Article

Improving ESG Performance with Life Cycle Sustainability Assessment-Lessons from Additive Manufacturing

Mohammad Raquibul Hasan * , Michele John , Wahidul K. Biswas , Ian J. Davies , Alokesh Paramanik

Posted Date: 16 March 2026

doi: 10.20944/preprints202603.1193.v1

Keywords: additive manufacturing; fused filament fabrication; recycled PLA (rPLA); circular manufacturing; ESG; Governance; LCA; Life cycle sustainability assessment (LCSA)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

Article

Improving ESG Performance with Life Cycle Sustainability Assessment-Lessons from Additive Manufacturing

Mohammad Raquibul Hasan [1,*], Michele John [1], Wahidul K. Biswas [1,*], Ian J. Davies [2] and Alokesh Paramanik [2]

[1] Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

[2] School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

* Correspondence: m.hasan21@postgrad.curtin.edu.au; raquibulh@yahoo.com

Abstract

Additive manufacturing is increasingly promoted as a pathway toward sustainable production; however, its Environmental, Social, and Governance (ESG) implications remain insufficiently defined at the operational level. This study addresses this gap by developing a governance implications assessment framework to interpret empirically validated life cycle sustainability assessment (LCSA) evidence for post-consumer recycled polylactic acid (PC-PLA)-based fused filament fabrication (FFF) within the Australian manufacturing context. The central contribution lies in demonstrating how LCSA evidence can be translated into decision-relevant ESG information without reliance on product declaration frameworks or simplified circularity claims. While LCAs and EPDs do not directly optimise production systems, sustainability-oriented governance can guide engineering and operational decisions by managing whole-system trade-offs and future risk. The framework integrates mechanical validation, service-life-normalised LCSA results, circularity metrics, and material flow modelling through a consequences analysis lens. Results indicate that a V50:R50 (vPLA:PC-PLA) blend achieves balanced performance, delivering a 57% reduction in global warming potential while maintaining functional durability. However, these benefits are governance-contingent; managing an 11.7% increase in service-life-normalised costs requires senior-level oversight, formalised material traceability, and structured workforce training. Waste diversion analysis further demonstrates that scalability is constrained primarily by upstream collection and sorting efficiency rather than fabrication performance. The study concludes with a strategic roadmap advocating regional recycling hubs, certified micro-credentials, and adoption of decision-relevant governance metrics aligned with ASRS S1 and S2 disclosure standards. The proposed framework offers a transferable approach for translating engineering-level sustainability evidence into credible governance insights, strengthening accountability and supporting Australia's transition toward resilient, circular manufacturing.

Keywords: additive manufacturing; fused filament fabrication; recycled PLA (rPLA); circular manufacturing; ESG; Governance; LCA; Life cycle sustainability assessment (LCSA)

---

1. Introduction

Manufacturing has long underpinned global economic development by driving technological innovation, creating employment opportunities, and fostering social advancement. It transforms material resources into the infrastructure and products that sustain modern life and contributes significantly to economic output [1]. However, this economic contribution has been accompanied by

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

substantial environmental and resource burdens. In 2022, manufacturing accounted for approximately 16.8% of global gross domestic product (GDP), while the broader industrial sector consumed nearly 37% of global energy [2]. The persistence of linear "take-make-dispose" production models has intensified resource depletion, waste generation, and climate pressures, rendering conventional manufacturing increasingly incompatible with planetary boundaries [3]. As a result, global manufacturing is transitioning toward cleaner, circular, and socially responsible systems that integrate economic performance with environmental integrity and social well-being [4–6].

Sustainable manufacturing aims to decouple industrial growth from environmental degradation by maximising resource efficiency, minimising waste, and embedding life cycle thinking across production systems [7,8]. Circular manufacturing strengthens this approach by closing material and energy loops through reuse, remanufacturing, and recycling, directly supporting SDGs 9 and 12 [9,10]. Consequently, manufacturing performance is now assessed not only by productivity and cost, but also by environmental, social, and governance (ESG) outcomes, including decarbonisation potential, material stewardship, workforce well-being, and responsible sourcing [11,12].

Australia's manufacturing trajectory highlights both the urgency and opportunity for a transition toward advanced, sustainable manufacturing systems. From contributing nearly 30% of GDP in the 1960s, the sector now accounts for approximately 6%, reflecting decades of offshoring, rising labour and energy costs, limited automation uptake, and policy prioritisation of raw material exports over domestic value addition [13,14]. These conditions position ESG performance as an operational imperative rather than a purely normative objective, as reducing material risk, energy exposure, and quality failures enhances resilience and long-term competitiveness [15,16].

This level of sustainability accountability will increasingly become de rigour as the world considers higher standards of carbon accounting and environmental impact reporting via mechanisms like the EU's Carbon Border Adjustment mechanism (CBAM) [17], the Agreement on Climate Change, Trade and Sustainability [18] and the Kunming-Montreal Global Biodiversity Framework (GBF) [19]. In addition, new international standards of governance and governance reporting are also being developed, including the International Sustainability Standards Boards (ISSB) development of the ESG Governance Convergence standards [20] and the Global Framework on Chemicals Management [21].

Historically, governance, sustainability reporting, traceability, and compliance mechanisms have been relatively weak across many jurisdictions. However, the increasing integration of artificial intelligence and blockchain technologies is expected to strengthen national governance architectures by enhancing transparency, accountability, and legal-institutional reporting obligations [22–24]. In parallel, growing pressures surrounding global carbon management, coupled with significant disparities in national accounting standards and net-zero commitments, indicate a likely shift toward more structured and harmonised global governance systems. Manufacturing industries, particularly those involved in plastics production, must therefore recognise regulatory convergence and carbon accountability as emerging production risks [25,26].

Within this evolving governance landscape, additive manufacturing (AM), commonly referred to as three-dimensional printing, represents a strategic pathway toward lower-carbon and more circular production systems [27,28]. By enabling localised, on-demand manufacturing, AM can reduce transport-related emissions, decrease reliance on carbon-intensive imports, and mitigate supply-chain vulnerabilities associated with traditional manufacturing [28–30]. Its digital flexibility supports distributed production closer to the point of use, shortening lead times and enhancing system resilience [31]. For small and medium-sized enterprises, AM may lower capital intensity barriers and democratise access to advanced production capabilities [32].

From an environmental and social standpoint, AM aligns with national decarbonisation and circular-economy objectives. Material efficiency improvements of up to 90% and energy reductions of approximately 25% relative to selected TM processes have been reported, though such benefits are highly context-dependent [33]. In addition to resource efficiency, AM enables decentralised and localised production models that enhance regional resilience, reduce supply chain dependency, and

 doi:10.20944/preprints202603.1193.v1

foster skilled employment in digital fabrication and repair-oriented ecosystems [34,35]. By supporting on-demand production and shorter supply chains, AM also expands opportunities for SMEs and regional manufacturing hubs within circular value systems [36–38].

These benefits, however, are conditional rather than inherent. Their realisation depends on effective workforce training, strong occupational health and safety standards, and responsible governance across recycling and feedstock supply chains. In the Australian context, the Future Made in Australia Act (2024) and the National Reconstruction Fund underscore the strategic priority placed on advanced manufacturing, sovereign capability, and circular economy innovation [39,40]. Realising these policy ambitions of reduced carbon and more circular production requires embedding life cycle and circular-economy principles directly into production systems, particularly through informed material selection.

Material choice is therefore a critical determinant of sustainability performance in fused filament fabrication (FFF), one of the most widely adopted AM technologies. Recycled and bio-based polymers provide a practical pathway to CM by reducing reliance on virgin feedstocks and strengthening domestic recycling capacity [41]. Among these, polylactic acid (PLA) is prominent due to its renewable origin and suitability for FFF [27]. However, the proliferation of PLA in packaging and prototyping has generated substantial post-consumer waste. Recycling this waste into FFF feedstock closes material loops but also introduces ESG-relevant governance risks, including contamination control, traceability, process consistency, and mechanical reliability assurance [42].

Empirical studies, including the author's prior work, demonstrate that recycled PLA (rPLA) can achieve mechanical and tribological performance comparable to virgin PLA when processed under optimised conditions [43–46]. Complementary life-cycle assessments indicate reductions in greenhouse-gas emissions, production costs, and the creation of local employment through waste valorisation [27]. While these findings confirm the triple-bottom-line potential of rPLA-based FFF, their robustness depends on durability constraints, quality variability, and governance controls, which are central to ESG performance.

Although life cycle sustainability assessment (LCSA) integrates environmental (ELCA), economic (LCC), and social (SLCA) dimensions, its outputs are often framed as technical results rather than operational decision-relevant governance insights. As AM increasingly intersects with policy, investment, and industrial strategy, there is a growing need to translate LCSA evidence into ESG-relevant indicators that reflect operational risks, capability requirements, and performance trade-offs [47]. In this study, ESG is applied as a sustainability lens encompassing environmental efficiency, social outcomes, and governance capabilities such as traceability, quality assurance, and responsible material management. This perspective extends LCSA beyond product or process assessment toward system-level and design-level decision making.

At the national level, Australia's CM transition is increasingly framed through material efficiency and recovery targets. The National Waste Policy Action Plan emphasises reducing material footprint, increasing materials productivity, and achieving an 80% resource recovery rate by 2030 [48]. Within this context, rPLA-based FFF represents a materially relevant yet governance-sensitive pathway, as its contribution depends not only on technical feasibility but also on system coordination, durability assurance, and organisational control capability.

However, it is important to note that the term rPLA is used inconsistently in the literature. this study demonstrates that LCSA evidence derived from PC-PLA-based FFF systems can be translated into decision-relevant ESG information without relying on product declaration frameworks or simplified circularity claims. Rather than treating LCSA as an endpoint, the analysis reinterprets quantified environmental, economic, and social performance through an organisational accountability lens, generating governance and risk signals that inform ESG performance improvement and future risk management.

Therefore, this study demonstrates that LCSA evidence derived from PC-PLA-based FFF systems can be translated into decision-relevant ESG information without relying on product declaration frameworks or simplified circularity claims. Rather than treating LCSA as an endpoint, the analysis reinterprets quantified environmental, economic, and social performance through an organisational accountability lens, generating governance and risk signals that inform ESG performance improvement and future risk management.

Accordingly, this study addresses three research questions: (1) How can empirical LCSA findings from PC-PLA-based FFF be translated into decision-relevant ESG signals that support the interpretation of ESG implications? (2) What governance mechanisms are required to manage ESG-relevant risks in circular FFF systems? (3) How can this integration support Australia's transition toward resilient and sustainable manufacturing?

To address these questions, the study develops an ESG-integrated framework for circular FFF, grounded in empirical process optimisation, mechanical testing, and life-cycle evidence drawn from six related publications covering material processing, functional performance, and sustainability outcomes. The framework translates technical sustainability outcomes into actionable ESG indicators, governance performance criteria, and circular economy benchmarks at the technology and process levels, aligned with organisational reporting needs. The findings will provide a practical roadmap for policymakers, sustainability professionals, and manufacturers seeking to operationalise ESG principles within advanced manufacturing.

2. Governance for Sustainable Manufacturing in Australia

Traditional linear production systems are increasingly incompatible with resource constraints, climate obligations, and material security concerns. Early sustainable manufacturing approaches such as green manufacturing and cleaner production improved process efficiency but did not fundamentally restructure linear value chains [49–51]. As a result, systemic transformation remains necessary.

Circular manufacturing represents a structural evolution beyond these early initiatives. Rather than optimising isolated processes, it embeds closed-loop material flows, life-cycle thinking, and value-retention strategies including reuse, remanufacturing, and recycling. In doing so, it reconceptualises value creation to integrate environmental and social performance alongside economic outcomes [9,52]. This systemic orientation aligns with SDG 9 and SDG 12, emphasising industrial resilience and responsible production [53]. In Australia, circular manufacturing has been institutionalised through a six-element circular economy strategy aimed at strengthening sovereign capability and resource recovery. The strategic pillars underpinning this transition are illustrated in Figure 1, situating circular manufacturing within a national industrial resilience framework.

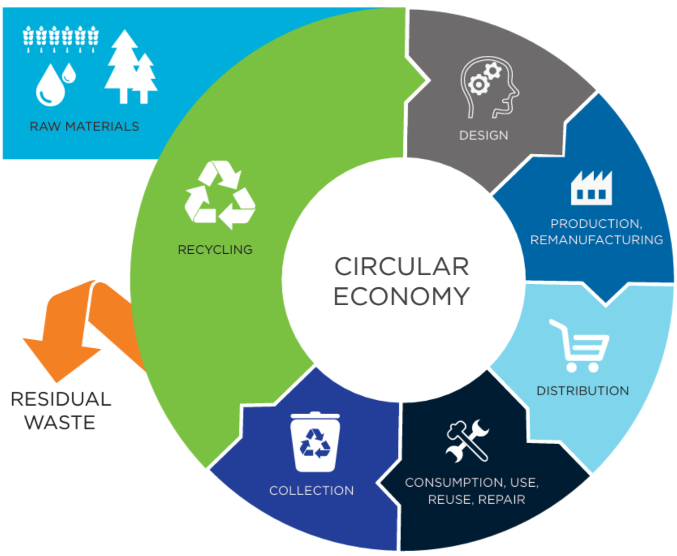


Figure 1. The six elements of the Australian circular economy strategy for sovereign manufacturing and resource recovery [54].

However, implementation occurs within a constrained industrial environment. Australia's manufacturing sector has experienced prolonged destabilisation due to energy price volatility, international competition, and declining capital investment [13]. Industrial gas prices have increased by approximately 50 percent since 2019, reducing firms' capacity to invest in decarbonisation technologies [55]. Concurrent labour and skills shortages have contributed to a productivity decline of approximately 3.7 percent over the past decade [55,56]. The interaction between these structural constraints and policy transition pathways is synthesised in Figure 2.

Within this constrained setting, advanced manufacturing technologies are positioned as enablers of circular transition. National initiatives such as the National Reconstruction Fund prioritise capital allocation toward strategic industrial sectors to accelerate decarbonisation and technological renewal [57,58]. Additive manufacturing is central to this transition, with the Australian AM market projected to reach AUD 3.85 billion by 2034 [59,60]. However, high capital costs, limited industry capability, and workforce readiness gaps continue to constrain the full realisation of AM's sustainability potential. Simultaneously, evolving international ESG reporting requirements signal a shift in which environmental, social, and governance considerations increasingly influence operational and strategic decision making [48].

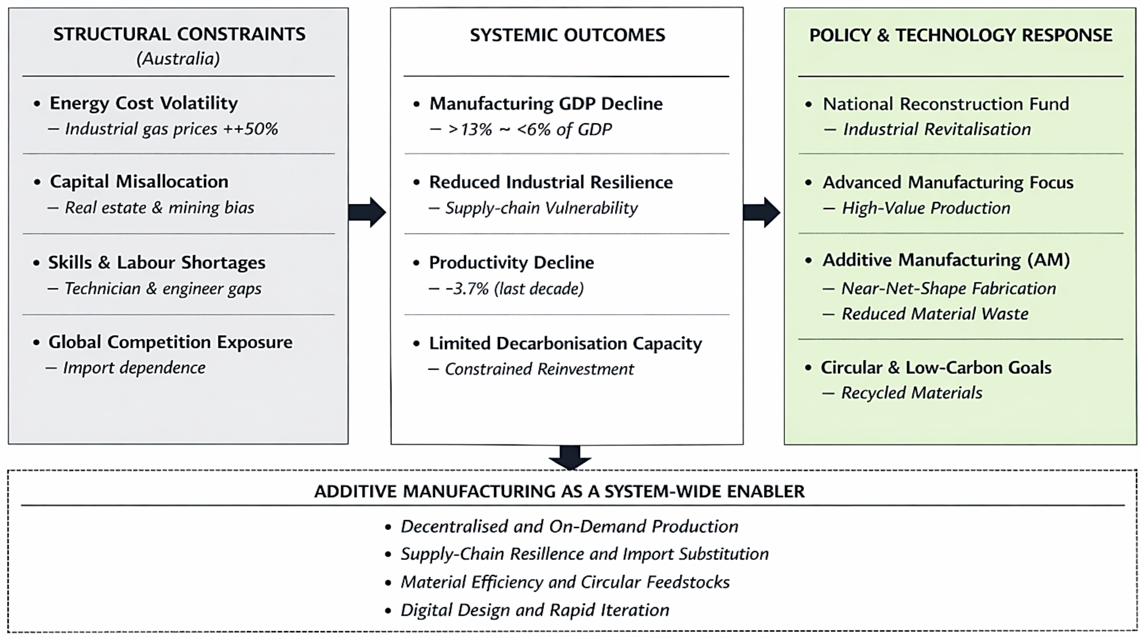


Figure 2. Structural challenges affecting the Australian manufacturing sector and corresponding policy-led transition pathways.

Rapid adoption of advanced technologies within capital-constrained systems can introduce structural risks if implemented as isolated upgrades. Misalignment between technological capability and system readiness may increase rigidity, skills dependency, and vendor lock-in without improving resilience. These risks are amplified in Australia's narrow-margin and energy-volatile context, particularly if international ESG standards exceed current domestic maturity. Nevertheless, AM demonstrates upcycling potential, including the conversion of post-consumer PLA cups into functional 3D printed gears, reducing virgin material demand and addressing waste management challenges[61].

Australia generates approximately 3.2 million tonnes of plastic waste annually, yet less than 14.1% is effectively recycled [62–64]. Although bioplastics such as PLA are often presented as sustainable alternatives, their benefits are undermined by inadequate labelling, limited sorting infrastructure, and the absence of dedicated recycling systems. Consequently, most PLA products, particularly packaging, are landfilled rather than recirculated within material loops [63].

FFF, the most widely adopted polymer-based AM technique, offers a viable pathway for valorising PLA waste. Its digital flexibility, low entry cost, and compatibility with recycled feedstocks support decentralised and on-demand manufacturing [65,66]. FFF can reduce material waste by up to 90% and energy use by approximately 25% compared to subtractive processes [67]. While its application in Australia has largely been limited to prototyping and education, its relevance for circular production and supply chain resilience is increasingly recognised [60].

Integrating post-consumer PLA into FFF enables conversion of bioplastic waste into functional components, reducing reliance on virgin polymers. Under controlled conditions, PC-PLA demonstrates acceptable mechanical performance for non-critical applications [44,45,68]. Moreover, localised filament production from source-separated PLA streams supports distributed CM models within universities, SMEs, and regional hubs, contributing to employment creation, workforce upskilling, and selected application-specific social benefits [69]. However, feedstock variability, degradation during reprocessing, and lack of standardised quality protocols remain barriers to industrial uptake [70]. Addressing these challenges is essential to transition PC-PLA-based FFF from conceptual promise to scalable industrial practice.

LCSA integrates ELCA, LCC, and SLCA to evaluate environmental, economic, and social impacts across product life cycles, making it suitable for assessing emerging circular manufacturing pathways such as PC-PLA-based FFF. However, a persistent methodological limitation is the weak alignment between LCSA outputs and ESG dimensions commonly used in organisational decision-making [71,72].

LCSA provides detailed, process-level insights expressed in technical units such as kg CO_2-eq, MJ, USD, and social risk indicators, and is sensitive to methodological choices, including allocation, normalisation, and weighting [73–75]. In contrast, ESG frameworks operate at the organisational level, prioritising comparability, materiality, and decision relevance for investors and regulators [76–78]. This divergence creates a translation gap whereby engineering-level sustainability improvements are not readily interpretable in terms of ESG-related risk exposure or governance performance [79].

From a manufacturing perspective, ESG functions as an implications-oriented lens through which engineering decisions shape environmental performance, social outcomes, and governance-related risk exposure [80]. In circular FFF systems, governance considerations extend beyond disclosure to include material traceability, process consistency, workforce competency, and quality assurance. The conceptual nature of this methodological gap between LCSA outputs and organisational ESG metrics is illustrated in Figure 3.

 doi:10.20944/preprints202603.1193.v1

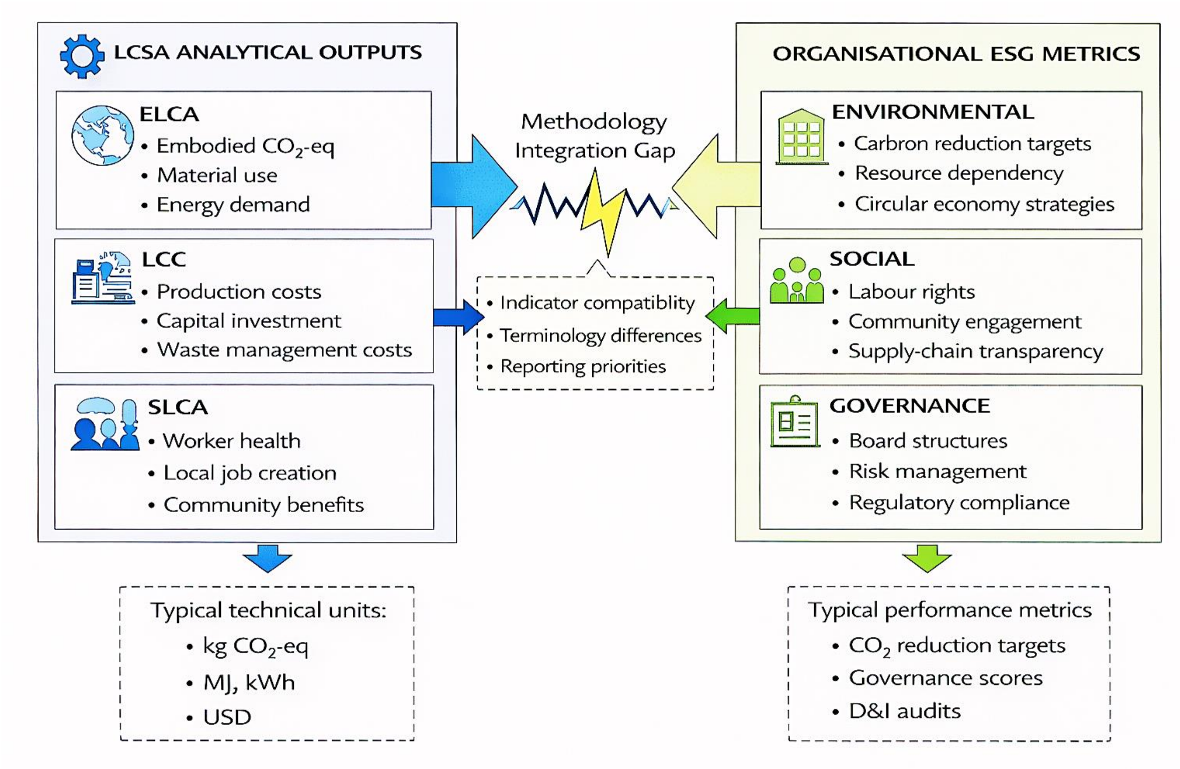


Figure 3. Methodological gap between LCSA outputs and organisational ESG metrics.

The urgency of resolving this gap is intensified by Australia's transition toward mandatory sustainability disclosure, reflecting increasing alignment with international reporting frameworks such as the ISSB, GRI, and TCFD [81,82]. The Australian Sustainability Reporting Standards, ASRS S1 and S2, adapted from IFRS S1 and S2, require disclosure of governance arrangements, risk management processes, and climate-related metrics, with implementation commencing in 2025 [81,83,84]. This regulatory convergence elevates sustainability performance from a voluntary reporting exercise to a compliance obligation. For manufacturing organisations, sustainability risks embedded within production systems now carry direct governance, financial, and strategic implications.

However, existing ESG-oriented frameworks, including those developed under ISSB and GRI architectures, were not designed to capture sustainability outcomes associated with emerging technologies such as circular additive manufacturing or PC-PLA valorisation pathways [85]. For manufacturing, these reporting requirements increase the visibility of sustainability-related risks embedded within production systems, including material sourcing, feedstock quality control, contamination management, workforce capability, and end-use reliability.

In this study, ESG is applied as an analytical lens to interpret how engineering decisions in circular additive manufacturing shape environmental, social, and governance-related risk exposure. While disclosure frameworks provide contextual relevance, the analytical emphasis remains on governance mechanisms embedded within PC-PLA-based FFF systems. The absence of a methodological bridge between LCSA outputs and ESG-oriented risk governance represents a critical research gap. Addressing this gap underpins the analytical framework advanced in the present study and supports the integration of engineering-level sustainability performance with organisational decision-making in the Australian manufacturing context.

3. Methodology

3.1. Research Design and Methodological Logic

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

This study adopts a framework-development and analytical methodology to examine how empirically validated LCSA evidence from PC-PLA-based FFF can be reinterpreted through a governance implications assessment lens. The objective is to determine how engineering-level sustainability performance translates into decision-relevant risks, organisational accountability, and future-oriented governance requirements.

The design addresses a methodological gap in which LCSA findings are typically presented as descriptive outcomes but remain weakly connected to organisational decision-making and governance practice. To ensure ESG implications are grounded in verified engineering behaviour and system-level scalability, the research follows a four-stage analytical structure (Figure 4), each aligned with a distinct decision-level question addressed in the Results section:

- **Evidence consolidation**, establishing a functionally valid and sustainability-balanced reference system integrating mechanical performance, service life, and LCSA results.
- **ESG-oriented translation**, reframing LCSA indicators as organisational risk and performance signals.
- **Circularity characterisation**, evaluating the depth and limits of material loop closure beyond recycled-content claims.
- **Waste diversion potential**, assessing whether process-level gains remain system-relevant under real-world waste governance and infrastructure constraints.

This staged design ensures ESG implications are derived from experimentally validated performance, quantitative sustainability evidence, and explicit system constraints rather than isolated indicators.

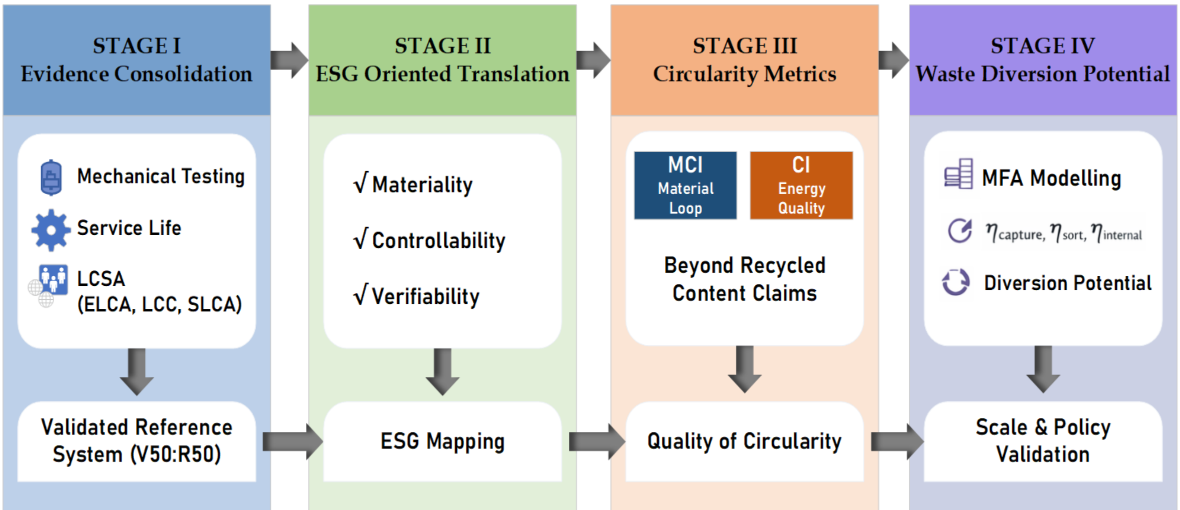


Figure 4. Methodology for translating engineering-level sustainability into ESG insights.

3.2. STAGE I – Evidence Consolidation and Baseline Definition

Stage I establishes a functionally validated and sustainability-balanced reference system by integrating mechanical performance, service life, and LCSA results. It ensures that ESG interpretation is grounded in verified engineering performance and avoids non-functional material configurations.

3.2.1. System Definition and Boundary Conventions

The assessed system is circular FFF enabled by PC-PLA. The life-cycle stages considered include post-consumer PLA waste collection and sorting, preprocessing and size reduction, filament extrusion, FFF printing, and post-processing, as well as the use phase of the printed component. The functional unit (FU) is defined as: One FFF-printed gear capable of transmitting mechanical power over its experimentally measured service life under defined operating conditions.

 doi:10.20944/preprints202603.1193.v1

A fixed garbage-to-gear (g2g) system boundary is applied across all analyses to maintain consistency. Within this fixed boundary, results are interpreted under two complementary scopes:

- *Process scope*, focusing on extrusion and FFF printing for operational benchmarking.
- *Value-chain scope*, incorporating upstream waste management and downstream end-of-life assumptions to support circularity and ESG-relevant interpretation.

All calculations are performed using the same life-cycle inventory (LCI). LCI was developed in SimaPro 9.6.0.1 using datasets primarily obtained from Ecoinvent 3.2 and AusLCI v2.44. Differences between scopes arise solely at the level of interpretation, not from changes in system boundaries or allocation rules.

3.2.2. Empirical and Life Cycle Evidence Inputs

The analytical framework builds on previously published and peer-reviewed experimental and LCSA studies conducted by the authors, providing validated datasets on mechanical performance, service life, environmental impacts, economic performance, and social indicators for virgin PLA, recycled PLA, and their blends. For ESG translation, the V50:R50 blend is selected as the reference system. This choice is methodologically deliberate. Prior findings show that V50:R50 provides the most balanced compromise between:

- environmental improvement through virgin material substitution,
- acceptable mechanical durability and service life, and
- economic feasibility when normalised by functional performance.

Fully virgin (V100:R0) and fully recycled (V0:R100) configurations are retained for comparison but are not used as governance baselines. Extreme compositions can distort ESG interpretation due to non-representative durability or cost behaviour. Anchoring the analysis to V50:R50 ensures that ESG implications reflect deployable and transitional manufacturing configurations rather than idealised or technically marginal cases.

3.2.3. Life Cycle Sustainability Assessment Structure

LCSA is employed to integrate environmental, economic, and social dimensions using a harmonised functional unit and a consistent system boundary. In this study, LCSA functions as a quantitative evidence base for subsequent ESG-oriented interpretation, rather than as an endpoint assessment.

A total of 16 key performance indicators (KPIs) were identified through expert consultation to capture decision-relevant sustainability attributes of circular FFF systems (Table A1). These include 10 environmental indicators, 3 economic indicators based on service-life-normalised life cycle costing, and 3 social indicators addressing employment, training intensity, and quality-of-life conditions associated with decentralised recycling and manufacturing.

For governance interpretation, KPIs are structured hierarchically and aggregated into headline performance indicators. Weighting is derived from expert judgement using a Likert-scale approach. Performance is assessed using a gap-to-threshold framework, enabling the identification of residual risks, trade-offs, and improvement priorities rather than masking weaknesses through aggregated scores.

3.3. STAGE II – Governance Implications Assessment of LCSA Evidence

Stage II reinterprets consolidated LCSA outputs as organisational risk, performance, and governance signals. This stage addresses the methodological gap between process-level sustainability metrics and ESG-relevant decision-making by applying materiality, controllability, and verifiability criteria.

3.3.1. ESG Implications and Governance Controls Mapping of LCSA Outputs

 doi:10.20944/preprints202603.1193.v1

ESG implications are derived by interpreting LCSA indicators through an organisational decision-making lens. This step does not generate ESG scores or claim compliance with disclosure standards. Instead, it provides a structured governance analysis linking verified LCSA performance to operational consequences and control requirements within manufacturing organisations.

Here, ESG implications are defined as decision-relevant consequences arising from adopting PC PLA feedstock in FFF systems, evidenced through changes in environmental performance, social conditions, and governance control needs. The focus remains on material, controllable, and verifiable outcomes directly attributable to PC PLA use, rather than a general assessment of corporate ESG performance.

- *Environmental indicators* are interpreted as efficiency and transition-risk signals, including avoided emissions, reduced energy dependency, and lower reliance on virgin materials.
- Social indicators are interpreted in terms of employment intensity, workforce skill requirements, and workplace risk exposure in decentralised production systems.
- Economic indicators are framed as cost-stability and durability-related risk signals rather than cost-minimisation metrics.
- Governance implications are identified by linking performance gaps to required organisational controls, including traceability systems, quality assurance procedures, training protocols, and process consistency mechanisms.

To operationalise this interpretation, LCSA indicators are mapped to ESG-relevant decision domains, decision implications, and primary governance controls (Table 1). The ESG pillars serve only as an organising structure for decision relevance, ensuring each indicator is explicitly tied to a controllable organisational lever and an auditable evidence base.

Table 1. Mapping of LCSA evidence to ESG decision pillars and relevance.

LCSA indicator	Measurement unit (functional unit basis)	ESG pillar	ESG-relevant decision domain	Decision implications for manufacturing governance	Primary governance control or organisational lever
Global Warming Potential (GWP)	kg CO_2-eq per functional unit	Environmental (E)	Performance metrics and transition risk	Supports assessment of decarbonisation performance and alignment with emissions-reduction objectives.	Energy metering, emissions accounting, and material substitution approval rules.
Cumulative Energy Demand (CED)	MJ per functional unit	Environmental (E)	Strategic energy management	Informs energy efficiency performance and operational exposure to energy price volatility.	Energy procurement strategy and machine utilisation scheduling controls.
Abiotic Resource Depletion (ARD)	kg Sb-eq per functional unit	Environmental (E)	Supply risk and material dependency	Indicates dependency on virgin material inputs and exposure to upstream	Recycled-content specifications and supplier qualification risk screening.

				supply disruption.	
Life Cycle Costing (LCC)	AUD per functional unit or per service hour	Economic (E) and Governance (G)	Investment and cost stability	Evaluates economic feasibility and durability-related cost stability under operational conditions.	Capital approval thresholds and total-cost-of-ownership decision rules.
Local employment and training	Jobs per tonne processed; training hours	Social (S)	Workforce capability and social value	Captures employment intensity and skill formation requirements in decentralised manufacturing.	Workforce training, micro-credentials, and health and safety protocols.
Material Circularity Indicator (MCI) and Circularity Index (CI)	Dimensionless index	Environmental (E) and Governance (G)	Resource efficiency and transparency	Substantiates circularity performance and enables consistent internal benchmarking.	Material flow documentation and waste tracking mass-balance verification.

3.4. STAGE III – Circularity Characterisation Beyond Recycled Content

Stage III evaluates the quality and limits of circular performance by supplementing LCSA results with material circularity metrics. This stage is necessary to distinguish between recycled-content claims and actual material loop closure and energy-quality performance.

3.4.1. Integration of Circularity Metrics

To complement LCSA and support transparent resource-efficiency interpretation, two circularity metrics are incorporated: the MCI and the CI. These metrics address a recognised limitation of sustainability assessments in which recycled content alone is often used as a proxy for circularity, without explicitly accounting for material losses, recovery efficiency, product utility, or the energy implications of secondary material production [86,87].

1. The MCI follows the methodology of the Ellen MacArthur Foundation [88] and quantifies material loop closure by integrating virgin and recycled inputs, unrecoverable waste across production and end of life stages, and lifetime normalisation. It is expressed as:

$$MCI = 1 - LFI \cdot F(x) \quad \text{(i)}$$

where LFI is the Linear Flow Index derived from virgin input and unrecoverable waste, and F(x) is a utility adjustment factor reflecting product lifetime and functional use relative to industry averages. The MCI ranges from 0 (fully linear) to 1 (fully circular), enabling standardised comparisons across product configurations.

2. The Circularity Index (CI) extends material-based circularity assessment by incorporating the relative energy benefit of secondary material production compared with primary production. This energy-adjusted perspective captures an important sustainability dimension not addressed by mass-based indicators alone [87,89]. The CI is calculated as:

 doi:10.20944/preprints202603.1193.v1

$$CI = \alpha \times \beta \quad \text{(ii)}$$

where α represents the fraction of recovered material and β represents the relative energy benefit of secondary production. The CI ranges from 0 for a fully linear system to 1 for a fully circular system characterised by complete material recovery and maximum energy advantage.

In this study, these circularity metrics function as interpretive support tools rather than ESG indicators. They contextualise environmental and governance interpretation by distinguishing between partial, transitional, and near closed loop manufacturing configurations. Full parameter definitions, assumptions, and step by step calculations are provided in the **Appendix** to ensure transparency and reproducibility without overburdening the main text.

3.5. STAGE IV – Waste Diversion Potential

Stage IV tests whether process-level sustainability improvements remain system-relevant at scale when constrained by real-world waste governance, collection, and sorting infrastructure. This stage prevents over-claiming circularity potential and establishes realistic boundaries for ESG and policy interpretation.

3.5.1. Material Flow Modelling of PLA Waste Diversion

A material flow analysis model is developed to estimate the upper bound diversion potential of post consumer PLA waste into recycled PLA based FFF. ESG relevance requires not only technical feasibility but also measurable system level impact under infrastructure constraints. The MFA therefore functions as a validation step to avoid overstating circularity outcomes.

The model follows a mass balance recovery framework in which diverted material is calculated as a fraction of total PLA waste generation. Diversion is constrained by sequential recovery efficiencies across collection, sorting, reprocessing, filament extrusion, and FFF printing. Diversion is defined as [90]:

$$Diversion\% = \frac{M_{FFF,rPLA}}{M_{PLA,waste}} \times 100 \quad \text{(iii)}$$

Where $M_{PLA,waste}$ is the annual global PLA waste generation (tonnes/year) and $M_{FFF,rPLA}$ is the annual mass of PC-PLA that can be processed into filament and consumed in FFF printing (tonnes/year).

Estimation of Annual PLA Waste Generation: Annual PLA waste generation is estimated using a production-to-waste conversion approach, consistent with global plastics flow modelling [91].

$$M_{PLA,waste} = M_{PLA,market} \times \emptyset_{pack} \times \emptyset_{waste} \quad \text{(iv)}$$

where $M_{PLA,market}$ is global PLA production or market volume, $\emptyset_{pack}$ is the share of PLA used in short-lived applications (proxy: packaging and disposables), and $\emptyset_{waste}$ is the fraction reaching end-of-life within the year. The use of packaging as a proxy for short-lived PLA applications is justified by market data indicating that packaging is the dominant bioplastics application segment, with typical service lives of less than one year [92].

Modelling PC-PLA Feedstock Availability: The recoverable mass of PC-PLA available for FFF is constrained by stage-specific yield efficiencies, expressed as a chained recovery formulation

$$M_{FFF,rPLA} = M_{PLA,waste} \times \eta_{capture} \times \eta_{sort} \times \eta_{reprocess} \times \eta_{filament} \times \eta_{print} \quad \text{(v)}$$

where $\eta_{capture}$ is the fraction of PLA waste collected; η_{sort} is the fraction correctly separated as PLA; $\eta_{reprocess}$ is the fraction retained after washing, shredding, and melt filtration; $\eta_{filament}$ is the extrusion yield into printable filament; and η_{print} is the fraction successfully converted into printed products (accounting for failures and support waste). This chained yield formulation follows established MFA practice, representing total recovery as the product of sequential process efficiencies. Explicit parameterisation of collection, sorting, and processing yields enables

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

identification of dominant leverage points governing system scalability. It differentiates technological constraints from governance controlled limitations, directly informing organisational strategy and policy intervention.

3.6. Methodological Contribution

Together, these methodological components establish a replicable and auditable pathway for translating engineering-level sustainability evidence into ESG-relevant insights. By aligning experimental validation, life cycle assessment, circularity metrics, and waste diversion potential within a fixed boundary, the framework ensures that ESG implications are earned through evidence, bounded by real constraints, and directly aligned with manufacturing decision contexts.

4. Results

4.1. Stage I – Evidence Consolidation and Baseline Performance Definition

This stage consolidates experimentally validated evidence of engineering performance and life cycle sustainability to establish a consistent empirical baseline for subsequent ESG translation. Mechanical performance, service life, and LCSA results are evaluated within *g2g* system boundary to ensure boundary-consistent interpretation and governance relevance.

4.1.1. Consolidation of Engineering and Life Cycle Evidence

The mixed-methods framework integrates process-level operational engineering data with full life cycle sustainability assessment results to define a validated baseline for circular FFF. Unlike proxy-based sustainability studies, the consolidated dataset spans mechanical durability, measured service life, and environmental, economic, and social impacts. This integration enables ESG translation grounded in experimentally observed manufacturing behaviour.

Mechanical testing and service-life measurements confirm the V50:R50 configuration as a technically viable and sustainability-balanced reference system. The blend achieved a tensile strength of approximately 52.8 MPa and a measured service life of 62 hours under controlled back-to-back gear testing at 1000 rpm and 1.5 Nm. These results demonstrate functional adequacy for power transmission applications. The selection of V50:R50 reflects balanced durability, environmental improvement, and economic feasibility rather than maximising recycled content alone. This balance provides a realistic basis for linking life cycle impacts and costs to an experimentally validated use phase, avoiding reliance on idealised material configurations.

An expert-validated KPI set comprising 16 indicators ensures that ESG-relevant outputs remain directly traceable to empirical LCSA results. Accordingly, the proposed framework operates as an evidence-anchored extension of LCSA rather than a parallel normative assessment layer.

4.1.2. System Boundary Structuring and Scope-Dependent Results

The system boundary follows a g2g life cycle, encompassing post-consumer PLA collection and preprocessing, filament extrusion, FFF fabrication, the use phase, and end-of-life assumptions. This boundary remains constant across all analyses to ensure that sustainability outcomes arise from material composition and service-life performance rather than boundary variation.

Within this fixed boundary, results are interpreted through two complementary views to support ESG translation without boundary mixing. The core performance view emphasises manufacturing and use-phase efficiency to inform engineering and operational decision-making. The extended circularity view interprets the same inventory to capture waste diversion, resource substitution, social value creation, and governance-related risk exposure.

Importantly, environmental and economic calculations remain unchanged across both views; only their interpretive emphasis differs. This structure enables transparent translation of LCSA evidence into ESG-relevant insights while preserving methodological consistency. The resulting interpretive views are summarised in Table 2.

 doi:10.20944/preprints202603.1193.v1

Table 2. Interpretive scopes applied within the g2g system boundary and resulting sustainability insights.

Aspect (within g2g)	Core Performance Interpretive View (g2g system)	Extended Circularity Interpretive View (g2g system)
System boundary	Garbage-to-gear	Garbage-to-gear
Life cycle stages included	Waste preprocessing, extrusion, FFF printing, use phase, and end-of-life assumptions	Waste preprocessing, extrusion, FFF printing, use phase, and end-of-life assumptions
Analytical emphasis	Manufacturing and use efficiency	Circularity and value-chain effects
Environmental interpretation	Highlights manufacturing and use-phase energy and material efficiency	Highlights virgin material substitution and resource retention
Economic interpretation	Equipment, energy, use-phase costs	Same LCC interpreted with circular value
Social interpretation	Limited visibility of upstream and reverse logistics impacts	Explicit visibility of local employment and skill development
Circularity interpretation	Implicit through recycled input	Explicit through diversion, recovery, and circularity indicators
ESG relevance	Operational E-pillar and cost metrics	Integrated environmental, social, and governance signals

Note: Both views derive from the same functional unit and inventory; differences arise from interpretive framing rather than boundary modification.

4.1.3. Environmental Impact Results

Environmental performance was evaluated using a comprehensive ELCA within the g2g system boundary (Islam et al., 2025). The assessment covered ten midpoint impact categories, with particular emphasis on global warming potential (GWP), cumulative energy demand (CED), and abiotic resource depletion (ARD), as these indicators received the highest expert-assigned weights in the LCSA framework (Islam et al., 2025). The life cycle inventory was developed in SimaPro 9.6.0.1 using Ecoinvent 3.2 and AusLCI v2.44 databases.

Across all material configurations, increasing PC-PLA content resulted in a consistent and monotonic reduction in environmental burdens across nearly all midpoint categories (Figure 5). Compared with virgin PLA (V100:R0), the V50:R50 blend reduced GWP from 67 to 22 kg CO_2-eq., representing approximately a 57% reduction. Over the same transition, CED decreased from 39 to 19.6 MJ (approximately 40%), while ARD declined by more than 95%.

Terrestrial acidification decreased from 0.0211 to 0.00258 kg SO_2-eq., and eutrophication potential declined substantially. Water use and land use also showed marked reductions relative to virgin PLA. These improvements are primarily attributable to avoided virgin PLA production and reduced upstream fossil resource extraction, while FFF electricity consumption remained broadly similar across blends [93,94].

Fully recycled PLA (V0:R100) achieved the lowest absolute environmental impacts across most categories, with GWP reduced to 1.12 kg CO_2-eq. and CED to 12.8 MJ. However, freshwater ecotoxicity and human toxicity showed comparatively smaller variations across blends, indicating that toxicity-related impacts are less sensitive to recycled content than climate- and resource-related indicators [95].

When impacts were normalised to equivalent functional performance, the environmental advantage of V0:R100 was moderated by its shorter service life, which increases replacement frequency over a given operating period. In contrast, the V50:R50 blend maintained substantially longer durability while achieving significant reductions across key environmental indicators.

Overall, these results confirm that material substitution is the dominant environmental leverage point in FFF-based gear production, while service life plays a critical moderating role in determining net environmental performance. Partial substitution of virgin PLA with post-consumer recycled PLA, therefore, enables substantial environmental improvement without incurring the durability penalties observed in PC-PLA-rich systems.

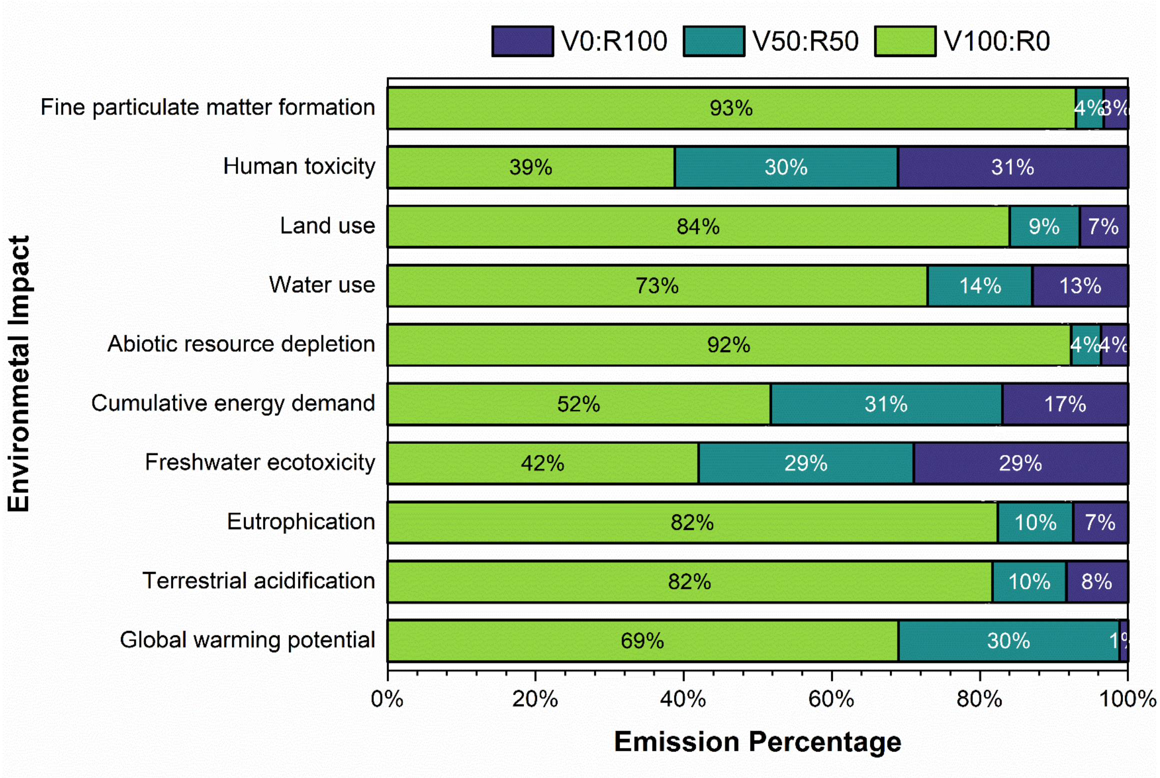


Figure 5. Environmental impact assessment results of FFF-printed PLA gears.

4.1.4 Economic Performance Results

Economic performance was evaluated using a detailed LCC framework aligned with the ELCA system boundary and functional unit. The analysis incorporated production costs, operational costs over the measured service life, and supplementary economic indicators, including net benefit (NB) and carbon tax saving (CTS).

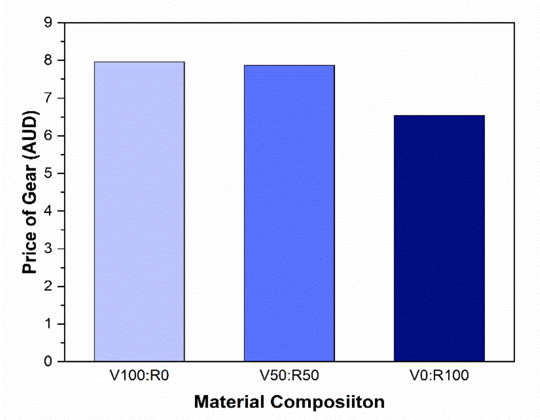
At the production stage, increasing recycled content resulted in a clear reduction in material costs. Material expenditure decreased from AUD 0.48 per gear for V100:R0 to AUD 0.24 for V50:R50, and further to zero for V0:R100. Electricity and labour costs increased modestly with higher recycled content, reflecting additional preprocessing and extrusion variability associated with PC-PLA-rich blends [96].

When expressed as the annuitised unit price of gear (PG), differences between material systems were comparatively small (Figure 6). Relative to AUD 7.95 for V100:R0, the V50:R50 blend showed a marginal reduction, while V0:R100 achieved a 17.7% reduction. These results indicate that recycled and blended systems do not incur a production-stage price penalty and may, in fact, offer modest cost advantages at the point of manufacture [27,97].

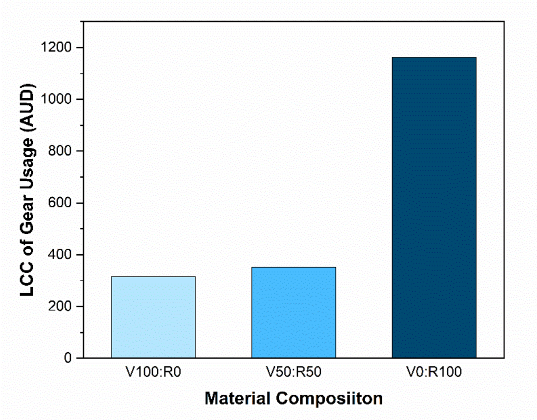
In contrast, service-life-normalised LCC showed substantially greater variation. Virgin PLA gears achieved the lowest LCC at AUD 314.54 per gear, reflecting superior durability and low replacement frequency. Relative to this baseline, the V50:R50 blend exhibited an 11.7% increase, attributable to moderately reduced service life. Fully recycled PLA gears exhibited a 269.6% increase in LCC, driven by significantly reduced durability and frequent replacement requirements.

 doi:10.20944/preprints202603.1193.v1

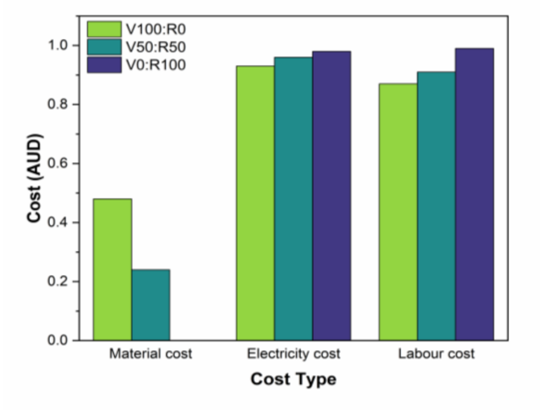
Net benefit analysis reinforced this pattern. Although the V0:R100 system achieved the largest reductions in material and energy costs at the production stage, these savings were outweighed by frequent replacement requirements at the functional level. In contrast, the V50:R50 blend achieved a more favourable balance between reduced material expenditure and acceptable operational durability. Carbon tax saving results further highlighted potential economic advantages of recycled and blended systems under carbon pricing scenarios.



(a)



(b)



(c)

Figure 6. (a) Annuitized production price (PG), (b) service-life-based LCC of FFF-printed PLA gears and (c) Operational cost of manufacturing gears.

4.1.5. Social Impact Results

Social performance was assessed using a SLCA framework following UNEP/SETAC guidelines and the indicator set defined through expert consultation. Three social indicators were evaluated: local employment, quality of life, and workplace training and skill development.

Relative to vPLA-based production, systems incorporating PC-PLA demonstrated improved social performance. The V50:R50 configuration showed higher local employment potential due to the additional labour required for waste collection, sorting, shredding, extrusion, and quality assurance activities. These processes are more labour-intensive than virgin polymer supply chains, which are typically centralised and capital-intensive [38,98].

Quality-of-life scores reflected moderate to positive working conditions across all configurations, with slightly higher scores observed for blended systems. This trend is attributed to increased technical engagement, skill utilisation, and task diversity associated with decentralised recycling and FFF-based production. However, the results also indicate that quality-of-life outcomes remain highly dependent on organisational practices, including workplace safety measures, ventilation, and job structure, rather than material choice alone [38,99].

Although recycled and blended systems demonstrated higher employment potential and training intensity, social benefits were not automatic. Quality-of-life and skill development outcomes remained strongly dependent on governance practices, workplace safety, and organisational implementation [100]. These results indicate that PC-PLA integration creates social value potential, but realising this potential requires deliberate governance and workforce management.

4.2. Stage II – ESG-Oriented Translation and Governance Implications

This stage interprets consolidated life cycle sustainability evidence as governance-relevant decision signals rather than as descriptive sustainability outcomes. Using the gap-to-threshold framework, the analysis identifies environmental, economic, and social risk hotspots and links them explicitly to organisational control requirements and future-oriented governance pressures. Stage II demonstrates how experimentally validated performance evidence can inform governance readiness, risk anticipation, and decision accountability in manufacturing systems facing escalating climate, regulatory, and resource constraints, thereby enabling anticipatory governance responses to sustainability pressures that are not yet fully formalised into regulatory or reporting requirements.

4.2.1. KPI Gap Outcomes Informing Governance Readiness

The application of the KPI gap-to-threshold framework produced differentiated and quantitatively interpretable sustainability outcomes across environmental, economic, and social dimensions. These outcomes are grounded in previously published LCSA results and are reformulated here to support governance-oriented prioritisation and forward-looking sustainability risk interpretation within the fixed garbage-to-gear system boundary.

Although multiple PC-PLA–vPLA blends were assessed in the underlying LCSA, the V50:R50 configuration is adopted as the governance reference system. Comparative results indicate that this blend achieved the lowest overall sustainability gap by balancing environmental improvement, economic feasibility, and mechanically validated durability. Virgin-dominant blends showed weaker circularity and greater material dependency, whereas PC-PLA-rich systems achieved stronger environmental gains but at the expense of service life and cost stability. V50:R50 therefore provides a technically robust and decision-relevant baseline for governance capability and risk exposure analysis.

- ***Environmental Resilience (E/G):*** The V50:R50 system exhibited the smallest aggregated environmental gap (−0.44), indicating near-threshold performance across key indicators including global warming potential, cumulative energy demand, and abiotic resource depletion. Partial substitution of vPLA with post-consumer PC-PLA delivered substantial environmental gains under a service-life-based functional unit, with material substitution representing the dominant leverage point. From a governance perspective, this near-threshold position signals early alignment with climate accountability pressures, including upstream Scope 3 emissions management, embodied carbon disclosure expectations, and potential carbon border adjustment mechanisms [101,102]. Demonstrable reductions in upstream material emissions therefore function as a governance-enabling capability aligned with broader risk domains such as natural capital preservation and critical resource security [103].
- ***Economic and Operational Risk (Ec/G):*** The V50:R50 configuration exhibited a residual economic gap of −1.73, lower than the virgin baseline (−2.23) and markedly smaller than PC-PLA-rich systems (V25:R75: −3.01; V0:R100: −2.72). Reduced material costs partially offset

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

preprocessing requirements, filament variability, and moderate durability penalties, although durability remains the primary contributor to the residual gap. From a governance standpoint, this gap reflects constraints in process standardisation, quality control, and durability assurance that affect scalability and repeatability [104]. Broader recycling assessments show that lower-quality recycled feedstock often requires additional sorting and quality assurance, increasing operational expenditure relative to virgin feedstock [105]. These findings identify management priorities required to stabilise recycled-feedstock advantages rather than economic infeasibility.

- **Social Licence and Accountability (S/G):** The social dimension for V50:R50 exhibited an intermediate aggregated gap (−1.88), lower than both the virgin baseline (−2.64) and PC-PLA-rich configurations. SLCA results indicate that partial incorporation of PC-PLA supports local employment and decentralised recycling activities [106]. However, the persistence of a residual gap indicates that these benefits are not yet institutionalised. Governance limitations relate to formal training systems, occupational health and safety structures, and workforce standardisation [107,108]. Without codified procedures and auditable labour practices, employment intensity does not automatically translate into durable social value [109]. The observed gap therefore highlights organisational control measures required to ensure that socially positive circular manufacturing outcomes are repeatable and accountable.
- **Synthesis of Governance Benefits:** Aggregated across all dimensions, the V50:R50 configuration achieved the lowest overall sustainability gap (−1.35), outperforming both virgin-only and fully recycled systems. The results indicate a typical progression in circular FFF: environmental gains emerge through material substitution, economic stability strengthens with improved durability and preprocessing control, and social outcomes remain contingent on governance structures. Adoption of V50:R50 therefore provides balanced sustainability performance while strengthening organisational capability to manage emerging sustainability risk domains, including circularity performance expectations, resource dependency exposure, Scope 3 emissions accountability, and resilience-oriented governance indicators, prior to formalisation through regulation or mandatory disclosure requirements.

4.2.3. ESG-Oriented Interpretation of LCSA Results

This section reports the results obtained from applying the integrated LCSA-to-ESG interpretive framework to circular FFF using recycled PLA. The results demonstrate how quantitative LCSA evidence is translated into governance-relevant decision signals across environmental and social domains, how governance-related risk exposure and organisational control requirements are identified through the interpretation of performance gaps, and how the strategic scale and system relevance of the circular FFF pathway are examined through waste diversion potential.

1. Environmental (E) and Resource Efficiency Measurements

Application of the interpretive framework to the LCSA evidence confirms that partial substitution of vPLA with post-consumer PC-PLA yields substantial and quantifiable environmental benefits that are relevant for governance decision-making across environmental domains, rather than constituting disclosure or reporting outputs. For the V50:R50 blend, environmental improvements are primarily driven by the avoided production of primary polymer rather than changes in FFF electricity demand, reinforcing material substitution as the dominant environmental leverage point.

The LCSA quantified the Global Warming Potential (GWP) of vPLA (V100:R0) at 62.80 kg CO_2-eq per kg of material, while the V50:R50 blend exhibited a reduced GWP of 15.60 kg CO_2-eq per kg. This difference is expressed as a specific avoided-emissions metric on a per-unit basis:

$$E_{GHG,Avoided} = GWP_{V100:R0} - GWP_{V50:R50}$$

$$E_{GHG,Avoided} = 39.8 - 19.2 = 20.6\ kg\ CO2eq./kg$$

Governance Signal: This calculated value represents the greenhouse gas emissions avoided per kilogram of product resulting from the adoption of recycled feedstock, reflecting reduced upstream

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

emissions associated with primary polymer production. As a governance-relevant climate risk signal, it supports organisational decision-making related to decarbonisation strategies and transition risk exposure by quantifying the mitigation contribution of recycled feedstock substitution, without implying formal emissions reporting.

In parallel, reductions in cumulative energy demand and abiotic resource depletion for the V50:R50 system indicate lower dependency on fossil energy inputs and virgin material extraction, strengthening the evidence base for procurement-led resource risk management and material security considerations.

2. Economic and Social Risk Quantification

The application of the gap-to-threshold logic to economic and social indicators reveals distinct performance asymmetries that are critical for interpreting governance-relevant risk exposure. Rather than indicating system failure, these residual gaps identify structural vulnerabilities that must be managed through organisational controls and operational decision-making.

- **Economic Risk: Life Cycle Cost and Preprocessing Consequences:** The life-cycle costing results show that preprocessing post-consumer PLA results in higher operational costs than virgin PLA, primarily due to labour-intensive sorting and handling. The normalised economic gap score for the V50:R50 system (−1.73) reflects this cost structure.

Governance Signal: When interpreted as an ESG-relevant governance signal, this result functions as a risk indicator rather than a performance score. Specifically, it indexes exposure to labour-intensive preprocessing risk, indicating vulnerability to wage inflation, workforce availability constraints, and operational variability. This finding, therefore, justifies governance responses focused on automation, process stabilisation, and capital investment, rather than reversal of recycled material adoption.

- **Social Risk: Employment Creation and Training Trade-off:** The social life cycle assessment indicates that integrating PC-PLA into FFF systems can generate positive local employment outcomes through decentralised waste collection, manual sorting, shredding, extrusion supervision, and quality control activities. These processes are inherently more labour-intensive than conventional virgin polymer supply chains, which are typically centralised and capital-intensive [110].

Labour intensity was estimated using a transparent, activity-based approach. In the absence of primary labour inventory data reporting labour-hours per unit mass for decentralised recycling systems, a conservative, scenario-based assumption was applied to estimate labour intensity associated with circular FFF operations, consistent with SLCA guidelines [111]. Based on an activity-based representation of small-scale mechanical recycling workflows, processing 0.1 tonnes of post-consumer PLA was assumed to require 0.25 job-months of local labour, corresponding to approximately 40 labour-hours distributed across collection, manual sorting, extrusion supervision, and quality control activities. Normalising labour input by material throughput yields a local employment intensity of:

$$Local\ employment\ intensity = \frac{0.25\ job - months}{0.1\ tonnes} = 2.5\ jobs - months\ per\ tonne$$

This value represents labour intensity rather than permanent job creation and is intended to illustrate the social engagement potential of decentralised CM rather than predict employment outcomes at scale.

The resulting employment intensity confirms that PC-PLA-based FFF can generate local employment opportunities through material recovery and processing activities. However, the V50:R50 blend simultaneously exhibited a lower score for workplace training and formal skill development, indicating a governance-relevant social risk rather than uniformly positive social performance.

Governance Signal: From an ESG perspective, this trade-off is critical. Elevated labour intensity without structured training, certification, and safety frameworks risks undermining long-term workforce wellbeing and ethical labour conditions. Accordingly, social value creation in circular FFF is shown to be governance-contingent, requiring auditable training targets, formalised workforce development programmes, and occupational safety controls to ensure that employment benefits are sustainable and responsibly managed.

4.2.3. Governance Risk Signals in LCSA-Derived ESG Performance

An ESG-oriented interpretation of the LCSA results indicates that governance serves as a mediating factor between quantified sustainability performance and its relevance for ESG decision-making in circular FFF systems. While environmental indicators for the V50:R50 configuration demonstrate strong, verifiable performance, the extent to which these outcomes translate into decision-relevant ESG information depends on the presence of organisational controls, accountability mechanisms, and verification practices.

From an environmental perspective, the availability of life-cycle-based metrics, such as avoided greenhouse gas emissions, enables internal monitoring and comparative assessment. However, in the absence of formally defined targets, escalation procedures, and independent verification, these metrics remain descriptive rather than decision-enforceable [112]. Environmental performance is therefore technically robust but governance-contingent in terms of its uptake, credibility, enforceability, and disclosure [113].

Social outcomes exhibit stronger dependence on governance [114]. Although PC-PLA-based FFF have the potential to generate local employment opportunities through decentralised waste collection and preprocessing, persistent gaps in formal training and skill development indicate that social value creation is not automatically realised. Without structured workforce development programmes, safety protocols, and auditable labour practices, employment benefits remain inconsistent and vulnerable to ethical and reputational risk [115].

Economic results further reinforce the governance dimension. Life cycle costing identifies preprocessing intensity and reduced service life as dominant contributors to residual cost gaps [75]. These findings shift the locus of improvement from material selection to governance decisions related to investment, automation, and process control, highlighting that economic viability in circular FFF systems is governed by organisational capability rather than feedstock choice alone [47].

Governance Signal: Collectively, these findings confirm that ESG relevance in circular FFF systems is not determined solely by sustainability performance, but by the extent to which performance evidence is embedded within organisational decision-making structures. Governance, therefore, functions as an enabling condition for credible, scalable, and verifiable ESG outcomes, rather than as a standalone single performance metric.

4.3. STAGE III – Circularity Metrics Integrated with LCA

This stage reports supplementary circularity indicators that complement the life-cycle assessment by quantifying material-flow circularity and energy-adjusted circular performance for the V50:R50 reference system. Circularity metrics are evaluated within the same g2g system boundary and are interpreted as diagnostic indicators rather than standalone sustainability claims.

4.3.1. Material Circularity Indicator (MCI) Results

The Material Circularity Indicator was applied to quantify material flow circularity for the V50:R50 reference system within the garbage-to-gear framework, following the methodology of the Ellen MacArthur Foundation (EMF, 2019). [88]The calculation incorporates recycled input, production-stage losses, unrecoverable waste, and end-of-life recycling efficiency, ensuring consistency with the life cycle inventory underpinning mechanical testing, LCC, and KPI gap analysis. Full parameter definitions and calculation steps are summarised in Table A2.

The V50:R50 configuration is defined at the filament inlet as 50% virgin PLA pellets and 50% shredded post-consumer PLA cups. For a functional output of 1,000 kg of printed gears, total material

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

demand at the blend inlet was calculated as 1,074 kg, based on filament extrusion and FFF printing yields of 0.98 and 0.95, respectively. These yield values reflect typical purge, start-up, support, and failed-print losses in additive manufacturing.

End-of-life was modelled as landfill-dominant disposal, reflecting the absence of dedicated take-back schemes for small polymer gears. A recycling collection rate of 0.15 was adopted based on Australian plastics recovery statistics, while recycling process efficiency was assumed to be 0.833 to represent realistic mechanical recycling yields, consistent with EMF guidance [88,116]. This produced an effective end-of-life recycling efficiency of 0.125.

Under these assumptions, unrecovered end-of-life material (W_0) totalled 850.0 kg, while waste generated during end-of-life recycling (W_C) and recycled feedstock production (W_f) amounted to 25.1 kg and 59.7 kg, respectively. Because the experimentally measured gear service life of 62 hours matched the reference lifetime, the utility adjustment was neutral, $F(x)$ = 0.9. Substitution into the EMF Linear Flow Index yielded an valuw of 0.709 and a corresponding MCI value of 0.362.

This value indicates moderate material circularity, characteristic of a transitional configuration in which upstream substitution of virgin material is constrained by limited end-of-life recovery. The result aligns with prior studies showing that recycled input alone does not guarantee high circularity without effective recovery pathways [89,117]. It also reflects established interpretations of circularity metrics recognising that partial virgin input may be necessary to maintain durability and functional performance [88,118].

4.3.2. Circularity Index (CI) Results

The CI integrates material recovery with the relative energy performance of secondary versus primary material production. Energy inputs were derived from cumulative energy demand values obtained from the life cycle inventory, considering material preparation and filament production while excluding printing energy. The cumulative energy demand for the secondary route was 23.6 MJ/kg, compared with 51.0 MJ/kg for the primary virgin PLA route, consistent with reported energy intensities for recycled and virgin PLA production [119,120].

These values yielded an energy benefit factor (β) of 0.537. Recovered recycled material at end-of-life was calculated as 125.0 kg, corresponding to a recovered material fraction (α) of 0.0625 on a product mass basis. Combining these terms resulted in a CI value of 0.0336.

The low CI highlights that, under landfill-dominant end-of-life conditions, the energy advantages of secondary PLA production are insufficient to compensate for weak material recovery, reinforcing the role of recovery infrastructure in determining circular performance [87–89].

4.3.3. Interpretation and Complementarity with LCA Results

Together, the MCI and CI results demonstrate that the circular performance of a garbage-to-gear system is driven by both material composition and process efficiency, rather than recycled content alone. For the V50:R50 configuration, circularity outcomes reflect a deliberate balance between circular material use and functional performance, supported by measured mechanical durability and service life.

The two indicators are mutually reinforcing rather than overlapping. The MCI captures overall material retention and loss across the system, while the CI highlights the energetic quality of the recycling pathway. When interpreted alongside conventional LCA indicators such as global warming potential and cumulative energy demand, these metrics strengthen the evidence base for resource efficiency and circularity claims while reducing the risk of overstatement [89].

Governance Signal: Overall, integrating supplementary circularity indicators with LCA provides a more complete and decision-relevant assessment of CM performance. By aligning circularity metrics with experimentally validated material systems and consistent system boundaries, the approach strengthens transparency and comparability, supporting credible ESG-relevant interpretation without relying on declarative claims. These results indicate that ESG-relevant

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

resource efficiency claims derived from PC-PLA-based FFF must be conditioned on material retention and energy-adjusted circular performance, rather than recycled content alone.

4.4. STAGE IV – Waste Diversion Potential Analysis

This stage evaluates the waste diversion potential of post-consumer PLA into circular FFF using a deterministic mass-balance framework. The objective is to estimate how much PLA waste could be redirected under defined collection, sorting, and processing efficiencies. The results quantify governance-constrained diversion potential and identify dominant leverage points beyond process-level optimisation.

4.4.1. Diversion Capacity of Circular FFF

The mass-flow model was applied to quantify the upper-bound diversion potential of post-consumer PLA into circular FFF under explicitly defined market, application, technical, and governance constraints. Rather than projecting future waste flows, the analysis establishes a bounded, governance-contingent opportunity space for circular PLA utilisation, consistent with ISO-aligned scenario modelling practices.

1. **Estimation of Annual Global PLA Waste Availability:** Global PLA availability was anchored to the projected 2025 global biobased plastics production capacity of 2.31 million tonnes, as reported by European Bioplastics [92]. Industry data indicate that PLA represents approximately 26.4% of total biobased plastics capacity, yielding an estimated global PLA production capacity of about 0.61 million metric tonnes in 2025 [92].

Because not all PLA enters the waste stream within a single year, two filtering assumptions were applied to estimate annual waste availability. First, the share of PLA used in short-lived applications, primarily packaging and disposable products, was set at 55%, consistent with application distribution data indicating packaging as the dominant end-use segment. Second, the proportion of this short-lived PLA reaching end-of-life within the assessment year was conservatively assumed to be 75%. This midpoint assumption reflects the predominance of short-lived plastic products in global waste streams while avoiding optimistic assumptions of immediate disposal in the absence of polymer-specific end-of-life data [121,122]. Applying these constraints yields the estimated annual global PLA waste generation:

$$M_{PLA,waste} = (0.61 \times 10^{6} t) \times 0.55 \times 0.75 = 250{,}000\ tonnes/yesr$$

This value represents the theoretical maximum waste pool from which circular FFF could draw feedstock, prior to accounting for system losses and governance constraints.

2. **Internal Technical Yield Constraint:** Not all available PLA waste can be converted into usable PC-PLA filament and successfully printed products due to processing losses across the recycling and manufacturing chain. Internal technical efficiency was therefore modelled as the product of stage-specific yields associated with mechanical reprocessing, filament extrusion, and FFF printing.

A mechanical reprocessing yield of 0.75 was adopted to account for sorting losses, contamination rejection, and polymer degradation, consistent with reported recovery efficiencies for post-consumer plastics under mechanical recycling pathways [123–126]. Filament extrusion yield was assumed to be 0.95, reflecting low material losses under controlled extrusion conditions, primarily associated with purge and start-up waste [127]. The FFF printing yield was conservatively set at 0.90, accounting for support structures, failed prints, trimming losses, and PC-PLA-specific warping or print instability. While modern high-speed FFF systems demonstrate improved reliability, practical waste-to-part ratios commonly involve 10–15% support material by mass, with additional variability arising from recycled feedstock behaviour [128].

The combined internal technical efficiency is calculated as:

$$\eta_{internal} = \eta_{reprocess} \times \eta_{filament} \times \eta_{print}$$

 doi:10.20944/preprints202603.1193.v1

$$\eta_{internal} = 0.75 \times 0.95 \times 0.90 = 0.64$$

This result indicates that, even under technically optimised conditions, only approximately 64.0% of collected and correctly sorted PLA waste can be converted into functional FFF products. The remaining fraction is lost due to contamination, degradation, extrusion instability, and printing failures.

3. **Governance-Constrained Diversion Capacity:** The internal technical efficiency defines an upper technical ceiling, but actual diversion capacity is further constrained by upstream governance factors, particularly collection and sorting efficiency. Scenario-specific values of $\eta_{capture}$ and η_{sort}, summarised in Table 5, were applied to generate conservative, moderate, and transformational governance conditions.

The conservative and moderate scenarios reflect current and incrementally improved plastic waste governance contexts, consistent with Australia's low plastics recovery rates and partial MRF upgrading pathways [116,126,129,130]. The transformational scenario adopts a collection efficiency of 50% and a sorting efficiency of 90%, representing an upper-bound benchmark achievable under coordinated national policy, advanced material recovery facilities, and clear polymer identification. These values are consistent with reported overall waste recovery rates in high-performing systems and documented sorting efficiencies of 85–95% for targeted polymer streams in modern MRFs [116,131].

Under transformational conditions, the model yields a maximum diverted PC-PLA mass of approximately 73,000 tonnes per year, corresponding to 28.8% of the global PLA waste pool. These scenarios are intended as governance benchmarks rather than forecasts.

Table 3. Global PLA waste diversion potential via circular FFF under alternative governance scenarios.

Scenario	Collection efficiency $\eta_{capture}$	Sorting efficiency η_{sort}	Internal technical yield $\eta_{internal}$	Diverted PC-PLA mass $M_{FFF,rPLA}$ (tonnes/year)	Diversion share of global PLA waste (%)	Governance and policy interpretation
Conservative	0.10	0.50	0.64	8,100	3.2	Circular FFF remains a high-value niche application, constrained by limited waste capture and separation infrastructure
Moderate	0.25	0.75	0.64	30,000	12.0	Diversion becomes strategically relevant with regional investment in collection and sorting hubs
Transformational	0.50	0.90	0.64	73,000	28.8	Requires coordinated

	national policy, procurement incentives, and high-performance waste governance

Governance signal: The diversion analysis indicates that the scalability of circular FFF is primarily constrained by governance capacity rather than process-level technical performance. While internal technical yield imposes a fixed upper bound, variation in diversion outcomes is dominated by collection and sorting efficiency, identifying waste capture and separation as the dominant governance-controlled leverage points rather than printing technology optimisation.

4.5. Integrated ESG Interpretation and Governance Signals

By integrating service-life-normalised LCSA outcomes with KPI gap-to-threshold and diversion analysis, these results provide a consolidated ESG-oriented interpretation of PC-PLA adoption in FFF systems [76,132]. The evidence indicates that PC-PLA-based FFF delivers robust environmental benefits, conditionally viable economic performance, and governance-dependent social outcomes. Importantly, sustainability performance in circular additive manufacturing should not be treated as a static score. It emerges from specific material substitution choices and process configurations, and it is mediated by the extent to which organisations can control, verify, and institutionalise those choices.

1. ***Environmental performance and energy shifting:*** Substantial environmental improvements are observed with partial substitution of vPLA by PC-PLA, particularly in the V50:R50 configuration. Reductions in GWP, CED, and ARD remain significant when normalised by measured service life, confirming that environmental gains are not artefacts of reduced durability [132]. At the same time, the results highlight a relevant operational sensitivity: as circularity increases, part of the environmental burden shifts from printing operations toward upstream steps such as sorting, washing, and extrusion [133]. This shift implies that the environmental credibility of PC-PLA becomes increasingly sensitive to the carbon intensity of local electricity and to the efficiency of preprocessing systems.
2. ***Economic viability and social value creation:*** In contrast to the environmental dimension, economic and social outcomes are more dependent on organisational practices and system coordination. The gap-to-threshold analysis identifies preprocessing intensity and functional-unit cost stability as primary contributors to residual economic gaps, indicating that cost performance is governed by material handling efficiency and quality consistency, not by the printing process alone [134]. Socially, the results indicate meaningful local employment potential associated with decentralised recycling and filament production. However, recycled filaments impose higher workforce demands, as feedstock variability requires more frequent process tuning and operator intervention compared with virgin filaments. Social value creation is therefore conditional on structured training systems, occupational health and safety practices, and robust process governance, rather than being an automatic outcome of recycled material adoption [135–137].
3. ***Governance and the Australian context:*** Waste diversion analysis further demonstrates that the sustainability relevance of PC-PLA-based FFF extends beyond material substitution. Diversion outcomes are highly sensitive to collection and sorting efficiency, which are shaped by governance maturity and recovery infrastructure rather than by FFF process capability alone [138,139]. Within the Australian manufacturing context, these dependencies are amplified by high energy costs, labour constraints, and historically fragmented recycling infrastructure [140]. Under these conditions, sustainability outcomes are increasingly determined by local

 doi:10.20944/preprints202603.1193.v1

coordination, standards, and accountability mechanisms rather than global material sourcing alone. Table 4 synthesises the principal ESG implications associated with PC-PLA-based FFF adoption and identifies the governance conditions required to translate technical potential into credible ESG performance.

Table 4. ESG implications associated with PC-PLA-based FFF adoption and their governance dependencies.

ESG Pillar	Implication	Performance signal	Governance condition required
E	Increased upstream energy sensitivity associated with recycled feedstock processing	Environmental impacts dominated by preprocessing rather than printing operations	Energy-efficient preprocessing, renewable electricity integration
S	Higher skills and training intensity across recycling and FFF operations	Employment growth accompanied by gaps in formal training and process control capability	Certified training pathways, safety systems, and quality standards
G	Heightened dependence of sustainability performance on governance capability, with potential for domestic capability building and reduced import reliance	Sustainability outcomes governed by local coordination, while gaps emerge where targets, controls, and verification are absent	Formal accountability roles, auditable controls, verification systems, and alignment with national standards and policy frameworks

5. Discussion

5.1. Reframing LCSA Evidence as ESG-Relevant Information

The central contribution of this study lies in demonstrating how empirically validated LCSA evidence can be translated into decision-relevant ESG information without relying on product declaration frameworks or simplified circularity claims. Consistent with the staged analytical framework developed in this study, quantified environmental, economic, and social performance is reinterpreted through an organisational accountability lens, where sustainability outcomes function as governance-relevant signals rather than endpoint sustainability metrics. Figure 7 synthesises this translation logic by illustrating how empirically derived LCSA indicators are mediated through governance to become ESG-relevant information.

In line with the stated aim, the discussion focuses on ESG implications arising from the use of recycled PLA in FFF, examined in terms of how PC-PLA adoption alters environmental risk exposure, conditions for social value creation, and governance requirements within manufacturing organisations, rather than absolute sustainability performance or disclosure compliance. Sustainability information becomes ESG-relevant only to the extent that it informs forward-looking assessments of organisational resilience, risk exposure, and long-term value creation [141,142]. Accordingly, the ESG implications identified here function as governance signals derived from empirically verified life-cycle evidence rather than as descriptive or promotional sustainability claims.

At the organisational level, the relevance of PC-PLA-based FFF lies in managing material, workforce, and transition-related risks rather than in sustainability claims alone. This is particularly salient in contemporary ESG contexts, where credibility increasingly depends on the traceability, verifiability, and governance of disclosed indicators rather than their volume [143,144].By constraining ESG interpretation to indicators that are materially significant, operationally

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 March 2026 doi:10.20944/preprints202603.1193.v1

controllable, and empirically verifiable, this study reduces the risk of symbolic or selective disclosure in circular manufacturing contexts.

Although the empirical analysis is grounded in PC-PLA-based FFF, the LCSA-to-ESG translation logic is not inherently material-specific. The framework can be applied to other waste-derived polymer systems in additive manufacturing, provided that material degradation behaviour and processing constraints are explicitly accounted for. When interpreted against Australia's circular economy objectives, the results highlight governance conditions required for policy-aligned material transitions. Reductions in service-life-normalised emissions and virgin material demand directly support material-footprint reduction objectives [48], while waste diversion potential results reframe recovery targets as system-level governance challenges rather than fabrication-level optimisation problems.

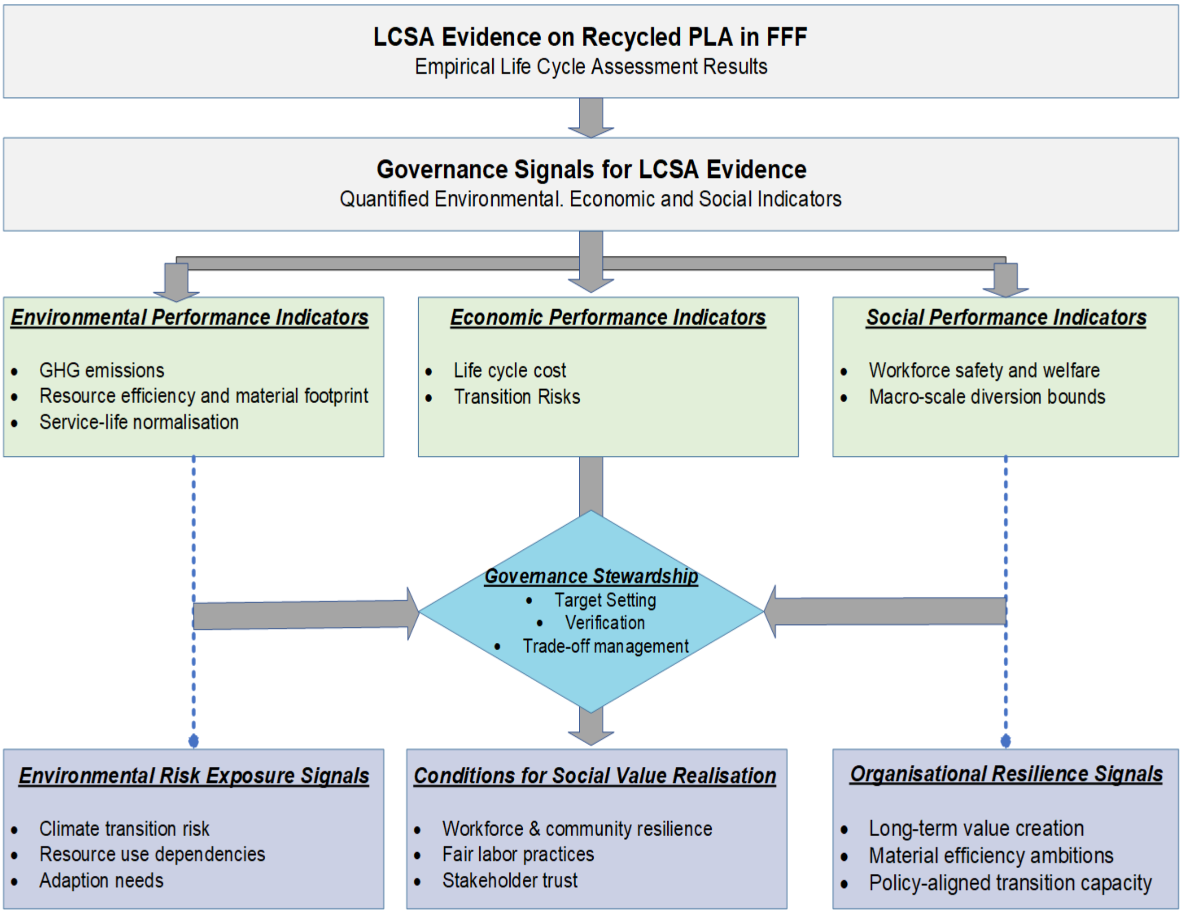


Figure 7. Governance-mediated translation of LCSA evidence into ESG-relevant signals in rPLA-based FFF.

5.2. Environmental Pillar (E): From Environmental Impact Reduction to Improved Environmental Governance Metrics

The quantified reduction in greenhouse gas emissions achieved through partial substitution of virgin PLA with recycled PLA represents a clear environmental benefit. When expressed using avoided-emissions logic, these results provide decision-relevant environmental evidence that can inform organisational sustainability governance, particularly in relation to transition-risk management and material sourcing decisions [145,146].

The analysis demonstrates that the environmental significance of circular FFF is driven primarily by upstream material substitution rather than marginal efficiency gains within the printing process itself. This challenges technology-centric narratives that prioritise manufacturing optimisation while overlooking the dominant influence of material sourcing [147]. Responsibility therefore shifts toward

 doi:10.20944/preprints202603.1193.v1

procurement strategy, supplier selection, and material stewardship as primary organisational levers for environmental performance [148,149].

The integration of circularity indicators strengthens environmental governance interpretation by distinguishing substantive material loop closure from nominal recycled-content claims. This distinction is critical for governance oversight, as recycled content alone is increasingly recognised as insufficient evidence of circular performance [89]. In the Australian context, where energy-price volatility and material-supply risk persist, these findings underscore procurement-led decarbonisation and material governance as central environmental ESG levers [144].

Accordingly, environmental outcomes associated with material sourcing, energy demand, and waste generation increasingly translate into operational disruption risk, regulatory exposure, and reputational harm [48,143,150]. Within PC-PLA-based FFF, demonstrated reductions in emissions and virgin material dependency function as transition-risk mitigation signals, while residual exposure linked to preprocessing intensity highlights the need for governance-led environmental management and verification.

5.3. Social Pillar (S): Conditional Social Value and Governance Inter-Dependency

Social life-cycle results indicate that circular FFF can generate local employment through decentralised waste collection, sorting, and reprocessing. However, social value creation is conditional rather than automatic and depends on enabling governance structures and accessible infrastructure, not material substitution alone [151,152]. The observed trade-off between employment intensity and gaps in formal training, occupational safety, and process control challenges the assumption that job creation inherently produces positive social outcomes [153]. Without structured oversight, employment expansion may instead increase ethical, human-rights, and reputational risks [154].

Social performance is further shaped by the availability and inclusiveness of recycling, extrusion, and FFF manufacturing infrastructure [155,156]. Where facilities are geographically concentrated or institutionally inaccessible, participation in circular supply chains remains limited. Decentralised systems also rely on stakeholder awareness across the value chain. Limited understanding of separation standards, recycling pathways, and quality requirements can undermine both product reliability and social outcomes [157,158].

Overall, social performance in CM is best understood as a governance-managed outcome rather than an intrinsic benefit of circular material use [159]. This reinforces the interdependence between the Social and Governance pillars, as limitations in governance capacity directly constrain the realisation of social benefits [160,161]. Weak workforce governance, limited infrastructure access, and inadequate stakeholder protection constrain social value realisation and expose firms to regulatory and reputational risks [143]. In PC-PLA-based FFF, these interdependencies directly affect social legitimacy and long-term value creation.

5.4. Governance Pillar (G): Ticking Box Performance Assessment Versus Improved Accountability and Stewardship

Governance functions as the mediating condition that determines whether LCSA-derived sustainability performance becomes decision-relevant and credible [76]. While LCSA identifies performance gaps and trade-offs, it does not prescribe organisational responses. The governance implications therefore depend on how environmental, economic, and social evidence is embedded within decision structures, accountability mechanisms, and assurance practices. Organisations may achieve favourable technical outcomes through material substitution yet remain governance-weak in the absence of explicit targets, oversight structures, traceability systems, and verification mechanisms [162,163].

Conversely, stronger governance requires leadership commitment, investment decisions, and institutionalisation of ESG oversight within routine operational and procurement practices [164].

 doi:10.20944/preprints202603.1193.v1

Whilst LCSA and EPD are valuable disclosure tools they will not help transform industrial production. From a broad governance perspective they help standardise sustainability reporting, facilitate improved information asymmetry in organisations and help achieve regulatory requirements. This paper suggests that linking LCSA frameworks to ESG frameworks can improve governance capacity and move the production system away from formal compliance to an entrenched culture of sustainability performance with a much clearer understanding of false or superficial assumptions of sustainability performance.

This reinforces the principle that sustainability transitions are organisational and institutional transformations rather than purely technological ones [165]. FFF should therefore be understood as an enabling system whose ESG relevance depends on how it is governed, monitored, and integrated into decisions. Without governance mechanisms for material traceability, quality assurance, workforce competence, and supplier accountability, the ESG value of circular FFF remains difficult to verify [162,166]. ESG outcomes are shaped more by governance maturity and internal capability than by access to circular manufacturing technologies alone [161]. Even where technically viable rPLA-based FFF options exist, limitations in data availability, reporting transparency, workforce training, and managerial capacity can constrain consistent ESG performance, particularly among small and medium-sized enterprises. This helps explain variability in governance outcomes across organisations operating under similar technological conditions and reinforces the role of internal controls and assurance systems in translating technical sustainability potential into credible ESG performance [141,167].

Governance capability also shapes how organisations engage with stakeholders affected by decentralised CM systems [168]. In rPLA-based FFF, social responsibility extends beyond internal workforce considerations to engagement with waste generators, recycling partners, suppliers, and downstream users. Structured and transparent engagement, supported by accessible infrastructure and awareness initiatives, can enhance local value creation and social legitimacy. Conversely, weak coordination and opaque practices risk undermining trust and diminishing perceived social value [167,169].

As investor scrutiny intensifies, the ability to collect, verify, and report life-cycle-based sustainability data becomes a material governance competence [170]. Robust reporting strengthens investor confidence by demonstrating verified emissions reductions, resource-efficiency gains, and social safeguards. In this context, the V50:R50 configuration operates as a governance benchmark, offering a credible pathway for managing Scope 3 exposure and resource dependency while signalling readiness for tightening regulatory and market expectations [171].

5.5. Scale, Boundaries, and the Risk of Over-Claiming Circularity

Governance considerations become particularly salient when extending analysis from organisational decision-making to system-level claims of circularity [167,172]. The waste diversion analysis provides a corrective to optimistic circular economy narratives by quantifying the maximum plausible diversion of PLA waste into FFF under defined governance and infrastructure conditions. The results indicate that circular FFF represents a strategic niche pathway rather than a comprehensive waste-management solution, underscoring the risks of extrapolating laboratory- or firm-level outcomes to economy-wide claims [122,138].

This insight has direct ESG relevance. Overstating the scalability or permanence of circular technologies can undermine the credibility of sustainability disclosures and increase exposure to greenwashing risk [173,174]. Responsible ESG communication, therefore, requires a clear distinction between technically viable circular niches and system-wide solutions, together with transparent articulation of the governance, infrastructure, and material-quality conditions required to realise projected benefits [143,174].

A further boundary condition concerns the temporal limits of recyclability. Repeated thermal and mechanical processing degrades polymer molecular weight, rheological stability, and functional

 doi:10.20944/preprints202603.1193.v1

performance, while circularity indicators such as MCI and CI are sensitive to these quality losses [89,123]. Recyclability, therefore, cannot be treated as a uniform or static material property. Diversion potential is primarily constrained by upstream factors including collection efficiency, sorting capability, preprocessing yield, and quality control rather than downstream manufacturing optimisation [175,176].

Collectively, these findings emphasise that credible circular manufacturing claims must be bounded, quality-aware, and governance-verified. Circular FFF can deliver environmental and resource-efficiency benefits only within clearly defined system limits and under governance arrangements capable of monitoring material quality, recycling efficiency, and long-term functional performance.

5.6. Implications for ESG Reporting, Policy, and Practice

Collectively, the discussion positions circular FFF using PC-PLA as a governance-sensitive sustainability pathway with clear but bounded ESG implications, particularly within the Australian manufacturing context. For Australian manufacturers, especially SMEs, ESG-aligned adoption of recycled materials requires more than material substitution alone [177]. Instead, it requires parallel investment in governance capability, including workforce training, quality assurance, and performance verification, to ensure that environmental and social benefits are credible, repeatable, and decision-relevant [178].

This finding is particularly salient in Australia, where manufacturers operate under high energy prices, labour shortages, and limited domestic recycling infrastructure [179]. The labour-intensive preprocessing hotspot reflects a governance challenge rather than an inherent material limitation, pointing to the need for targeted automation, skills development, and regional recycling hubs [57]. From an ESG perspective, such measures align operational risk management with national objectives related to sovereign manufacturing capability, resource security, and decarbonisation [56]. In the Australian context, where ESG scrutiny increasingly extends to capital allocation decisions, investments in preprocessing automation, recycling infrastructure, and workforce capability function not only as operational improvements but also as governance signals reflecting an organisation's transition strategy and risk management approach [60,85].

For policymakers, the quantified diversion potential derived from the waste diversion potential analysis provides a defensible, evidence-based basis for targeted support mechanisms, such as procurement incentives, co-investment in waste sorting infrastructure, and regionally focused CM initiatives [48]. Rather than blanket CE mandates, the results support selective policy intervention aimed at unlocking governance and infrastructure constraints that currently limit the scalability of circular FFF in Australia [66].

From a reporting and assurance perspective, the study demonstrates how LCSA evidence can be translated into indicators aligned with governance, strategy, risk management, and metrics pillars of emerging disclosure standards, including ASRS S1 and S2 [180]. By prioritising organisational accountability over declarative product claims, the analytical framework provides manufacturers with a structured pathway for integrating engineering-level sustainability evidence into credible and auditable ESG disclosures, thereby reducing greenwashing risk and enhancing transparency [180].

5.7. Contribution to Sustainable Manufacturing Research

This study advances sustainable manufacturing research by presenting an empirically grounded framework for translating detailed LCSA evidence into ESG-relevant governance insights, with particular relevance to advanced manufacturing in Australia. Rather than conceptualising ESG as an external reporting obligation, the framework embeds governance logic within engineering-based sustainability assessment, linking material performance, organisational capability, and system-level scale.

Within the Australian context, where manufacturing resilience is shaped by decarbonisation targets, supply-chain fragility, and skills availability, the findings indicate that sustainability transitions are governance- and capability-driven rather than technology-limited [181]. The identification of collection efficiency as the dominant system constraint further highlights the absence of Extended Producer Responsibility as a structural limitation in circular manufacturing systems, with implications for both material recovery performance and formalisation of recycling-related employment [182,183].

The results demonstrate that PC-PLA-based FFF can deliver environmental and social benefits when supported by organisational systems capable of managing material quality, workforce competence, and performance verification. This insight is particularly relevant for Australia's advanced manufacturing sector, where rebuilding domestic capability requires sustainability strategies that are credible to investors, regulators, and procurement authorities [60].

More broadly, the study responds to growing calls for sustainability assessments that move beyond impact quantification toward decision-useful, governance-aligned information capable of supporting real-world transition pathways. By integrating LCSA, circularity metrics, and waste diversion potential analysis within an ESG implications lens, the work provides a transferable analytical approach for evaluating emerging manufacturing technologies in policy-relevant contexts, particularly in economies such as Australia that seek to rebuild domestic manufacturing capacity while meeting increasingly stringent sustainability expectations.

6. Conclusions and Future Research

By focusing explicitly on PC-PLA use within FFF, this study demonstrates that ESG implications arise directly from material substitution decisions. Environmental benefits, social outcomes, and governance requirements emerge as interdependent consequences of PC-PLA adoption rather than inherent attributes of additive manufacturing technology. The findings reveal a misalignment between observed sustainability performance and the pace at which governance signals evolve to guide and validate that performance.

This study demonstrates that PC-PLA-based FFF can deliver meaningful environmental and social benefits for manufacturing; however, these benefits do not automatically translate into ESG relevance. By reframing life cycle sustainability assessment as an evidence-based assessment rather than an endpoint, the research shows how quantified environmental, economic, and social performance can be interpreted through an ESG implications lens that emphasises governance capability, accountability, and decision relevance moving from 'informational' to 'transformational' sustainability performance.

The results confirm that partial substitution of vPLA with post-consumer PC-PLA yields significant reductions in greenhouse gas emissions, energy demand, and dependency on virgin materials when assessed using service-life-based functional units. However, economic and social outcomes exhibit residual performance gaps linked to preprocessing intensity, durability constraints, and workforce training requirements. These gaps are not intrinsic failures of recycled materials but governance-managed risks that require organisational intervention through investment, automation, skills development, and quality assurance.

Importantly, the waste diversion potential analysis highlights that the sustainability significance of circular FFF is primarily governed by upstream waste collection and policy coordination, rather than by the additive manufacturing technology itself. Consequently, this study offers the following final conclusions for the Australian context:

- *Policy-Led Scalability*: Realising the transformational diversion potential of 28.8% of global PLA waste requires a shift from fabrication research to waste system governance and infrastructure.
- *Integrated ESG Strategy*: For Australian SMEs operating under high energy costs and labour shortages, investments in recycling infrastructure and certified workforce training emerge as core elements of a credible ESG strategy rather than mere operational improvements.

 doi:10.20944/preprints202603.1193.v1

- *Evidence-Based Disclosure:* The proposed framework provides a practical pathway for manufacturers to integrate engineering-level evidence into auditable ESG narratives, reducing exposure to greenwashing risk while meeting emerging disclosure standards such as ASRS S1 and S2.

Limitations of the Study: Despite its contributions, this study has several limitations that should be acknowledged. The ESG interpretation is anchored to a single technically and sustainability-balanced reference configuration (V50:R50), and outcomes may vary across material blends, feedstock qualities, and component geometries. While the ESG translation framework enhances decision relevance and traceability, it does not provide compliance-ready disclosures or third-party assurance.

Directions for Future Research: Future research should extend the framework across a wider range of recycled–virgin blends, feedstock qualities, and component types to test robustness and scalability, including applications to higher-load or safety-critical components. Further work is also required to strengthen the empirical basis of social assessment through primary data collection, including workforce surveys and enterprise-level case studies, and to explore pathways for integrating experimentally grounded LCSA evidence into auditable ESG reporting and assurance processes.

Author Contributions: Conceptualisation, M.R.H., M.J., and W.K.B.; methodology, M.R.H., IM.J., and W.K.B.; validation, M.R.H., M.J., W.K.B., I.J.D., and A.P.; formal analysis, M.R.H.; investigation, M.R.H.; data curation, M.R.H.; writing—original draft preparation, M.R.H.; writing—review and editing, M.R.H., I.J.D., A.P., M.J., and W.K.B.; and supervision, M.J., W.K.B., I.J.D. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors acknowledge the support of Curtin University and the Sustainable Engineering Group. The authors also gratefully acknowledge the technical staff of the School of Civil and Mechanical Engineering, Curtin University, Australia, for their valuable technical assistance and support throughout this research.

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

Appendix

Table A1. List of the selected indicators.

Sustainability Indicators	Headline Performance Indicator (HPI)		Key Performance Indicator (KPI)	
Environmental Indicators	E-1	Climatic condition	E-1.1	Global Warming Potential
	E-2	Ecosystem quality	E-2.1	Terrestrial Acidification
			E-2.2	Eutrophication
			E-2.3	Freshwater ecotoxicity
	E-3	Energy	E-3.1	Cumulative energy demand
	E-4	Natural resources and ecosystem collapse	E-4.1	Abiotic Resource Depletion
			E-4.2	Water Use
			E-4.3	Land use
	E-5	Human health	E-5.1	Human Toxicity
			E-5.2	Fine particulate matter formation
Economic indicators	Ec-1	Circular Cost Efficiency	Ec-1.1	Life Cycle Cost
			Ec-1.2	Net Benefit
	Ec-2	Green Return on Investment	Ec-2.1	Carbon Tax Saving

doi:10.20944/preprints202603.1193.v1

Social Indicators	S-1	Local Community	S-1.1	Local employment
	S-2	Workers	S-2.1	Quality of Life
			S-2.2	Workplace Training and Skill Development

Table A2. Material Circularity Indicator (MCI) and Circularity Index (CI) calculations.

Group	Symbol	Parameter	Value
Product basis	M	Mass of product (kg)	1000
Blend	F_r	Recycled fraction at blend inlet (cups feedstock)	0.500
Blend	F_u	Re-used fraction	0.000
Blend	η_{fil}	Filament extrusion yield	0.980
Blend	η_{prn}	Printing yield (accounts for supports, failed prints)	0.950
Material demand	$M^{'}$	Total material demand at blend inlet (kg)	1074
End-of-life	C_r	Collection rate for recycling at EoL	0.150
End-of-life	C_u	Collection rate for reuse at EoL	0.000
End-of-life	E_C	Recycling efficiency at EoL (yield)	0.833
End-of-life	E_f	Effective EoL recycling $= C_r E_C$	0.125
Recycled feedstock	$E_{rec,in}$	Recycling efficiency to produce recycled feedstock	0.900
Utility	L	Product lifetime (hr)	62.0
Utility	L_{av}	Industry-average lifetime (hr)	62.0
Utility	U	Utility factor (uses)	1.00
Utility	U_{av}	Industry-average utility	1.00
Energy for CI	E_s	CED for secondary route (MJ/kg), material prep plus filament	23.6
Energy for CI	E_p	CED for primary route (MJ/kg), virgin resin plus filament	51.0

MCI calculation (Ellen MacArthur Foundation)

Description	Equation	Value
Material Inputs		
Total material demand	$M^{'} = \frac{M}{\eta_{fil}\eta_{prn}}$	1074 kg
Virgin material input	$V = M^{'}(1 - F_r - F_u)$	537 kg
Recycled material input	$R_i = M^{'}F_r$	537 kg
EMF recycled fraction basis	$F_R = \frac{R_i}{M}$	0.537
Waste terms		
Uncollected EoL product	$W = M(1 - C_r - C_u)$	850 kg
Waste from recycling at EoL	$W_c = MC_r(1 - E_c)$	25.1 kg
Waste from recycled feedstock production	$W_f = M\frac{(1 - E_F)F_R}{E_F}$	59.7 kg
Utility adjustment		
Utility fraction	$X = (\frac{L}{L_{av}})(\frac{U}{U_{av}})$	1.00
Utility adjustment	$F(x) = 0.9/X$	0.900
Linear Flow Index and MCI		
Description	Equation	Value

Linear Flow Index	$LFI = \dfrac{V + W_0 + \dfrac{W_c + W_f}{2}}{2M + \dfrac{W_f - W_c}{2}}$	0.709
MCI	$MCI = 1 - LFI \cdot F(x)$	**0.362**
CI calculation (energy-adjusted circularity)		
Description	**Equation**	**Value**
Recovered recycled material	$R_r = E_f \cdot R_i$	67.1 kg
Recovered fraction	$\alpha = R_r/(V^{'} + R_i)$	0.0625
Energy benefit factor	$\beta = 1 - E_s/E_p$	0.537
CI	$CI = \alpha \times \beta$	**0.0336**

References

1. Khan, K. I.; Mahmood, S.; Khalid, A., Transforming manufacturing sector: bibliometric insight on ESG performance for green revolution. *Discover Sustainability* **2024,** *5*.
2. UNIDO Statistics *International Yearbook of Industrial Statistics*; Vienna, Austria, 07/11/2025, 2023.
3. Moita, A.; Lopes, J. C.; Mendes, J. Z., Circular economy and sustainability: The case of the automotive industry in Portugal. *Innovation and Green Development* **2024,** *3*.
4. Kazakova, E.; Lee, J., Sustainable Manufacturing for a Circular Economy. *Sustainability* **2022,** *14*.
5. Bag, S.; Pretorius, J. H. C., Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework. *International Journal of Organizational Analysis* **2020,** *30*, 864-898.
6. Macarthur, E.; Heading, H., How the circular economy tackles climate change. *Ellen MacArthur Found* **2019,** *1*, 1-71.
7. Kumar, M.; Mani, M., Chapter 11 - Sustainability assessment in manufacturing: perspectives, challenges, and solutions. In *Sustainable Manufacturing*, Gupta, K.; Salonitis, K., Eds. Elsevier: 2021; pp 287-311.
8. Korevaar, G., Industry 4.0 approaches to sustainability. In The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century, 2025; pp 337-351.
9. Roci, M.; Salehi, N.; Amir, S.; Shoaib-ul-Hasan, S.; Asif, F. M. A.; Mihelič, A.; Rashid, A., Towards circular manufacturing systems implementation: A complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool. *Sustainable Production and Consumption* **2022,** *31*, 97-112.
10. Ahmed, W.; Siva, V.; Bäckstrand, J.; Sarius, N.; Sundberg, H.-Å., Circular economy: Extending end-of-life strategies. *Sustainable Production and Consumption* **2024,** *51*, 67-78.
11. Sharma, R.; Gupta, H., Harmonizing sustainability in industry 5.0 era: Transformative strategies for cleaner production and sustainable competitive advantage. *Journal of Cleaner Production* **2024,** *445*.
12. Wang, D.; Wang, T., Does ESG Information Disclosure Improve Green Innovation in Manufacturing Enterprises? *Sustainability* **2025,** *17*.
13. Tortorella, G.; Li, W.; Staines, J.; Vassolo, R., Australian manufacturing industry: a 20-year scoping study on barriers, opportunities and trends for its strategic development. *Production* **2021,** *31*.
14. Zeller, J. The Investment Paradox: Misaligned Capital and the Case for Revitalising Australian Manufacturing. https://www.internationalaffairs.org.au/australianoutlook/the-investment-paradox-misaligned-capital-and-the-case-for-revitalising-australian-manufacturing/ (5 Dec),
15. Rainnie, A.; Dean, M., Manufacturing. In *The Fourth Industrial Revolution*, Springer Nature Singapore: 2021; pp 39-56.
16. Shi, X.; Cheong, T. S.; Zhou, M., COVID-19 and Global Supply Chain Configuration: Economic and Emissions Impacts of Australia-China Trade Disruptions. *Front Public Health* **2021,** *9*, 752481.
17. European Commission, Carbon Border Adjustment Mechanism (The EU's environmental policy tool for fair carbon emissions pricing). In Union, T. a. C., Ed. Directorate-General for Taxation and Customs Union: Brussels, Belgium, 2026.
18. ACCTS, Agreement on Climate Change, Trade and Sustainability (ACCTS) Overview. In Trade, N. Z. F. A., Ed. New Zealand Foreign Affairs & Trade: Wellington, New Zealand, 2024.

19. CBD, Kunming-Montreal Global Biodiversity Framework. In Diversity, C. o. B., Ed. UN Environment Programme: Montreal, Canada, 2022.
20. ISSB, IFRS S1: General Requirements for Disclosure of Sustainability-related Financial Information. In Board, I. S. S., Ed. IFRS Foundation: Canary Wharf, London, 2025.
21. UNEP *Global Framework on Chemicals*; United Nations Environment Programme: Geneva, Switzerland, 2023.
22. Cordeiro, C. M.; Adomaitis, L.; Huang, L., The AI-policy-governance nexus: How regulation and AI shift corporate governance toward stakeholders. *Technology in Society* **2026,** *84*.
23. Akgiray, V., The potential for blockchain technology in corporate governance. **2019**.
24. Ogedengbe, F. A.; Adelowotan, M. O., Revolutionising corporate governance: blockchain's transformative impact and potential. *Frontiers in Blockchain* **2025,** *8*.
25. Yadav, A.; Sachdeva, A.; Garg, R. K.; Qureshi, K. M.; Mewada, B. G.; Qureshi, M. R. N. M.; Mansour, M., Achieving Net-Zero in the Manufacturing Supply Chain through Carbon Capture and LCA: A Comprehensive Framework with BWM-Fuzzy DEMATEL. *Sustainability* **2024,** *16*.
26. Leal Filho, W.; Aina, Y. A.; Gatto, A.; Rampasso, I. S.; Sigahi, T. F. A. C.; Anholon, R.; Bella, R. L. F.; Quelhas, O. L. G.; de Vasconcelos, C. R. P.; Luetz, J. M., Greening the factory floor and reducing the climate impact of the manufacturing sector. *Discover Sustainability* **2025,** *6*.
27. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Potential of Recycled PLA in 3D Printing: A Review. *Sustainable Manufacturing and Service Economics* **2024,** *3*.
28. Jayawardane, H.; Davies, I. J.; Gamage, J. R.; John, M.; Biswas, W. K., Sustainability perspectives – a review of additive and subtractive manufacturing. *Sustainable Manufacturing and Service Economics* **2023,** *2*.
29. Prasad, G.; Arunav, H.; Dwight, S.; Ghosh, M. B.; Jayadev, A.; Nair, D. I., Advancing Sustainable Practices in Additive Manufacturing: A Comprehensive Review on Material Waste Recyclability. *Sustainability* **2024,** *16*, 10246.
30. Dzogbewu, T. C.; de Beer, D. J.; Nooni, I. K., Additive Manufacturing as a Catalyst for Low-Carbon Production and the Renewable Energy Transition in Electric Vehicles. *Technologies* **2025,** *13*.
31. Dipta, S. D.; Rahman, M. M.; Ansari, M. J.; Uddin, M. N., A Comprehensive Review of Sustainable and Green Additive Manufacturing: Technologies, Practices, and Future Directions. *Journal of Manufacturing and Materials Processing* **2025,** *9*.
32. CSIRO *CSIRO empowers SMEs to turn advanced manufacturing solutions into R&D opportunities*; Commonwealth Scientific and Industrial Research Organisation: Australia, 2024.
33. Maware, C.; Muvunzi, R.; Machingura, T.; Daniyan, I., Examining the Progress in Additive Manufacturing in Supporting Lean, Green and Sustainable Manufacturing: A Systematic Review. *Applied Sciences* **2024,** *14*.
34. Ford, S.; Despeisse, M., Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production* **2016,** *137*, 1573-1587.
35. Belhadi, A.; Kamble, S. S.; Venkatesh, M.; Chiappetta Jabbour, C. J.; Benkhati, I., Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view. *International Journal of Production Economics* **2022,** *249*.
36. Patel, S.; Liu, Y.; Siddique, Z.; Ghamarian, I., Metal additive manufacturing: Principles and applications. *Journal of Manufacturing Processes* **2024,** *131*, 1179-1201.
37. Chauhan, D.; Singh, A. P.; Chauhan, A.; Arora, R., Sustainable supply chain: An optimization and resource efficiency in additive manufacturing for automotive spare part. *Sustainable Futures* **2025,** *9*.
38. Prats De Arquer, M. E., The Social impact of additive manufacturing: a study on companies and makerspaces. *Industrial Engineering* **2025,** *Master's*.
39. Parliament of Australia, Future Made in Australia Bill 2024. In Parliament of Australia: Australia, 2024.
40. Department of Finance, National Reconstruction Fund Corporation Act 2023. In Department of Finance: Australia, 2025.
41. Dokl, M.; Copot, A.; Krajnc, D.; Fan, Y. V.; Vujanović, A.; Aviso, K. B.; Tan, R. R.; Kravanja, Z.; Čuček, L., Global projections of plastic use, end-of-life fate and potential changes in consumption, reduction, recycling and replacement with bioplastics to 2050. *Sustainable Production and Consumption* **2024,** *51*, 498-518.
42. Rosenboom, J.-G.; Langer, R.; Traverso, G., Bioplastics for a circular economy. *Nature Reviews Materials* **2022,** *7*, 117-137.

43. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Impact of process parameters on improving the performance of 3D printed recycled polylactic acid (rPLA) components. *The International Journal of Advanced Manufacturing Technology* **2024**.
44. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Fabrication and Characterisation of Sustainable 3D-Printed Parts Using Post-Consumer PLA Plastic and Virgin PLA Blends. *Processes* **2024,** *12*.
45. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Recycling Post-Consumed Polylactic Acid Waste Through Three-Dimensional Printing: Technical vs. Resource Efficiency Benefits. *Sustainability* **2025,** *17*.
46. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Technical Assessment of 3D-Printed Spur Gears Produced from Recycled Polylactic Acid. *Smart and Sustainable Manufacturing Systems* **2025,** *9*, 106-144.
47. John, M., The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century. Taylor & Francis: 2025.
48. DCCEEW *Australia's Circular Economy Framework*; Department of Climate Change, Energy, the Environment and Wate: Canberra ACT, 2024.
49. Setyadi, A.; Pawirosumarto, S.; Damaris, A., Embedding Circular Operations in Manufacturing: A Conceptual Model for Operational Sustainability and Resource Efficiency. *Sustainability* **2025,** *17*.
50. Islam, N. F.; Gogoi, B.; Saikia, R.; Yousaf, B.; Narayan, M.; Sarma, H., Encouraging circular economy and sustainable environmental practices by addressing waste management and biomass energy production. *Regional Sustainability* **2024,** *5*.
51. Haleem, A.; Javaid, M.; Singh, R. P.; Suman, R.; Qadri, M. A., A pervasive study on Green Manufacturing towards attaining sustainability. *Green Technologies and Sustainability* **2023,** *1*.
52. Fohl, F.; Rajčić, V.; Ungureanu, V.; Palermo, M.; Arrè, L.; Carević, I.; Buzatu, R., Circular Manufacturing. In *Springer Tracts in Civil Engineering*, Springer Nature Switzerland: 2025; pp 69-91.
53. Sandeep, N.; Suresh, R., A Study of the Circular Manufacturing System: Issues and Prospects. *系统科学与信息学报(英文)* **2024,** *12*, 790-803.
54. CSIRO *A circular economy roadmap for plastics, tyres, glass and paper in Australia*; Commonwealth Scientific and Industrial Research Organisation: Australia, 2021.
55. Wilson, J. Research Note: Hard times in Australian manufacturing. https://www.australianindustrygroup.com.au/resourcecentre/research-economics/economics-intelligence/2025/hard-times-in-australian-manufacturing/ (12 Dec),
56. Burgering, C. ESG Economist - Pressure on energy-intensive industry still high. https://www.abnamro.com/research/en/our-research/esg-economist-pressure-on-energy-intensive-industry-still-high (12 Dec),
57. Corematic A future roadmap to advanced manufacturing in Australia. https://corematic.com.au/blog/a-future-roadmap-to-advanced-manufacturing-in-australia/ (12 Dec),
58. Hettiarachchi, B. D.; Brandenburg, M.; Seuring, S., Connecting additive manufacturing to circular economy implementation strategies: Links, contingencies and causal loops. *International Journal of Production Economics* **2022,** *246*.
59. Madeleine P. What Is the Current State of 3D Printing in Australia? https://www.3dnatives.com/en/what-is-the-current-state-of-3d-printing-in-australia-260520254/#! (12 Dec),
60. Cheesman, R. Opportunities and Challenges for Australia's Manufacturing Sector in 2025. https://atturra.com/au-en/insights/perspectives/opportunities-and-challenges-for-australias-manufacturing-sector-in-2025/ (10 Dec),
61. Hasan, M. R.; Davies, I. J.; Pramanik, A.; John, M.; Biswas, W. K., Advancing circular additive manufacturing: Life cycle sustainability assessment of gears made from recycled polylactic acid. *Materials Today Sustainability* **2026,** *33*.
62. Stock, P., Australia's amount of plastic waste surges as recycling rates fail to improve. *The Guardian* 2025.
63. CSIRO The State of bioplastics in Australia report aims to increase understanding of bioplastics and their credentials for sustainable waste management; Commonwealth Scientific and Industrial Research Organisation: Australia, 2024.

 doi:10.20944/preprints202603.1193.v1

64. DAWE, National Plastics Plan 2021. In Department of Agriculture, W. a. t. E., Ed. Commonwealth of Australia: Department of Agriculture, Water and the Environment: Canberra, Australia, 2021.
65. EMR Australia 3D Printing Market Size, Share, and Trends: Forecast and Growth Analysis Report (2026-2035). https://www.expertmarketresearch.com.au/reports/australia-3d-printing-market (10 Dec),
66. Fernandes, E., Australia Industrial 3D Printing Plastic Market Size 2026 | Key Drivers, AI Highlights & Regions 2033. In LinkedIn, Ed. Flavor Savvy Dynamic: 2025.
67. Goh, G. D.; Wong, K. K.; Tan, N.; Seet, H. L.; Nai, M. L. S., Large-format additive manufacturing of polymers: a review of fabrication processes, materials, and design. *Virtual and Physical Prototyping* **2024,** *19*.
68. Al Rashid, A.; Koç, M., Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste. *Materials Today Sustainability* **2023,** *24*.
69. Sola, A.; Trinchi, A., Recycling as a Key Enabler for Sustainable Additive Manufacturing of Polymer Composites: A Critical Perspective on Fused Filament Fabrication. *Polymers (Basel)* **2023,** *15*.
70. Romani, A.; Perusin, L.; Ciurnelli, M.; Levi, M., Characterization of PLA feedstock after multiple recycling processes for large-format material extrusion additive manufacturing. *Materials Today Sustainability* **2024,** *25*.
71. Guinee, J. B.; Heijungs, R.; Huppes, G.; Zamagni, A.; Masoni, P.; Buonamici, R.; Ekvall, T.; Rydberg, T., Life cycle assessment: past, present, and future. *Environ Sci Technol* **2011,** *45*, 90-6.
72. Wulf, C.; Werker, J.; Zapp, P.; Schreiber, A.; Schlör, H.; Kuckshinrichs, W., Sustainable Development Goals as a Guideline for Indicator Selection in Life Cycle Sustainability Assessment. *Procedia CIRP* **2018,** *69*, 59-65.
73. Lim, C.; K. Biswas, W., Sustainability Implications of the Incorporation of a Biogas Trapping System into a Conventional Crude Palm Oil Supply Chain. *Sustainability* **2019,** *11*, 792.
74. Janjua, S. Y.; Sarker, P. K.; Biswas, W. K., Sustainability implications of service life on residential buildings – An application of life cycle sustainability assessment framework. *Environmental and Sustainability Indicators* **2021,** *10*.
75. Biswas, W. K.; John, M., *Engineering for Sustainable Development : Theory and Practice*. John Wiley & Sons, Incorporated: Newark, United Kingdom, 2022.
76. Padilla-Rivera, A.; Hannouf, M.; Assefa, G.; Gates, I., Enhancing environmental, social, and governance, performance and reporting through integration of life cycle sustainability assessment framework. *Sustainable Development* **2025,** *33*, 2975-2995.
77. Tăbîrcă, A.-I.; Radu, V.; Cozorici, A.-N.; Tanase, L.-C.; Radu, F., Professional Determinants in ESG Reporting for Sustainable Financial Assessment. *Systems* **2025,** *13*, 898.
78. Pinedo-López, J.; Baena-Navarro, R.; Carriazo-Regino, Y.; Urrea-Ortiz, A.; Reyes-Guevara, D., Sustainability strategies: A proposal for food sector SMEs, based on the integration of life cycle assessment and ESG strategies. *Journal of Infrastructure, Policy and Development* **2024,** *8*.
79. Ngan, S. P.; Ngan, S. L.; Lam, H. L., A Holistic Approach to Sustainability Reporting: Integrating Social and Governance Dimensions in Life Cycle Assessment. *Chemical Engineering Transactions* **2024,** *114*, 49-54.
80. Zhang, W.; Zhong, S., From Control to Incentive: How Market-Driven Environmental Regulation Shapes ESG Performance in Manufacturing Industries. *Sustainability* **2025,** *17*.
81. PwC Sustainability Reporting in Australia: A tipping point; PricewaterhouseCoopers: Australia, 2024.
82. Boshoff, A. Mandatory sustainability reporting in Australia. https://www.bdo.com.au/en-au/insights/esg-sustainability/mandatory-sustainability-reporting-in-australia-starts-on-1-january-2025 (12 Dec),
83. AASB S1, General Requirements for Disclosure of Sustainability-related Financial Information. In Australian Sustainability Reporting Standard: Australia, 2024.
84. AASB S2, Climate-related Disclosures. In Australian Sustainability Reporting Standard: Australia, 2024.
85. Pollett, R.; Byrne, D. Sustainability in Australian Manufacturing. https://www.bdo.com.au/en-au/insights/manufacturing/sustainability-in-australian-manufacturing (12 Dec),
86. Jiang, L.; Bhochhibhoya, S.; Slot, N.; de Graaf, R., Measuring product-level circularity performance: An economic value-based metric with the indicator of residual value. *Resources, Conservation and Recycling* **2022,** *186*.

87. Cilleruelo Palomero, J.; Freboeuf, L.; Ciroth, A.; Sonnemann, G., Integrating circularity into Life Cycle Assessment: Circularity with a life cycle perspective. *Cleaner Environmental Systems* **2024,** *12*.
88. EMF *Circularity Indicators: An approach to measuring circularity*; Ellen MacArthur Foundation and ANSYS Granta: 2019; pp 1-98.
89. Cullen, J. M., Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *Journal of Industrial Ecology* **2017,** *21*, 483-486.
90. Brunner, P. H.; Rechberger, H., Practical handbook of material flow analysis. *The International Journal of Life Cycle Assessment* **2004,** *9*, 337-338.
91. Geyer, R.; Jambeck, J. R.; Law, K. L., Production, use, and fate of all plastics ever made. *Science Advances* **2017,** *3*, e1700782.
92. European Bioplastics, Bioplastics market development update 2025. In European Bioplastics e.V: Germany, 2025.
93. Islam, M. M.; Chaudry, S.; Thornton, A. W.; Haque, N.; Lau, D.; Bhuiyan, M.; Pramanik, B. K., Environmental footprint of polylactic acid production utilizing cane-sugar and microalgal biomass: An LCA case study. *Journal of Cleaner Production* **2025,** *496*.
94. Pinlova, B.; Sudheshwar, A.; Vogel, K.; Malinverno, N.; Hischier, R.; Som, C., What can we learn about the climate change impacts of polylactic acid from a review and meta-analysis of lifecycle assessment studies? *Sustainable Production and Consumption* **2024,** *48*, 396-406.
95. Fonseca, A.; Ramalho, E.; Gouveia, A.; Figueiredo, F.; Nunes, J., Life Cycle Assessment of PLA Products: A Systematic Literature Review. *Sustainability* **2023,** *15*.
96. Torkelis, A.; Dvarionienė, J.; Denafas, G., The Factors Influencing the Recycling of Plastic and Composite Packaging Waste. *Sustainability* **2024,** *16*.
97. Yousaf, A.; Al Rashid, A.; Polat, R.; Koç, M., Potential and challenges of recycled polymer plastics and natural waste materials for additive manufacturing. *Sustainable Materials and Technologies* **2024,** *41*.
98. Tsalis, T.; Stefanakis, A. I.; Nikolaou, I., A Framework to Evaluate the Social Life Cycle Impact of Products under the Circular Economy Thinking. *Sustainability* **2022,** *14*.
99. Matos, F.; Godina, R.; Jacinto, C.; Carvalho, H.; Ribeiro, I.; Peças, P., Additive Manufacturing: Exploring the Social Changes and Impacts. *Sustainability* **2019,** *11*, 3757.
100. Bhatnagar, A.; Härri, A.; Levänen, J.; Niinimäki, K., Exploring the role of social life cycle assessment in transition to circular economy: A systematic review. *Resources, Conservation and Recycling* **2024,** *207*.
101. Yang, X.; Smith, T. M.; Prado, A. M.; Yang, Y., Net-zero greenhouse gas mitigation potential across multi-tier supply chains. *Communications Earth & Environment* **2025,** *6*.
102. Thomas, J.; Patil, R. S.; Patil, M.; John, J., Navigating the Labyrinth of Polymer Sustainability in the Context of Carbon Footprint. *Coatings* **2024,** *14*.
103. Bui, B.; Houqe, M. N.; Zaman, M., Climate governance effects on carbon disclosure and performance. *The British Accounting Review* **2020,** *52*.
104. Wu, W.; Shah, F.; Ahmad, A.; Ma, C.; Shun Chan, F. K.; Zou, G., Challenges and solutions for global plastic governance. *Innovation (Camb)* **2025,** *6*, 100943.
105. Garcia-Gutierrez, P.; Amadei, A. M.; Klenert, D.; Nessi, S.; Tonini, D.; Tosches, D.; Ardente, F.; Saveyn, H., Environmental and economic assessment of plastic waste recycling. *A Comparison of Mechanical, Physical, Chemical Recycling and Energy Recovery of Plastic Waste* **2023**.
106. Huysman, S.; Debaveye, S.; Schaubroeck, T.; Meester, S. D.; Ardente, F.; Mathieux, F.; Dewulf, J., The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling* **2015,** *101*, 53-60.
107. Schulte, P. A., A global perspective on addressing occupational safety and health hazards in the future of work. *Med Lav* **2020,** *111*, 163-165.
108. Yıldız-Geyhan, E.; Yılan, G.; Altun-Çiftçioğlu, G. A.; Kadırgan, M. A. N., Environmental and social life cycle sustainability assessment of different packaging waste collection systems. *Resources, Conservation and Recycling* **2019,** *143*, 119-132.

109. Social Traders The ESG blind spot: why the 'S' is essential to business success. https://www.socialtraders.com.au/news/the-esg-blind-spot-why-the-s-is-essential-to-business-success (21 Jan),
110. Lange, J.-P., Managing Plastic Waste─Sorting, Recycling, Disposal, and Product Redesign. *ACS Sustainable Chemistry & Engineering* **2021,** *9*, 15722-15738.
111. UNEP Guidelines for social life cycle assessment of products and organizations 2020; United Nations Environment Programme: 2020.
112. Niero, M.; Rivera, X. C. S., The Role of Life Cycle Sustainability Assessment in the Implementation of Circular Economy Principles in Organizations. *Procedia CIRP* **2018,** *69*, 793-798.
113. Wu, Y.; Tham, J., The impact of environmental regulation, Environment, Social and Government Performance, and technological innovation on enterprise resilience under a green recovery. *Heliyon* **2023,** *9*, e20278.
114. Kaufmann, W.; Lafarre, A., Does good governance mean better corporate social performance? A comparative study of OECD countries. *International Public Management Journal* **2020,** *24*, 762-791.
115. O'Keeffe, V.; Howard, S.; Neall, A.; Cebulla, A.; Hordacre, A.-L. *Harmful Behaviours in the Workplace: A Literature Review*; Australian Industrial Transformation Institute: Adelaide:, 2024.
116. Pickin, J.; Macklin, J. *National Waste and Resource Recovery Report 2024*; The Department of Climate Change, Energy, the Environment and Water: Melbourne, Australia, 2025.
117. Bracquené, E.; Dewulf, W.; Duflou, J. R., Measuring the performance of more circular complex product supply chains. *Resources, Conservation and Recycling* **2020,** *154*.
118. Vadoudi, K.; Deckers, P.; Demuytere, C.; Askanian, H.; Verney, V., Comparing a material circularity indicator to life cycle assessment: The case of a three-layer plastic packaging. *Sustainable Production and Consumption* **2022,** *33*, 820-830.
119. Madival, S.; Auras, R.; Singh, S. P.; Narayan, R., Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology. *Journal of Cleaner Production* **2009,** *17*, 1183-1194.
120. Papong, S.; Malakul, P.; Trungkavashirakun, R.; Wenunun, P.; Chom-In, T.; Nithitanakul, M.; Sarobol, E., Comparative assessment of the environmental profile of PLA and PET drinking water bottles from a life cycle perspective. *Journal of Cleaner Production* **2014,** *65*, 539-550.
121. Geyer, R.; Jambeck, J. R.; Law, K. L., Production, use, and fate of all plastics ever made. *Sci Adv* **2017,** *3*, e1700782.
122. OECD, Global Plastics Outlook: Economic drivers, environmental impacts and policy options. OECD publishing: Paris, 2022.
123. Ragaert, K.; Delva, L.; Van Geem, K., Mechanical and chemical recycling of solid plastic waste. *Waste Manag* **2017,** *69*, 24-58.
124. Eriksen, M. K.; Christiansen, J. D.; Daugaard, A. E.; Astrup, T. F., Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling. *Waste management* **2019,** *96*, 75-85.
125. Schyns, Z. O. G.; Shaver, M. P., Mechanical Recycling of Packaging Plastics: A Review. *Macromol Rapid Commun* **2021,** *42*, e2000415.
126. O'Farrell, K.; Caggiati-Shortell, G.; Rhodes, L.; Harne, F. *Australian Plastics Flows and Fates Study 2024*; P1442; Department of Climate Change, Energy, the Environment and Water: 2025.
127. Kirch, C.; Saloni, D., Closing the loop: Recycling PLA waste from 3D printing into value-added filament at NC State University. *BioResources* **2025,** *21*, 13-15.
128. Grand View Research Recyclable 3D Printing Filament Market (2025 - 2033). https://www.grandviewresearch.com/industry-analysis/recyclable-3d-printing-filament-market-report (27 Jan),
129. Emami, N.; Nguyen, Q. A.; Miatto, A.; Fry, J.; Taskhiri, M. S.; Li, M.; Lenzen, M.; Lau, D.; Schandl, H., Material flow analysis of plastics in Australia: Towards a circular economy of polymers. *Resources, Conservation and Recycling* **2026,** *227*.
130. ACR Australian Recycling Infrastructure, Capacity and Readiness (Plastic and Paper); Australian Council of Recycling: Kensington, VIC, 2022.

 doi:10.20944/preprints202603.1193.v1

131. Dri, M.; Canfora, P.; Gaudillat, P.; Antonopoulos, I., Best Environmental Management Practice for the Waste Management Sector. 2018.
132. ISO14040, Environmental management — Life cycle assessment — Requirements and guidelines. In the International Organization for Standardization: 2017.
133. Bui, M.; Adjiman, C. S.; Bardow, A.; Anthony, E. J.; Boston, A.; Brown, S.; Fennell, P. S.; Fuss, S.; Galindo, A.; Hackett, L. A.; Hallett, J. P.; Herzog, H. J.; Jackson, G.; Kemper, J.; Krevor, S.; Maitland, G. C.; Matuszewski, M.; Metcalfe, I. S.; Petit, C.; Puxty, G.; Reimer, J.; Reiner, D. M.; Rubin, E. S.; Scott, S. A.; Shah, N.; Smit, B.; Trusler, J. P. M.; Webley, P.; Wilcox, J.; Mac Dowell, N., Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science* **2018,** *11*, 1062-1176.
134. Baumers, M.; Dickens, P.; Tuck, C.; Hague, R., The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change* **2016,** *102*, 193-201.
135. United Nations Environment Programme Sustainability and Circularity in the Textile Value Chain - A Global Roadmap; Paris, 2023.
136. Kianian, B.; Tavassoli, S.; Larsson, T. C., The Role of Additive Manufacturing Technology in Job Creation: An Exploratory Case Study of Suppliers of Additive Manufacturing in Sweden. *Procedia CIRP* **2015,** *26*, 93-98.
137. Kirchain, R.; Moore, E.; Field, F. Preparing the Advanced Manufacturing Workforce: A Study of Occupation and Skills Demand in the 3D/Additive Manufacturing Industry; 2022.
138. Graedel, T. E.; Allwood, J.; Birat, J.-P.; Buchert, M.; Hagelüken, C.; Reck, B. K.; Sibley, S. F.; Sonnemann, G., What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology* **2011,** *15*, 355-366.
139. EMF, Towards a circular economy: business rationale for an accelerated transition. *Greener Manag International* **2015,** *20*.
140. Productivity Commission Australia's circular economy: unlocking the opportunities; Canberra, 2025.
141. Cardillo, M. A. d. R.; Basso, L. F. C., Revisiting knowledge on ESG/CSR and financial performance: A bibliometric and systematic review of moderating variables. *Journal of Innovation & Knowledge* **2025,** *10*.
142. Cort, T.; Esty, D., ESG Standards: Looming Challenges and Pathways Forward. *Organization & Environment* **2020,** *33*, 491-510.
143. ACSI *ESG Reporting Guide for Australian Companies*; Australian Council of Superannuation Investors: Victoria, 2015.
144. Dye, J.; McKinnon, M.; Van der Byl, C., Green Gaps: Firm ESG Disclosure and Financial Institutions' Reporting Requirements. *Journal of Sustainability Research* **2021,** *3*.
145. Tunn, V. S. C.; Bocken, N. M. P.; van den Hende, E. A.; Schoormans, J. P. L., Business models for sustainable consumption in the circular economy: An expert study. *Journal of Cleaner Production* **2019,** *212*, 324-333.
146. Marrucci, L.; Daddi, T.; Iraldo, F., The integration of circular economy with sustainable consumption and production tools: Systematic review and future research agenda. *Journal of Cleaner Production* **2019,** *240*.
147. Singh, S.; Ramakrishna, S.; Gupta, M. K., Towards zero waste manufacturing: A multidisciplinary review. *Journal of Cleaner Production* **2017,** *168*, 1230-1243.
148. Parida, V.; Sjödin, D.; Reim, W., Reviewing Literature on Digitalization, Business Model Innovation, and Sustainable Industry: Past Achievements and Future Promises. *Sustainability* **2019,** *11*.
149. Lianos, T. P., Population, environment and welfare. In The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century, 2025; pp 116-130.
150. Biswas, W.; John, M., The important role of environmental impact assessment methodologies in sustainability education. In *The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century*, 2025; pp 288-306.
151. Luthin, A.; Traverso, M.; Crawford, R. H., Circular life cycle sustainability assessment: An integrated framework. *Journal of Industrial Ecology* **2023,** *28*, 41-58.
152. Yuan, H.; Luan, H.; Wang, X., The Impact of ESG Rating Events on Corporate Green Technology Innovation under Sustainable Development: Perspectives Based on Informal Environmental Regulation of Social Systems. *Sustainability* **2024,** *16*.
153. Padilla-Rivera, A.; Russo-Garrido, S.; Merveille, N., Addressing the Social Aspects of a Circular Economy: A Systematic Literature Review. *Sustainability* **2020,** *12*.

 doi:10.20944/preprints202603.1193.v1

154. Wu, J.; Yang, L.; Wang, B.; Liu, Y., How Does ESG Performance Enhance the Export Competitiveness of Chinese Manufacturing? *Sustainability* **2025,** *17*.
155. Larsson, A.; Lindfred, L., Digitalization, circular economy and the future of labor: How circular economy and digital transformation can affect labor. In 2020; pp 280–315.
156. Tavares, T. M.; Ganga, G. M. D.; Godinho Filho, M.; Rodrigues, V. P., The benefits and barriers of additive manufacturing for circular economy: A framework proposal. *Sustainable Production and Consumption* **2023,** *37*, 369-388.
157. Tanimoto, K., Corporate social responsibility and responsible leadership education. In *The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century*, 2025; pp 774-786.
158. Stevenson, S. L.; Hilliam, K.; Faubel, C.; Venegas, R.; Treml, E. A., Sustainability within a global environmental change context. In *The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century*, 2025; pp 98-115.
159. Dissanayaka Mudiyanselage, C. H. B.; Irwin, S.; Chappel, S. E.; Fisher, G.; Crozier, A. J.; Vandelanotte, C., External Stakeholder Engagement With State Government Physical Activity Strategies: A Qualitative Exploration. *Health Promot J Austr* **2026,** *37*, e70124.
160. Benn, S., New processes of governance: cases for deliberative decision-making? *Managerial Law* **2007,** *49*, 196-205.
161. Bolton, D.; Landells, T.; Roberts, B., Sustainable Governance and Responsive Regulation: The Higher Education Sector and Maritime Industry in Australia. *Journal of Sustainability Research* **2020,** *2*.
162. Sendra, O. A.; Carbonell, B. S., Sustainable human development and the need for climate change governance. In *The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century*, 2025; pp 653-663.
163. Elseknidy, M.; Al-Mhdawi, M. K. S.; Qazi, A.; Ojiako, U.; Mahammedi, C.; Rahimian, F. P., Developing a sustainability-driven risk management framework for green building projects: A literature review. *Journal of Cleaner Production* **2025,** *519*.
164. Godfrey, P. C.; Lewis, B., Pragmatism and pluralism: A moral foundation for stakeholder theory in the twenty-first century. In *The Cambridge companion to stakeholder theory*, Harrison, J.; Barney, J., et al., Eds. Cambridge University Press: Cambridge (UK), 2019; pp 19-34.
165. Austin, J. E.; Seitanidi, M. M., Collaborative value creation: A review of partnering between nonprofits and businesses. Part 2: Partnership processes and outcomes. *Nonprofit and Voluntary Sector Quarterly* **2012,** *41*, 929-968.
166. Huang, H.; Yang, J.; Ren, C., Unlocking ESG Performance Through Intelligent Manufacturing: The Roles of Transparency, Green Innovation, and Supply Chain Collaboration. *Sustainability* **2024,** *16*.
167. Bröhmer, J., Democracy deficit or governance deficit. In The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century, 2025; pp 787-801.
168. Rauch, E.; Dallinger, M.; Dallasega, P.; Matt, D. T., Sustainability in Manufacturing through Distributed Manufacturing Systems (DMS). *Procedia CIRP* **2015,** *29*, 544-549.
169. Afieroho, U. E.; Li, Y.; Han, Y.; Soomro, M. A.; Radujkovic, M., Transformational Community Engagement in Urban Infrastructure Public-Private Partnerships: A Governmentality Approach to Create Social Value. *Buildings* **2023,** *13*.
170. Shmelev, S. E.; Gilardi, E., Corporate Environmental, Social, and Governance Performance: The Impacts on Financial Returns, Business Model Innovation, and Social Transformation. *Sustainability* **2025,** *17*.
171. Mohammadi, N.; Omranpoor, A.; Maghsoudi, M., Drivers of Circular Economy Adoption in SMEs: Evidence from Developing Countries. *Sustainability* **2025,** *18*.
172. Blomsma, F.; Brennan, G., The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology* **2017,** *21*, 603-614.
173. Lin, W. L.; Chong, S. C.; Pek, C. K.; Yong, J. Y.; Ming, K. L. Y.; XeChung, N. L., The Causal Relationship Between Corporate Environmental Responsibility and Technological Innovation: A Conceptual Framework. In *Proceedings of the International Conference on Environmental, Social, and Governance (ICESG 2024)*, 2025; pp 33-47.

 doi:10.20944/preprints202603.1193.v1

174. Lin, W. L.; Chong, S. C.; Pek, C. K.; Yong, J. Y.; Ming, K. L. Y.; XeChung, N. L., The Impact of Greenwashing: Risks and Implications for Corporate Performance and Stakeholder Trust. In *Proceedings of the International Conference on Environmental, Social, and Governance (ICESG 2024)*, 2025; pp 77-94.
175. Octaviani, E.; Masudin, I.; Khoidir, A.; Restuputri, D. P., Material Flow Analysis for Demand Forecasting and Lifetime-Based Inflow in Indonesia's Plastic Bag Supply Chain. *Logistics* **2025,** *9*.
176. Bernat, K., Post-Consumer Plastic Waste Management: From Collection and Sortation to Mechanical Recycling. *Energies* **2023,** *16*.
177. Wang, C., Sustainable Supply Chain Practices in Australian Smes in the Post-COVID Recovery Era. *Frontiers in Business, Economics and Management* **2025,** *20*, 47-54.
178. Sakao, T.; Bocken, N.; Nasr, N.; Umeda, Y., Implementing circular economy activities in manufacturing for environmental sustainability. *CIRP Annals* **2024,** *73*, 457-481.
179. UniSA Opportunity knocks for Australian manufacturing. https://www.unisa.edu.au/research/covid-19/opportunity-knocks-for-australian-manufacturing/ (5 Dec),
180. De Silva Lokuwaduge, C.; de Silva, K., ESG Risk Disclosure and the Risk of Green Washing. *Australasian Business, Accounting and Finance Journal* **2022,** *16*, 146-159.
181. DCCEEW *Circular Economy Ministerial Advisory Group: Final report*; Department of Climate Change, Energy, the Environment and Water: John Gorton Building, Parkes ACT 2600, December 2024, 2024.
182. Rumsa, M.; John, M.; Biswas, W.; Brown, R. J., Waste(d) values. In The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century, 2025; pp 131-156.
183. Tumu, K.; Vorst, K.; Curtzwiler, G., Global plastic waste recycling and extended producer responsibility laws. *J Environ Manage* **2023,** *348*, 119242.