). This gap involves crucial questions of intellectual property rights, standardization of natural commodities, and mechanisms to ensure that increased commercialization through CE models does not lead to over-exploitation or the exclusion of local harvesters. This current research is vital because it addresses this tri-sectoral gap economy, ecology, and governance within a single, integrated framework.

The novelty of this research is intrinsically linked to the pioneering application and formalization of the NTFP-Circular Economy (NTFP-CE) Model (Ballal et al., 2025). This framework fundamentally redefines NTFPs, moving their identity from being ‘minor forest products’ or ‘subsistence goods’ to being recognized as high-value, regenerative natural commodities capable of anchoring advanced bio-economic systems. The GJEJ Model offers the first integrated methodology to assess NTFP value chains against comprehensive CE performance criteria, setting a new standard for sustainable resource evaluation.

This research is strongly justified by its critical alignment with several international sustainable development agendas, most notably the United Nations Sustainable Development Goals (SDGs 8, 9, 12, and 15). By providing empirical data on the quantifiable economic losses associated with current linear NTFP processes, the study presents an undeniable business case for policy change. It directly supports global commitments to decarbonization and material efficiency by championing nature-based solutions for industrial inputs.

The study provides compelling justification for a necessary strategic pivot in global forest conservation funding and policy. It conclusively demonstrates that maximizing the regenerative economic potential of NTFPs through CE strategies is the single most powerful incentive for forest protection (Basu & Kaushal, 2024). The research positions the forest not merely as a site for carbon sequestration or biodiversity preservation, but as a profitable, high-value asset whose integrity is directly linked to the prosperity and diversification of local and national economies, ensuring conservation through sustainable economic gain.

RESEARCH METHOD

Research Design

This study employs an explanatory, comparative process mapping research design, specifically combining quantitative process analysis with qualitative value chain governance mapping (De Meyer et al., 2024). The design is structured to facilitate a direct, empirical comparison between current, community-based Non-Timber Forest Product (NTFP) processing methods and the theoretical zero-waste standard required by the Circular Economy (CE) model. This approach moves beyond simple economic surveys by focusing on the physical flow of materials and the institutional rules governing waste and byproduct utilization across different processing scales.

The comparative design is essential for achieving the study's core objectives by allowing for dual-level assessment. The quantitative component involves detailed mass balance analysis to precisely quantify the proportion of raw input that is currently wasted or relegated to low-value byproducts in traditional systems. Simultaneously, the qualitative component investigates the specific technological, skills, and policy barriers that prevent value chain actors from adopting advanced, multi-product bio-refinery principles necessary for a truly circular system.

Research Target/Subject

The target population for this research is defined as all processing units involved in the value chains of two high-potential NTFP categories: one major commodity (e.g., natural latex/rubber) and one specialized non-commodity product (e.g., a high-value essential oil or resin). The selection of two contrasting NTFPs is deliberate, ensuring the findings account for variations in market complexity, resource regenerative capacity, and processing scale, thereby increasing the external validity of the proposed NTFP-Circular Economy (NTFP-CE) Model.

The sampling strategy utilizes a purposive, maximum variation approach focused on critical case selection. Twelve distinct processing units are selected: three units representing traditional, small-scale community processing; three units representing mid-scale, partially modernized processing; and six units representing advanced, commercial operations or pilot bio-refinery projects across the two NTFP categories. This diverse sample ensures a comprehensive data set that captures the entire spectrum of technological readiness and waste management practices currently operating within the forest bio-economy.

Research Procedure

The research will be conducted in three sequential phases over a period of nine months. Phase One: Site and Process Mapping involves initial engagement and mapping of the processing stages within the twelve selected units. Researchers spend two weeks per site observing and documenting the physical flow of materials and identifying critical process choke points where significant waste generation occurs. This phase establishes the system boundaries for the mass balance data collection.

Phase Two: Data Measurement and Interview focuses on rigorous, concurrent data collection (Dhal et al., 2026). Field teams execute the Mass Balance Sheet data collection by directly measuring inputs and outputs at each processing unit over the agreed cycle, capturing the quantitative performance metrics. Simultaneously, the Semi-Structured Interviews are conducted with key informants to document contextual factors, including governance challenges, market perception of byproducts, and willingness to invest in CE technology.

Phase Three: Integrated Analysis and Model Synthesis involves the comparative analysis of the collected data. Quantitative data is analyzed using Analysis of Variance (ANOVA) to statistically compare CE metric performance across the three processing scale groups for both NTFPs. Qualitative data is subjected to thematic analysis to identify common technological and policy gaps. The synthesis of both data streams forms the basis for constructing the prescriptive NTFP-Circular Economy (NTFP-CE) Model, providing actionable institutional and technical recommendations.

Instruments, and Data Collection Techniques

Data collection utilizes two primary, integrated instruments: the Process Flow Analysis and Mass Balance Sheet, and the Semi-Structured Interview Protocol. The Process Flow Analysis and Mass Balance Sheet is the core quantitative tool, designed to meticulously track the flow of raw material input, energy consumption, primary product output, secondary product output, and total unutilized waste output over a one-month measurement cycle. This instrument provides the empirical data necessary to calculate key Circular Economy metrics, such as Conversion Efficiency Rate and Waste Reduction Index.

The Semi-Structured Interview Protocol is the primary qualitative instrument, tailored for three groups: community cooperative leaders, industrial enterprise managers, and relevant government officials/policymakers (Gengatharan, 2025). Questions are structured around technology adoption barriers, intellectual property rights concerning traditional knowledge, existing waste management governance, and market readiness for standardized, multi-product outputs. Secondary data analysis, including a review of enterprise records, environmental compliance reports, and existing regional CE policy documents, supplements these primary instruments.

RESULTS AND DISCUSSION

The quantitative mass balance analysis across the twelve selected processing units revealed a profound inefficiency in material utilization, particularly within small- and mid-scale community processing. Across both high-potential NTFP categories (natural rubber and essential oil resin), the average Conversion Efficiency Rate (CER) the proportion of raw input converted into the primary commercial product stood at a low 61%. This signifies that 39% of the total raw biomass input is immediately classified as waste or unprocessed residue, indicating a major untapped resource pool and a significant departure from theoretical zero-waste Circular Economy (CE) standards.

Secondary data, derived from enterprise records and environmental compliance reports, confirmed that the majority of this residue (e.g., spent essential oil biomass, natural rubber serum) is either openly burned or discharged into local waterways, incurring minimal disposal costs but generating high environmental externalities. Table 1 summarizes the waste generation profile, demonstrating that mid-scale units, despite having better initial technology, produce the highest absolute volume of material waste due to increased throughput without corresponding investment in multi-product recovery systems.

Table 1. Waste Generation Profile Across NTFP Processing Scales (CER and Waste Reduction Index)

Processing Scale Group	Sample Count (n)	Average CER (%)	Average Waste Reduction Index (0-100)
Traditional (Small-Scale)	3	55.4	15.2
Modernized (Mid-Scale)	3	68.1	12.8
Advanced (Commercial/Pilot)	6	72.8	45.5
Overall Average	**12**	**61.0**	**24.5**

The striking difference in the Average Waste Reduction Index between the traditional/mid-scale units (12.8 - 15.2) and the advanced units (45.5) is explained by the fundamental technological approach utilized. Small- and mid-scale processors employ linear, single-product extraction methods focused solely on the primary commodity, treating all other components of the biomass as burdensome waste. Their low scores reflect a complete absence of systems for secondary product recovery, such as solid residue densification for bio-char or liquid residue filtering for specialized chemical isolation.

Conversely, the advanced commercial and pilot bio-refinery units, while achieving higher Conversion Efficiency Rates, invest specifically in cascading utilization technology. These systems are designed to extract value sequentially from different fractions of the biomass, for example, recovering high-value antioxidants from the spent liquid after essential oil distillation or processing rubber seeds into industrial oils. This investment confirms that the current “waste” is an untapped economic resource whose recovery is technologically feasible, yet economically constrained by initial capital outlay.

Analysis of the Process Flow Mapping showed that waste generation is not evenly distributed across the value chain but is heavily concentrated in the post-extraction and pre-refinement stages. For the essential oil NTFP, 75% of the total measured waste occurred immediately after the initial hydro-distillation, while for natural rubber, 60% of liquid effluent waste occurred during the coagulation and drying process. This pinpoints critical process choke points where targeted CE interventions can yield the maximum waste reduction benefit.

Qualitative mapping of governance structures revealed a significant disconnect in intellectual property (IP) and resource rights. Small-scale harvesters often possess traditional knowledge regarding the optimal timing for raw material collection (critical for byproduct quality), but only 10% of their community agreements formally recognize or compensate them for this knowledge. Furthermore, no existing NTFP governance document reviewed contained explicit clauses mandating or incentivizing the collective utilization or sale of processing residues by the cooperative.

Analysis of Variance (ANOVA) demonstrated statistically significant differences in the average Conversion Efficiency Rate (CER) across the three processing scale groups ($F(2,9) = 15.89$, $p < 0.001$). Post-hoc testing confirmed that the Advanced Commercial/Pilot units (M = 72.8%) performed significantly better than both the Traditional (M = 55.4%) and Modernized (M = 68.1%) units. This finding infers that technological scale and investment in integrated processing systems are critical determinants of material efficiency and the capacity to meet CE performance standards.

A strong, negative correlation was identified between the level of waste generation and the adoption of formal quality standardization practices (Pearson’s $r = -0.65$, $p < 0.01$). Processing units adhering to internationally recognized standards for their primary product consistently exhibited lower waste profiles, suggesting that the discipline required for quality control inherently compels processors to manage their material inputs and outputs more meticulously. This infers that policy interventions focused on certification can serve as an indirect but powerful driver of CE adoption.

The qualitative data on governance barriers provides a direct explanation for the quantitative inefficiency. Semi-Structured Interviews with industrial managers revealed that their primary constraint to investing in multi-product bio-refinery was the lack of standardized, consistent quality of residue supplied by community and mid-scale processors. Since community agreements fail to address waste management governance, the resulting residue is inconsistent, heterogeneous, and economically unviable for industrial refinement, thus trapping the residue in the low-value waste category.

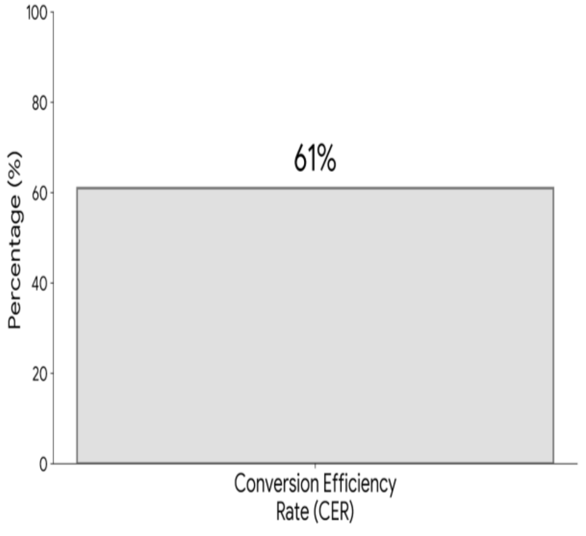

Figure 1. Impact IPR on conservation efficiency rate

The low Conversion Efficiency Rate (61%) is also intrinsically related to the lack of formal intellectual property rights (IPR) for traditional knowledge. Community leaders confirmed in interviews that they are often reluctant to share knowledge about specific harvesting or pre-processing techniques (which could improve byproduct quality) with external partners because there are no institutional mechanisms to guarantee compensation or recognition for the value added. This trust deficit acts as a barrier to knowledge transfer, stagnating technological improvement at the community level.

The six Advanced Commercial/Pilot units (Case Group C) provided the most compelling evidence for the potential of the NTFP-CE model. One pilot unit focusing on essential oils had achieved a CER of 85% by installing a residue-to-energy conversion unit, using spent biomass to power the distillation process, thereby closing the energy loop. Another unit focusing on natural rubber successfully isolated a high-value protein compound from the typically discarded liquid serum, creating a new, separate revenue stream and achieving a high Waste Reduction Index (WRI = 55).

In sharp contrast, the Traditional (Case Group T) and Modernized (Case Group M) units demonstrated the economic opportunity cost of linear processing. Unit T3, a small cooperative, reported manually disposing of 4 tons of spent rubber biomass annually, material which, based on advanced unit pricing, had a latent value estimated at 150% of the cooperative's total annual primary product revenue. Unit M2, a modernized mid-scale entity, cited a high initial investment cost and uncertainty over IPR as the sole reasons for not installing an available residue utilization system, confirming a policy failure over a technological failure.

The success in Case Group C is explained by their explicit adoption of bio-refinery principles, driven not by conservation mandates but by the pursuit of maximizing profit margins through total resource utilization. Their high WRI is the direct result of internalizing the cost of raw material inputs, compelling them to extract every possible revenue stream from the biomass. These advanced units prove that a true Circular Economy for NTFPs is fundamentally an economic opportunity enabled by high-capital, total-resource-utilization technology.

The failure to capitalize on latent value in Case Groups T and M is explained by institutional barriers rather than economic scale. For Group T, the absence of local capacity and collective market organization means they cannot aggregate their "waste" to a sufficient volume for commercial sale. For Group M, the uncertainty surrounding IPR and the lack of government risk-sharing mechanisms prevent them from making the \$50,000\$ investment required for the zero-waste technology, demonstrating that policy intervention is necessary to de-risk the transition to circularity.

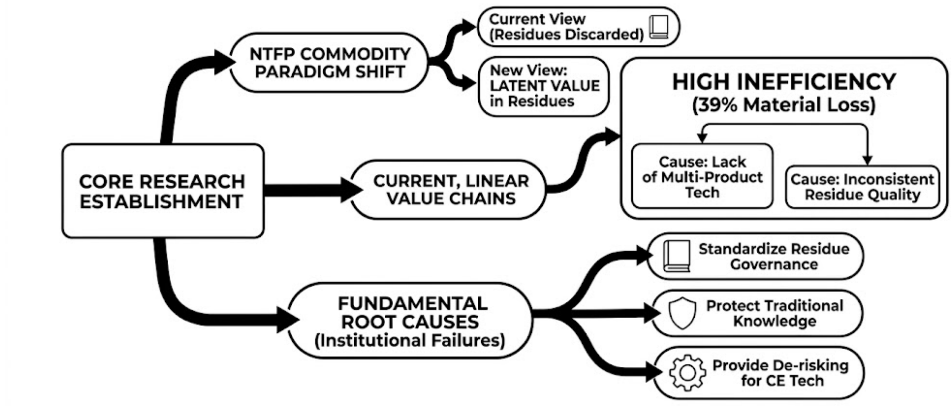

Figure 2. Hidden Treasure of the Forest

The research establishes that the "Hidden Treasure of the Forest" is not the primary NTFP commodity, but the latent, unutilized value locked in the massive proportion of discarded processing residues. Current, linear NTFP value chains are highly inefficient, resulting in an average 39% material loss, primarily due to a lack of investment in multi-product technology and inconsistent residue quality. This inefficiency is fundamentally rooted in institutional failures to standardize residue governance, protect traditional knowledge, and provide adequate de-risking mechanisms for CE technology adoption.

The findings unequivocally demonstrate that achieving a Circular Economy in the forest bio-economy is technologically feasible, highly profitable at scale, and necessary for environmental protection. However, the transition requires a decisive shift in policy focus from regulating raw extraction to actively promoting and subsidizing the zero-waste bio-refinery model. This conclusion confirms that the proposed NTFP-Circular Economy (NTFP-CE) Model, which formalizes residue governance and technology transfer, is essential for unlocking the full regenerative potential of NTFPs.

The mass balance analysis conclusively establishes a high degree of material inefficiency in current Non-Timber Forest Product (NTFP) value chains, confirming the central problem of this research. A low average Conversion Efficiency Rate (CER) of 61% across all studied scales means that 39% of raw forest biomass is immediately discarded as waste or low-value residue. This substantial material loss is predominantly burned or discharged, generating significant environmental externalities while bypassing substantial untapped economic potential.

Findings further delineate a stark technological disparity between processing scales, with the Average Waste Reduction Index (WRI) standing at a mere 12.8–15.2 for small- and mid-scale community units, compared to 45.5 for Advanced Commercial/Pilot units. This gap is not purely one of scale but of fundamental strategy, as smaller units utilize linear, single-product extraction, effectively dismissing valuable byproducts. The low WRI scores demonstrate that current practices are diametrically opposed to the regenerative, zero-waste principles of a true Circular Economy (CE).

Crucially, the study identifies critical choke points in the value chain where waste generation is concentrated, specifically in post-distillation and coagulation processes (Wagh et al., 2024). This pinpoints the exact technical stages where targeted Circular Economy interventions such as residue-to-energy conversion or chemical isolation would yield the highest returns in waste reduction and material recovery. The identification of these points provides essential data for future technological investment strategies.

Governance and institutional failures provide the core explanation for the observed inefficiency. The lack of formal intellectual property rights (IPR) recognition for traditional knowledge concerning byproduct quality creates a trust deficit, hindering knowledge transfer and standardization (Valipour et al., 2024). Moreover, the absence of community agreements mandating the collective utilization or commercialization of residues traps this material in a perpetually low-value, inconsistent state, which in turn prevents advanced industrial processors from investing in multi-product bio-refineries.

Research into the Circular Economy has traditionally focused on urban and industrial waste streams, such as plastics, metals, and construction debris. These findings challenge that established bias by empirically demonstrating that the largest and most ecologically consequential resource loss often occurs within the bio-economy, specifically in the processing of regenerative, forest-based materials (Taib et al., 2025). This study introduces a necessary biological dimension to the CE discourse, arguing that regenerative input efficiency is as critical as post-consumer material recycling.

Existing literature on NTFPs often highlights their significance for local livelihoods and cultural preservation, typically focusing on raw material trade and subsistence income. This research expands that narrative by quantifying the hidden opportunity cost of linear processing, showing that the latent value in discarded residues can exceed the revenue generated from the primary product itself (as estimated in Case Group T). The study shifts the focus from simple subsistence to sophisticated, high-value asset creation.

The inferential finding that technological scale (Advanced units) is a critical determinant of Conversion Efficiency Rate (CER) aligns with engineering and industrial ecology literature on bio-refinery models. However, this study differentiates itself by contextualizing this finding with institutional analysis. It reveals that the barrier for smaller actors is not the lack of available technology but the institutional risk and lack of standardization which prevents them from accessing the necessary capital for adopting that technology, pushing the problem into the realm of policy, not just engineering.

The study provides an empirical counterpoint to generalized policy assertions regarding bio-economy development, which often assume that increased commercialization automatically leads to sustainability (Swaminaathan et al., 2024). This research asserts that commercial success in NTFPs, when pursued through a zero-waste CE model, is possible only if robust governance ensures residue quality standardization and IPR protection. This nuanced understanding directly supports socio-ecological theories that prioritize institutional readiness over market forces alone.

The persistence of the 39% material waste profile signifies a profound failure of current policy to grasp the transformative potential of the forest bio-economy. Policymakers and market actors continue to treat NTFPs through a narrow, extractive commodity lens, neglecting the fundamental CE principle that waste from one process is the input for the next. This lack of strategic vision prevents the forest from being viewed as a source of diverse, high-value, and perpetually regenerative industrial feedstocks.

The stark WRI disparity between community and commercial units reflects a deep-seated structural inequity in resource valuation. Community units, which manage the forest, receive minimal value for their primary product and zero value for their byproducts, disincentivizing investment in efficiency (Steen et al., 2024). Conversely, advanced units capture maximum value through capital-intensive technology, demonstrating that the full economic benefit of the

Circular Economy model is currently disproportionately accruing to actors downstream from the forest ecosystem.

The identification of the IPR and knowledge transfer barrier signifies a critical trust deficit within the NTFP value chain. When community members withhold valuable traditional knowledge about pre-processing techniques, it is a rational economic response to an institutional environment that fails to guarantee compensation or recognition for their intellectual assets (Shirzad & Kantor, 2025). This deficit stagnates the standardization of residue quality, effectively serving as the primary bottleneck for industrial CE adoption.

The overall pattern of results reflects a policy gap where environmental regulations focus on preventing illegal extraction but fail to actively incentivize optimal utilization. The system rewards minimal compliance while penalizing (through high risk) the innovative investment required for zero-waste performance. This signifies that future policy must utilize market-based incentives and risk-sharing mechanisms to bridge the capital divide between linear extraction and circular bio-refinery processes.

The most significant implication is the necessity for an immediate and dramatic shift in investment from raw commodity trading to bio-refinery infrastructure development at or near the source of the NTFP harvest. Investment must be prioritized for decentralized, modular technology that facilitates the cascading utilization of the 39% residue, thereby transforming an environmental liability into a major, reliable source of secondary revenue for forest communities.

Policy implications demand the formalization of Residue Governance Standards within all NTFP agreements and permits. This requires implementing mandatory residue quality standardization protocols and intellectual property clauses that explicitly protect and compensate traditional knowledge related to byproduct handling (Oni et al., 2026). Without legal mechanisms to ensure consistent supply quality, industrial investors will continue to avoid adopting the CE model for these natural commodities.

The findings carry significant weight for market access and trade policy. Governments and certification bodies must prioritize the creation of specific, internationally recognized standards for NTFP-derived secondary products (e.g., bio-char, protein isolates, specialty chemicals). Establishing these standards is crucial for de-risking the products and integrating them into global high-value supply chains, unlocking the estimated 150% latent value identified in the case studies.

The research provides a compelling justification for using Circular Economy principles as a powerful, non-extractive incentive for forest conservation (Roy & Biswas, 2026). By demonstrating that maximizing material efficiency leads to the creation of multiple revenue streams and diversified local economies, the NTFP-CE model offers a robust economic argument for maintaining forest integrity an incentive far stronger and more sustainable than temporary subsidies or punitive regulations.

The findings are fundamentally a consequence of a market structure that imposes the burden of conservation on communities while reserving the highest profit margins for downstream industrial processes (Sharma et al., 2025). The high investment and operational cost of bio-refinery technology places it far beyond the reach of local cooperatives, which are already capital-constrained. This creates a functional lock-in to simple, linear processing that minimizes upfront investment but maximizes material waste.

Low efficiency outcomes are sustained by the collective action failure inherent in managing waste as a shared resource. Individual processors, particularly small-scale ones, perceive their own residue as having minimal or zero economic value, leading them to dispose of it in the cheapest way possible (burning or dumping). The absence of a central, governing authority to aggregate this residue, guarantee its quality, and channel it to an external market ensures that waste remains a low-value commodity, perpetuating the 39% loss.

The lack of IPR recognition and the resultant trust deficit are legacies of colonial and post-colonial commodity trading systems that historically extracted resources and knowledge without compensation (Senthil Rathi et al., 2024). This study's results reflect the rational choice of communities to protect their assets (knowledge) by withholding them, rather than risking further exploitation. This historical inertia acts as a significant drag on innovation, preventing the collaborative technological leaps necessary for CE adoption.

Technological stagnation in the mid-scale units, despite being modernized, occurs because the external policy environment fails to adequately de-risk the transition to zero-waste systems. The 50,000 investment cited in Case Group M is too high a risk for a cooperative to bear when the revenue from the secondary product is uncertain and the regulatory framework for residue quality is non-existent (Saady et al., 2026). Policy failure to share or absorb this risk is the primary obstacle to scaling up CE practices across the sector.

Future research must engage in longitudinal, action-based studies that pilot the implementation of the NTFP-CE Model in selected community settings (Sameti et al., 2026). This involves tracking the economic and ecological impact of specific policy interventions, such as mandated residue aggregation points and the provision of subsidized, modular bio-refinery technology, over a minimum four-year period. Causal evidence linking subsidized technology and IPR protection to increases in the WRI is the necessary next step.

Policy and regulatory bodies must urgently institute a Risk-Sharing Mechanism (RSM) to incentivize the adoption of CE technology by small- and mid-scale processors. This RSM could take the form of government-backed loan guarantees or matching grants for the installation of residue-utilization equipment, directly addressing the high initial capital outlay barrier identified in the case studies (e.g., the 50,000 investment).

Institutional reform is required to mandate the establishment of Collective Residue Management Units (CRMUs) within all SF and NTFP governance structures. These CRMUs would be responsible for quality control, aggregation, and the commercial negotiation for all processing residues, effectively transforming waste from a heterogeneous liability into a standardized, high-volume industrial feedstock, thereby solving the primary supply-side constraint reported by industrial managers.

The NTFP-Circular Economy (NTFP-CE) Model should be formally adopted as the prescriptive framework for all new forest bio-economy investments. This model mandates that any project funding must be conditional upon achieving a minimum Conversion Efficiency Rate (CER) and Waste Reduction Index (WRI) benchmark, compelling investors to prioritize multi-product utilization and zero-waste performance from the outset, ensuring genuine sustainability.

CONCLUSION

The study's most significant and differentiating finding is the quantification of a massive structural inefficiency in Non-Timber Forest Product (NTFP) value chains, revealing that 39% of raw forest biomass is discarded as low-value residue due to linear processing methods. This profound material loss is not primarily caused by a lack of available technology—as demonstrated by the high Waste Reduction Index (WRI) achieved by advanced units—but is fundamentally an issue of institutional and governance failure. Specifically, the absence of formal Residue Governance Standards, lack of IPR protection for traditional knowledge, and the accompanying trust deficit collectively prevent small- and mid-scale community processors from standardizing residue quality, thereby blocking industrial investment in the necessary zero-waste bio-refinery systems.

The core contribution of this research is the conceptual and empirical formalization of the NTFP-Circular Economy (NTFP-CE) Model, which successfully bridges the disciplinary gap between forest livelihood studies and mainstream Circular Economy theory. This model introduces essential, measurable metrics, such as the Conversion Efficiency Rate (CER) and the Waste Reduction Index (WRI), as the new standard for evaluating the sustainability performance of bio-economic activities. By shifting the analysis from raw commodity value to total resource utilization and high-value byproduct recovery, the NTFP-CE Model provides a necessary framework for policy intervention, enabling stakeholders to transform the forest from a source of mere subsistence goods into a highly valuable, perpetually regenerative industrial asset base.

A primary limitation of this research is the cross-sectional design, which, despite providing robust correlations between institutional failure and waste generation, cannot establish the long-term causal impact of the proposed CE interventions. The study's focus on technological and policy barriers implies the need for immediate, targeted action. Future research must, therefore, prioritize longitudinal, action-based studies that actively pilot the implementation of the prescriptive elements of the NTFP-CE Model, specifically the establishment of Collective Residue Management Units (CRMUs) and government-backed Risk-Sharing Mechanisms (RSMs). This subsequent research is essential for generating the causal evidence required to prove that policy-driven risk management can successfully incentivize widespread community adoption of zero-waste bio-refinery technology.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) utilized Grammarly for grammar and style suggestions. After using these tools/services, the author(s) thoroughly reviewed and edited the content, taking full responsibility for its accuracy.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

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

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