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Review

Advancing Bioresource Utilization to Incentivize a Sustainable Bioeconomy: A Systematic Review and Proposal of the Enhanced Bioresource Utilization Index

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Abstract

Over 15 billion tonnes year^{-1} of biomass is used globally, yet 14% is downcycled for energy, forfeiting billions in potential revenue for higher-value products. Robust metrics that couple cascading use with cradle-to-gate greenhouse gas (GHG) emissions and economic value are essential for identifying superior biomass pathways. The aim of this review is to systematically map biomass utilization indicators published between 2010 and 2025; compare their treatment regarding circularity, climate, and economic value; and introduce the enhanced Bioresource Utilization Index (eBUI). A PRISMA-aligned search of Scopus and Web of Science yielded 80,808 records, of which 33 met the eligibility criteria. Each indicator was scored on cascading, data intensity, and environmental and economic integration, as well as computational complexity and sector scope. The Material Circularity Indicator, Biomass Utilization Efficiency, the Biomass Utilization Factor, and legacy BUI satisfied no more than two criteria simultaneously, and none directly linked mass flows to both GHG emissions and net revenue. The eBUI concept integrates mass balance, lifecycle carbon intensity, and value coefficients into a single 0–1 score. An open-access calculator and data quality checklist accompany the metric, enabling policymakers and industry to prioritize biomass pathways that are circular, climate-smart, and economically attractive.

Keywords: circular economy; bioeconomy; biomass; residues; bio-based products; carbon footprint; multi-criteria decision analysis; sustainability; value chain

Academic Editors: Deepak Kumar, Ankita Juneja, Anuj Kumar Chandel and Obste Therasme

Received: 2 August 2025
Revised: 23 August 2025
Accepted: 29 August 2025
Published: 3 September 2025

Citation: Ugwu, C.O.; Berry, M.D.; Winans, K.S. Advancing Bioresource Utilization to Incentivize a Sustainable Bioeconomy: A Systematic Review and Proposal of the Enhanced Bioresource Utilization Index. *Processes* **2025**, *13*, 2822. https://doi.org/10.3390/pr13092822

1. Introduction

In the 21st century, sustainable management of resources and waste streams has become a desirable growth direction, considering its non-negligible impacts on human health, environmental integrity, and economic stability. Yet, annually, over 15 billion tonnes of biomass is consumed worldwide, while about 14 percent is diverted to low-value energy conversion, sacrificing billions in potential revenue from higher-value applications and releasing more than 2 Gt of carbon dioxide equivalent (CO_2e) [1]. Hence, global ambitions to decarbonize, safeguard material security, and revitalize rural economies are accelerating the shift from fossil resources towards biomass and other renewables [2–4]. More than thirty jurisdictions now publish bioeconomy strategies that foreground food and feed, bio-based materials, and bioenergy [5]. While these strategies may differ, they commonly center on utilizing biological resources and a sustainable bioeconomy [6]. A sustainable bioeconomy supports rural economies, increases job creation, and enables technological innovation. Importantly, biomass drives the carbon cycle by absorbing atmospheric carbon dioxide during photosynthesis, storing it as organic matter, and recycling it through processes like respiration and combustion. This dynamic system is essential for sustaining life and regulating the global climate [7]. Yet intensified biomass extraction can exacerbate deforestation, biodiversity loss, and social inequity if value chains remain linear [8], referring to a situation where material flow is entirely dependent on virgin feedstock that ends as waste rather than being recycled into useful products. A sustainable bioeconomy therefore hinges on three operational levers: (i) cascading use—multi-stage and sequential high-value deployment; (ii) production efficiency—maximizing conversion yields; and (iii) value prioritization—steering residues to premium markets [9,10]. Effectively combining these levers promotes a holistically sustainable bioeconomy, where various products and by-products are simultaneously produced from the same or different processes, with the aim of maximizing output while reducing or eliminating wastages.

Prior studies have modeled biomass utilization using tools such as material-flow analysis, bio-based value pyramids, or environmental assessment to assess trade-offs or values associated with the use of biomass. While these tools and other factors have helped to demonstrate the efficiency of bio-based material utilization in various contexts, they often overlook key financial considerations for sustainable resource management. Some indicators or metrics that partially capture these levers include: the Material Circularity Indicator (MCI), a 0–1-scale metric developed to quantify a product's circularity by integrating material flows, recycled and bio-based feedstock content, reuse and recovery efficiencies, and product lifespan; Biomass Utilization Efficiency (BUE), a ratio metric that compares the molar mass of carbon, hydrogen, and oxygen incorporated into a bio-based chemical, polymer, or fuel with that of the original biomass feedstock to benchmark conversion efficiency and land-use implications; the Biomass Utilization Factor (BUF), is a mass-balance-based metric that quantifies industrial biomass efficiency by combining production efficiency with cascading reuse factors; and the original Bioresource Utilization Index (BU_{ind}) quantifies how efficiently bio-based residues are converted into primary products and higher-tier by-products by combining their masses weighted by value-pyramid coefficients, ranging from 0 (all downcycled or wasted) to 1 (maximally cascaded into high-value uses), to optimize bio-based material utilization pathways. However, none of these has directly integrated environmental and economic value within a single metric. This paper aims to advance these existing indicators and metrics by developing a data-driven decision-making tool considering not only the carbon footprint but also the net revenue generated for products and co- or by-products from bio-based resources at industry and regional scales. The tool will help elucidate the overall potential value of co- or by-products from bio-based resources, encouraging high-value use throughout the life cycle of the bio-based resources. This tool supports cascading, improved production efficiency, economic competitiveness, and environmental sustainability hence, closing this gap in the current indicators or metrics reviewed for this study It will be useful to policymakers, industry leaders, and investors in elucidating the trade-offs associated with bio-based products in terms of mass flow, environmental footprint, and net revenue.

Therefore, the objective of this paper is to (i) synthesize existing biomass efficiency indicators; (ii) evaluate their coverage of cascading, climate, and value; and (iii) propose the enhanced Bioresource Utilization Index (eBUI).

2. Materials and Methods

2.1. Systematic Review Protocol

A literature search was carried out to identify indicators that support and enhance sustainable and circular bioeconomy principles that are applicable to bio-based systems. The review followed the PRISMA 2020 guidelines, which involved three basic steps—the identification, screening, and selection of studies to include in this review [11]. Search strings combined terms for biomass utilization metrics (e.g., "bioresource utilization" and "material circularity") using Boolean operators. Two databases were queried, as described in the Search Strategy and Databases section.

Search Strategy and Databases

The literature search was conducted across two scholarly databases, Scopus and Web of Science, covering the period from January 2010 to June 2025. We employed the Boolean query ("bioresource utilization index") OR ("material circularity indicator") OR ("biomass utilization factor") OR ("biomass utilization efficiency") to capture relevant studies in Scopus and Web of Science. We selected article titles, abstracts, and keywords for the period 1 January 2010 to 30 June 2025; these searches were conducted on 7 July 2025. We also retrieved specific articles from ResearchGate (e.g., [7]) and government reports (e.g., [3]). No data collection was involved in this review. The search followed a three-step process to identify, screen, and select the articles that were included in this review study. Studies were excluded at the full-text stage if they lacked sustainable and circular economy metrics or if their contexts and concepts did not align with the bioresource utilization topic (Figure 1). The initial literature search in scholarly databases returned 80,808 records. Of these, 80,601 were immediately excluded – either as duplicates or because their titles did not reference circularity or bio-based materials - leaving 207 unique articles for further screening.

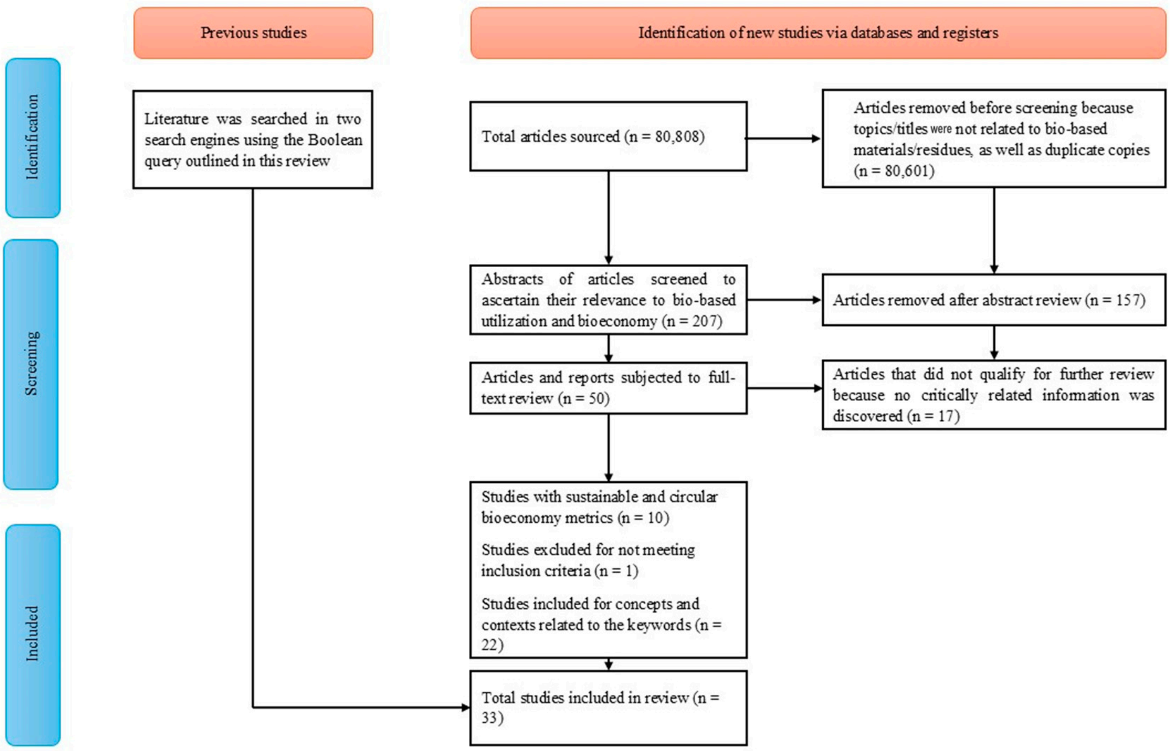

Figure 1. Methodology to collect related works on bioresource utilization indicators following the PRISMA guidelines.

During the abstract screening and review, 157 additional articles were excluded due to duplications or lack of relevance to the keywords or bioresource utilization indicators. The full texts of the remaining 50 articles were further reviewed to ensure that each contained critical information tied to our review scope. This process led to the exclusion of 17 articles due to their lacking critically related contexts, methodologies, and other necessary information, resulting in 33 studies advancing to the inclusion stage.

In the final inclusion stage, the 33 selected studies were organized into three categories: 10 studies presenting sustainable and circular bioeconomy indicators or quantitative metrics, 1 indicator being excluded because it did not address bio-based products or residues, and 22 studies addressing related conceptual ideas, background, contexts, or methodological advances. In Table 1, we outline the additional criteria for inclusion or exclusion of the studies that developed circularity and bioeconomy metrics. Importantly, these ensured the exclusion of any metric(s) that was not developed for bio-based products.

Table 1. Criteria for inclusion or exclusion of indicators and metrics.

Inclusion Criteria
Peer-reviewed article and relevant published grey literature.
Developed or applied for bio-based products or residues.
Used scientific- and data-driven approach
Described methodology approach used for developing the indicator or metric.
Included at least one of mass flow, environmental, economic, or social factors.
Aligned with circular economy and sustainability principles.
Included metrics and indicators irrespective of system-wide, material-, or process-specific application.
Excluded articles duplicated from different databases (Web of Science and Scopus).
Excluded articles that did not include key concepts identified for review.

2.2. Index Evaluation Rubric

The criteria used to evaluate the indices included cascading, data intensity, life-cycle environmental coverage, economic integration, computational complexity, predicting higher-value applications, and sectoral scope.

i. Cascading recognition gauges whether an indicator accounts for sequential high-value reuse of biomass (e.g., pharmaceuticals, biochemicals, or bioplastics that yield higher revenue per unit mass compared to bulk applications like energy). Cascading, or cascading use is the repeated application of a feedstock across successive uses [9,12], recognized as an effective approach to enhance bioresource utilization efficiency.
ii. Life-cycle environmental coverage measures the depth of cradle-to-gate impact accounting.
iii. Economic weighting captures the extent to which monetary value is built into the score.
iv. Data intensity implies how much detailed input is required.
v. Computational complexity reflects the analytical sophistication needed to run the model.
vi. Predicting higher-value uses—focusing on using or recovering materials at their highest use value during production, recycling, or waste management.
vii. Integrative—defines whether the indicator is combined as a single or multidimensional indicator or metric.
viii. Sectoral scope defines how broadly the metric can be applied across different industries or biomass streams.

We stated the inclusion and exclusion criteria in a tabular form (Table 1). While information about the outcome of the indicator assessment was presented narratively, there was no data extraction from studies, but each study's metrics, strengths, and weaknesses were described and summarized in tables (Tables 2 and 3). We defined our outcomes as indicator strengths and weaknesses and reported contextual variables such as citation use and application areas (Table 2). Risk of bias was judged without any automation method, although we did not present a domain-level bias table. For synthesis methods, we applied a priori criteria to group and narratively evaluate studies, required no data preparation, displayed findings under summary tables, and performed no meta-analysis, meta-regression, or sensitivity analyses. Reporting bias assessment and quantitative synthesis results were not applied in this review given the descriptive focus. Finally, we note that the review was not registered and no external protocol was prepared, and therefore no protocol amendments occurred.

Table 2. Brief descriptions of identified indicators.

Indicator/Author	Key Focus	Application Area	Strengths/Limitations
Sustainability Assessment Indicators [8]	Triple-bottom-line framework for environmental, economic, and social sustainability assessment	To improve East Asia biomass policy	Robust environmental, economic, and social metrics; lacks mass-balance/cascading analysis
Cascading Wood Utilization [9]	Cascading use through material-flow model and LCA integration	For Bavaria's wood sector	Demonstrates GWP reduction and resource efficiency; region-specific and may not generalize to other wood systems
BUE [13]	Stoichiometric conversion efficiency	Bio-based chemicals, polymers, fuels	Simple, rapid benchmarking of material conversion; omits environmental impacts and financial and full material-flow considerations
MCI [14]	MCI adapted for bio-based and biodegradable products	Mulch films	Includes biodegradation as circular process; does not address economic trade-offs or broader environmental impacts
MCI [15]	MCI modified for biological cycles in agriculture	Livestock application	Captures feed conversion and manure management in poultry farming; excludes cross-system nutrient loops, has an incomplete circularity scope, and lacks environmental and economic weighting
MCI [16]	MCI modified for BCS estimation	Lignin-based asphalt production	Accounts for carbon storage and reclaimed asphalt; lacks economic/financial weighting
MCI [17]	Coupled MCI and LCA for single-objective optimization	Europe's plastic packaging value chain	Demonstrates environmental gains via recycling; focused on linear optimization, limited system-wide cascading
BUF [10]	Mass-balance approach, combining production efficiency and cascading	Biomass used for industrial or material application	Quantifies multi-stage reuse; does not prioritize high-value outputs or economic weighting
Hybridized Sustainability Indicators (HSI) [18]	Combines resource circularity principles with LCA approach	To compare bio-based products with fossil-based products	Evaluates and compares resource efficiency of bio-based products with petrochemical products; lacks system-wide cascading
BU_{ind} [19]	Combines material-flow and bio-based value pyramid weighting of primary products and by-products in multi-scenario modeling	Latvian food production enterprises	Evaluates production efficiency and rewards high-value cascading; does not include carbon footprint or financial weighting factors

Table 3. Indicators—evaluation criteria and comparative framework.

Criterion	BUE	MCI	BUF	BU_{ind}	Sustainability Assessment Indicators	Cascading Wood Utilization	HSI
Cascading recognition	c	b	a	a	c	a	b
Life-cycle environmental coverage	c	b *	c	c	a	a	a
Economic weighting	c	c	c	c	a	c	c
Data intensity	b	b	b	b	a	a	b
Predicting higher-value uses	c	c	c	a	c	a	c
Integrative	a	b	a	a	c	a	c
Computational complexity	b	b	b	b	b	b	b
Citations	33	248	2	19	27	149	80
Sectoral scope	Chemicals, fuels	All products	Bio-based materials	Forests, fuels, agri-food	Materials, chemicals	Wood	Chemicals, materials, energy

BUE = Biomass Utilization Efficiency, MCI = Material Circularity Indicator, BUF = Biomass Utilization Factor, BU_{ind} = Bioresource Utilization Index, HSI = Hybridized Sustainability Indicator. a strong; b partial; c omitted/not applicable; b * applicable to one to the four MCI metrics reviewed in this paper (i.e., ref. [16] modified MCI to incorporate biogenic carbon and uses LCA).

Generally, the PRISMA approach for systematic reviews is acceptable; however, it is designed for medical studies. Consequently, not all criteria are applicable to every review work (e.g., no registration was required for this review).

3. Results

3.1. Landscape of Biomass Indicators (2010–2025)

Ten indicators tied to bio-based systems were included for review from the literature search. Sustainability Assessment Indicators is a region-specific sustainability assessment framework developed by an expert working group for biomass utilization in East Asia for policymakers [8]. The group adopted a triple-bottom-line approach, defining three pillars of sustainability metrics, viz., environmental, economic, and social metrics, each supported by one primary and two secondary indicators. The indicators were field-tested through four pilot case studies: Jatropha biodiesel in India; cassava ethanol and Jatropha biodiesel in Indonesia; coconut biodiesel in the Philippines; and sugarcane ethanol in Thailand. Höglmeier et al. [9] integrated cascading wood utilization into regional resource management strategies by employing a material-flow model coupled with Life-Cycle Assessment (LCA), particularly global warming potential (GWP). The study highlighted how cascading enhances both environmental performance and resource efficiency in Bavaria's wood sector, particularly in reducing reliance on virgin biomass and optimizing material flows across multiple applications before final energy recovery, ensuring that wood resources are retained in high-value applications for longer periods. Iffland et al. [13] developed the BUE to assess stoichiometric conversion efficiency by comparing the moles of C, H, and O in products (e.g., chemical, fuel, or polymer) versus feedstock. It was designed to evaluate process-level efficiency and theoretical versus practical/actual conversion yields.

Razza et al. [14] modified the original MCI to account for bio-based and biodegradable (BB) products, specifically mulch films, treating bio-based feedstock as recycled material and biodegradation in soil as a circular process, thereby improving the eco-design of BB products. Rocchi et al. [15] modified it to assess circularity in poultry farming by incorporating feed conversion rates, manure management, and a utility factor, quantifying how efficiently resources are reused or recycled in livestock production, revealing that intensive broiler farming remains largely linear. Corona et al. [16] modified the MCI by exploring the sustainability aspect of lignin-based asphalt, focusing specifically on biogenic carbon storage (BCS) to capture both linear and circular flows within asphalt production. The findings revealed that lignin-based asphalt achieved better circularity compared to bitumen-based counterparts. Karayılan et al. [17] combined the MCI with LCA concurrently to solve linear single-objective optimization models, assessing how circular economy strategies can improve environmental outcomes and material circularity in Europe's plastic packaging value chain. Their results showed that implementing circular economy principles combined with improved recycling significantly reduced environmental impacts in the packaging sector. Vom Berg et al. [10] developed the BUF that evaluates the efficiency of biomass use for industrial or material applications, employing a mass-balance approach integrated with principles of the circular economy. This approach focuses on two main elements—production efficiency and cascading use to account for multi-stage material flows. It quantifies to what extent bio-based materials remain in use across multiple product stages. Lokesh et al. [18] introduced a set of Hybrid Sustainability Indicators (HSIs) based on green chemistry and resource circularity principles in combination with LCA to evaluate and compare the resource efficiency of bio-based products with petrochemical products. This provides insights into the gate-to-gate stages of hazardous chemical use, waste, energy efficiency, and resource circularity. The findings highlight their value in improving sustainability reporting, operational optimization, and decision-making across the supply chain. Vamza et al. [19] developed the BU_{ind} to optimize the use of bio-based resources while aligning with circular bioeconomy goals. It weighs each co-product or by-product mass by its position in the bio-based value pyramid, favoring high-value outputs like pharmaceuticals over low-value energy streams. The study employed a multiple-scenario analysis, where different by-product pathways were evaluated. A scenario BUI score closer to 1 shows better bio-based resource utilization, where 0 score represents a scenario where all by-products are either used for bioenergy applications or wasted. A brief description of the identified indicators are presented in Table 2. Each offers unique perspectives and methodological strengths for evaluating bio-based systems.

3.2. A Brief Illustrative Gap Analysis

Cascading delivers measurable system benefits. In Bavaria's wood sector, routing sawn-wood residues through a cascading sequence to energy cuts global warming potential by 7% and primary-timber demand by 14% versus direct combustion (Figure 2) [9].

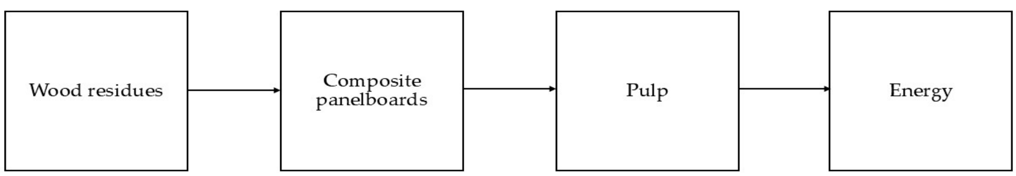

Figure 2. Example cascading flow diagram.

However, integrating an economic factor would present the study as a more holistic approach. High-yield pathways identified via the BUE shown in Equation (1) can shrink cultivation footprints without sacrificing output; conversely, low-yield BUE flags processes where optimization or feedstock switching are essential [13]. The metric has been applied in various studies aimed at determining the utilization efficiencies of bioplastics, for instance, the authors of [20] applied it to determine the efficiency of various polyhydroxyalkanoate (PHA) yields from glucose, and the authors of [21] applied the BUE to determine the stoichiometric and yield efficiencies of neutralized and non-neutralized corncobs. But this approach lacked environmental and economic dimensions, limiting its applicability for holistic evaluation in sustainability and circularity analysis. The original MCI in Equation (2) [22], though not explicitly intended for bio-based resources, has been modified (e.g., [14–16]) and applied to different areas of bio-based systems. The modified metric has demonstrated its strength in evaluating the circularity of bio-based materials, yet lacks the pillars of sustainability, limiting its versatility. The integration of LCA into the MCI in [17] showed that implementing circular economy principles combined with improved recycling significantly reduced environmental impacts in the packaging sector. Incorporating the economic factor would identify the revenue savings associated with improving circularity in plastic packaging. As another example, adding biogenic carbon storage highlighted the circularity of lignin asphalt above that of bitumen blends, yet economic feasibility remained unaddressed [16]. The BUF in Equation (3) in [10] accurately combined production efficiency and cascading use, focusing only on bio-based materials used for industrial application. This means that other portions were not considered [23]. Just as with other indicators, environmental and economic factors were omitted. Additionally, scenario modelling in Latvian bio-based value streams showed that redirecting materials to higher-value products increased the BU_{ind} score, revealing otherwise hidden revenue potential for similar residues [19]. The BU_{ind} in Equation (4) assigns coefficients to products based on their position on the bio-based value pyramid. According to [24], the hierarchy ensures that bio-based products are channeled toward higher-value applications. This index has the capacity to aid in strategic planning, helping managers and policymakers choose higher-value utilization pathways. However, the omission of the environmental aspect and direct economic integration still limits the comprehensiveness of the BU_{ind}. The criteria described in Section 2.2 were used to summarize the strengths and gaps associated with each indicator in Table 3.

Generally, cascading wood utilization performed best across the evaluation criteria, having a strong rating for cascading recognition, life-cycle environmental coverage, and integrative capacity, while maintaining low data intensity and computational complexity; however, it lacks economic weighting. Sustainability Assessment Indicators uniquely top economic weighting and life-cycle coverage, but cascading recognition and value-use prediction were omitted. BUE and BUF offer minimal data demands and computational simplicity, yet are constrained by poor environmental coverage, no economic integration, and an inability to predict higher-value uses, limiting their holistic applicability. The BUind leads in predicting higher-value uses and integrative scope with moderate data intensity but lacks life-cycle environmental coverage and economic weighting, even though the value is represented by the coefficients resulting from the bio-based value pyramid. The MCI, despite the highest citations and broadest sectoral scope, only achieves moderate ratings for most criteria, omitting economic weighting, underscoring that no single indicator simultaneously satisfies cascading recognition, climate stewardship, and financial viability, such that there is a need for a more comprehensive eBUI.

The four versions of the modified MCI reviewed were represented as one in Table 3 because major differences were found regarding applications. For instance, Razza et al. [14] applied MCI to account for bio-based and biodegradable products specifically in mulch films, Rocchi et al. [15] assessed circularity in poultry farming, and Corona et al. [16] explored the sustainability aspect of lignin-based asphalt, focusing specifically on biogenic carbon storage; hence, MCI was attributed partial life-cycle environmental coverage in Table 3. The number of citations for MCI is 248; Razza et al. [14], Rocchi et al. [15], Corona et al. [16], and Karayılan et al. [17] were cited 74, 87, 24, and 63 times, respectively.

$$BUE = \frac{RMM_P^{biomass} * ideal\ moles_P}{\sum\left(RMM_R^{biomass} * ideal\ moles_R\right)} * Yield_P \quad (1)$$

where $RMM_P^{biomass}$ is the molar mass of the biomass fraction incorporated into the product $_P$, $ideal\ moles_P$ is the stoichiometric (theoretical) number of moles in the product, $RMM_R^{biomass}$ is the molar mass of each reactant $_R$, $ideal\ moles_R$ is the stoichiometric (theoretical) number of moles of reactants in the product, and $Yield_P$ is the actual conversion yield of product $_P$, expressed as a fraction.

$$MCI = 1 - LFI * F(X) \quad (2)$$

where LFI is the linear flow index and $F(X)$ is the utility factor built as a function of the utility X of a product.

$$BUF_n = BUF_{n-1} + BI_n * PE_n \quad (3)$$

where BUF_{n-1} is the biomass utilization at cascade stage $n-1$, BI_n is the biomass input in cascade stage n (in %) of the starting biomass BI_0, and PE_n is the production efficiency (in %) in any cascading stage n.

$$BU_{ind} = \frac{P + BP_1 * c_1 + BP_2 * c_2 + BP_3 * c_3 + BP_4 * c_4 + BP_5 * c_5}{RM} \quad (4)$$

where p is the primary product, BP_n is the by-product, c_n is the coefficient assigned to the bio-based value pyramid, and RM is the used raw material.

In general, circularity concepts and accounting measures continue to evolve and are promising yet remain incomplete for bio-based systems. Table 3, above, illustrates that no single indicator simultaneously addresses cascading recognition, climate stewardship, and financial viability. Hence, we developed the eBUI, a scalable indicator that integrates mass flow, cascading use, life-cycle environmental coverage, and economic weighting, to enable broader application across bio-based sectors and predict higher-value uses.

4. The Enhanced Bioresource Utilization Index (eBUI)

4.1. Conceptual Framework

The eBUI is founded on the BUI, which combined mass flows of raw materials and by-products with value coefficients from a bio-based value pyramid (1.0 for pharmaceuticals and fine chemicals; 0.75 for food and feed; 0.50 for bioplastics and polymers; 0.25 for bulk chemicals and biogas; and 0 for energy, heat, and fuels). While circularity strategies present valuable opportunities for resource conservation, they may also carry potential risks if they lead to negative environmental trade-offs [25]. To address the omission of environmental and economic dimensions in the BU_{ind}, we integrated two weighting factors, carbon footprint (Cf) reported in (kg CO_2-eq per unit mass) (resulting from LCA modeled from raw material extraction to end of production—factory gate) and net revenue (reported in USD per unit mass), into the eBUI (Equation (5)). The eBUI assigns each utilization scenario a score between 0 and 1 by multiplying the mass of the by-products or co-products with normalized carbon and revenue weights. This composite metric allows direct comparison of scenarios based on material efficiency, greenhouse gas impact, and financial return, guiding the identification of the highest-value use pathways for bio-based residues in processing facilities. For simplicity, we have only used the notation for by-products (BPs), not co-products (CPs).

$$eBUI = \frac{P + \sum_{i=1}^{n}(BP_n * NR_n * Cf_n)}{RM} \quad (5)$$

where BP_n is the mass of the by-product (kg), NR_n is the net revenue (USD per unit mass of by-product), and Cf_n is the carbon footprint (kg CO_2-eq per unit mass of by-product).

4.1.1. Net Revenue

The net revenue highlights the need for businesses to assess the economic feasibility of bio-products, balancing production costs with market value [26]. According to [27], sourcing bio-based materials for consistent and sufficient supply remains challenging, highlighting the need for business models that ensure a fair distribution of costs and benefits while managing resources and knowledge effectively. The net-revenue evaluation includes capital expenditures (CAPEX) (e.g., equipment costs, land, tax, etc.), operational expenditures (OPEX) (e.g., transportation cost, distance, labor, maintenance, and feedstock procurement costs), market values of primary products and potential secondary products, and output quantities that are current for the company in question.

In addition to supporting and guiding internal industry decision-making, net revenue reflects a broader economic contribution of bio-based material production to national and regional economies. Higher economic returns from bio-based enterprises signal that bio-based products are not only environmentally beneficial but also economically viable, supporting market growth, attracting government and private investment, and strengthening long-term industrial resilience [28]. In the US, the direct value added by bioeconomy industries was estimated at USD 402.5 billion, or 2.2% of GDP, in 2016. If bio-based production reached its full potential, this contribution could rise to USD 571.6 billion, or 3.1% of GDP, underscoring the sector's significance as a driver of economic growth and sustainability [3].

4.1.2. Carbon Footprint

Also, assessing the environmental impact of various products made from bio-based materials, such as sawmill residues, is essential to identify the activities that are most impactful during a product's life cycle (e.g., [29]). From residue sourcing to production stage, both stakeholders and consumers expect manufacturers, brands, and retailers to understand the environmental impact of their products and take steps to minimize it. Without looking at a life cycle using methodologies like Life-Cycle Assessment (LCA) and LCA tools, industry decision-makers cannot achieve this goal efficiently and effectively. One of the key benefits of LCA is its ability to assess impacts, ensuring that environmental burdens are not merely transferred between stages or regions. Among the various impact categories, global warming potential is one of the most widely applied indicators in the wood and textile industries [30].

4.1.3. Normalization

The resulting NRn values for by-products are normalized to fall within a range of 0–1 and incorporated into the eBUI as the net-revenue weighting factor for each by-product. Similarly, the resultant carbon footprint values from the life-cycle-based analysis are normalized to fall within a range of 0–1 and used as the weighting factor in the eBUI. Since higher carbon footprint values indicate greater environmental impact (i.e., worse performance), inverse normalization is applied to reflect this before incorporating it into the eBUI as the environmental weighting factor.

4.1.4. Scenario Analysis

Multiple scenarios based on varying product and by-product combinations are evaluated using the eBUI formula for each scenario to generate eBUI scores for comparative purposes. Comparing scores across all scenarios will aid the identification of the combination that provides the highest production efficiency [19], lowest carbon footprint, and highest economic return.

4.2. Implementation Tool

The eBUI is implemented in Microsoft Excel. All normalization, inverse-normalization, and averaging operations are required to calculate the eBUI composite score and enable direct comparison of utilization pathways. This spreadsheet-based approach ensures that practitioners and researchers can apply the eBUI without programming expertise, while maintaining the full transparency of each calculation step. The excel worksheet is attached as a Supplemental document (Supplemental Worksheet). This a very simplified version of the model for quick streamlined calculations. During the multi-scenario analysis for finding the optimal use combinations, you may modify the BP_n mass percentages directly in the attached Supplemental Worksheet to reflect your specific requirements. Please keep in mind that the variations provided are for demonstration purposes only.

4.3. Sensitivity Analysis

In carbon footprint and financial modeling, sensitivity analysis is essential for determining which input parameters notably influence outcomes and drive output uncertainty, thereby guiding further investigation, improving data quality, and enriching result interpretation [31,32]. In the eBUI, sensitivity analysis enables prioritization of data quality improvements by revealing whether refining carbon footprint data or obtaining more precise market-price forecasts will most effectively reduce overall score uncertainty.

In the Supplemental Worksheet, we included three additional columns, carbon footprint, cost of production, and selling-price variations, allowing us to adjust these values individually or in combination to perform a sensitivity analysis on the resulting eBUI score and identify which variables most strongly drive its increase or decrease. We also recommend performing this sensitivity assessment within your LCA modeling to identify the key input parameters that dominate the carbon footprint and any other impact categories of interest and the extent to which such variations can impact the score.

5. Discussion

Unlike the indicators reviewed in this study, the eBUI combines both carbon footprint and net-revenue metrics for a fully integrated bio-based material assessment using a single 0–1 score. To further highlight its simplicity in application, it is modelled in an excel worksheet that is less complex and scenario-ready (Supplemental Worksheet).

5.1. Cascading as a Systemic Rapid Assessment Strategy

eBUI quantifies how extending cascade length can simultaneously assist decision makers in assessing tradeoffs between net revenue and carbon footprint, enabling industry leaders and policymakers to see that multiple use of bioresources is not just environmentally profitable (lower GHGs) but also economically smarter (higher net revenue). It is a tool to quantify the synergy between mass flow and selected aspects of sustainability like carbon footprint and profitability. Additionally, the eBUI's designed to align industry incentives with circular economy goals, steering residues toward pharmaceuticals, food, and advanced polymers ahead of energy recovery, to uncover profitable re-routes. Further, integrating cascading bio-based material utilization into resource management reduces reliance on virgin biomass, enhances carbon storage potential, and minimizes waste generation [9,10,19]. This approach ensures that bio-based resources are retained in high-value applications for longer durations, mitigating environmental pressures associated with primary resource use. According to [19], cascading use promotes resource optimization, ensuring that biomass is not prematurely downcycled into low-value applications such as energy recovery. This is not to say that utilizing biomass resources for energy use is a bad idea. However, the efficient use of biomass following a cascading approach maximizes its value by prioritizing material use (e.g., bio-based chemicals and materials) before energy applications, such as biofuels [12,24]. The eBUI is a tool designed to capture these nuances, promoting material circularity in a sustainable and circular bioeconomy.

5.2. Towards a Multi-Criteria Decision-Making Index

The eBUI unifies mass flow, carbon footprint, and net revenue in a single transparent score, enabling clear trade-off analysis across environmental and economic axes—a functionality absent from current indices reviewed in this paper. Building a sustainable, circular bioeconomy demands multidimensional metrics that reflect cascading use pathways, production efficiency, high-value applications, environmental impacts, and financial viability. While existing indices shed light on biomass efficiency and circularity, their lack of economic assessment prevents a fully holistic evaluation. Decision-makers in both policy and industry therefore require a unified framework or indicator that combines environmental metrics (e.g., carbon footprint), economic metrics (e.g., investment viability), and circular economy principles.

By revealing the convergence of resource utilization, revenue generation, and carbon benefits, we hypothesize that the eBUI guides the identification of optimized pathways and supports transparent reporting, thereby potentially contributing to more robust sustainability goals.

5.3. Limitations and Uncertainties of the eBUI

eBUI presents a novel and integrative approach to evaluating biomass utilization pathways. Limitations and sources of uncertainty are acknowledged in the following sections.

5.3.1. Data Gaps and Reliance on Proxy Values

Some of the by-products evaluated using the eBUI framework are either emerging technologies or have not yet been commercially produced (e.g., cotton mote co-products). As a result, primary data for current market values may be unavailable, and estimations are made using proxy values derived from the peer-reviewed literature, established databases, and online retail markets. Our approach to working with proxy data is in accordance with Dijk et al. [33], who noted that proxy data are modelled, aggregated, or estimated data used in place of unavailable, inconsistent, or incomplete company-specific data used to bridge data gaps. This further limits the integration of actual market values into economic evaluation, because when such a market is not in existence, integrating such factors becomes challenging. Additionally, this reliance on proxy data or assumptions (e.g., data associated with pure cotton to estimate cotton motes where data are unavailable) and further calculations introduce uncertainty into an analysis, particularly for carbon footprints if using economic allocation and in overall financial estimates. To mitigate this, a sensitivity analysis was integrated into the methodology to identify which input parameters most significantly influence the eBUI outcomes. This approach helps prioritize areas for further investigation, improve data quality, and strengthen the reliability of scenario comparisons.

5.3.2. Allocation Constraints for Non-Commercialized Products

The eBUI has allocation limitations, whether economic, mass, or energy allocation in LCA modeling. For instance, applying an allocation approach to evaluate production costs for products like the cotton motes mentioned earlier (in Section 5.3.1) is challenging at this moment due to a lack of detailed primary or proxy data to ensure accuracy.

Using retail prices to derive costs is also highly problematic. An approach to this challenge involves calculating the total cost of production across all products and co-products, then allocating that cost based on their respective weights—typically normalized to a standard mass, such as one ton. However, whenever price values are used, it is essential to account for additional factors like transportation, marketing expenses, and profit margins. Importantly, this method should not replace the use of wholesale or bulk prices when these values are available, as they more accurately reflect the actual production costs of the final products and co-products compared to retail prices.

5.3.3. Social Sustainability Metrics

The current eBUI formulation focuses exclusively on environmental and economic dimensions, without incorporating a social weighting factor. Bio-based material valorization and utilization are labor-intensive processes that often generate employment and supplemental income, particularly in rural communities [8]. Job creation occurs in both bio-based material handling and conversion stages. Including social indicators such as employment generation or Human Development Index scores could strengthen the eBUI's ability to assess sustainability more holistically. Future iterations of the eBUI may benefit from integrating these social metrics to better capture the triple-bottom-line of sustainable development.

6. Conclusions

This review identified the limited integration of economic, environmental, and mass-flow considerations in evaluating the utilization of bio-based resources and their residues, a gap that has constrained the ability to make informed, comparative decisions across multi-scenario pathways. While prior studies often examined individual dimensions (e.g., circularity, product applications, production efficiency, or carbon emissions), few approaches holistically connected some of these aspects into a single decision-support indicator or metric. By synthesizing insights from across the literature, this paper highlighted the need for indicators to integrate these aspects to optimize utilization pathways. The eBUI proposed in this review paper fills this gap by providing a transparent, multi-criteria score that supports evidence-based decisions for a sustainable, profitable bioeconomy. It integrates (1) mass flows, (2) normalized carbon footprints, and (3) normalized net-revenue estimates into a transparent 0–1 score and (4) predicts the highest use values from current utilization pathways, as well as other potential pathways. Implemented entirely within a Excel workbook, eBUI enables rapid scenario screening. Our approach creates a bridge between technical assessment and decision-making. Potential users of this framework span a wide range of stakeholders. Policymakers and regulatory agencies can benefit from the tool to design policies, regulations, and incentives that promote higher-value applications of bioresources while reducing environmental impacts. Industry actors such as sawmill operators, bioenergy producers, and manufacturers of fiber products can also apply it to guide investment and operational choices. Finally, researchers can use the framework as an enhanced foundation for extending methodological development in bioresource utilization. This paper presents the eBUI as an audience-responsive decision-making tool that addresses strategic, operational, and regulatory interests and hence contributes to advancing a more sustainable and economically resilient bioeconomy. Future work should

(i) validate eBUI for different bio-based material streams, (ii) harmonize data collection and management protocols, and (iii) link eBUI thresholds to a tailored approach using weighting factors. Together, these steps will ensure that eBUI evolves into a robust, multi-sector decision-support tool for a sustainable, profitable bioeconomy.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/pr13092822/s1, The excel worksheet and the PRISMA criteria are the Supplementary Materials discussed in this work.

Author Contributions: Conceptualization, C.O.U.; writing—original draft preparation, C.O.U.; writing—review and editing, K.S.W.; writing—review and editing, M.D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the Supplementary Materials. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors extend their sincere thanks to the industry partners who engaged in thoughtful conversations regarding the applicability of this tool to their situational real-world scenarios.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BUE	Biomass Utilization Efficiency
BUI	Bioresource Utilization Index
BUF	Biomass Utilization Factor
HSI	Hybridized Sustainability Indicators
GHG	Greenhouse gas
MCI	Material Circularity Indicator
LCA	Life-Cycle Assessment
LCIA	Life-Cycle Inventory Assessment
GDP	Gross Domestic Product

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