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PERSPECTIVE

Paradigm Shift to the Cross Economy: Transforming Waste Into Innovative Material Platforms

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ABSTRACT

The Cross Economy offers a forward-looking framework that reimagines resource use through the processes of Transform, Create, and Multiply. Rather than focusing primarily on closed-loop recycling, as seen in most Circular Economy models, the Cross Economy enables systemic value creation by unlocking new material streams, technologies, and economic opportunities. Using spent coffee grounds (SCGs) as a case in point, we illustrate how precision fractionation yields high-purity cellulose, lignin, lipids, and polyphenols that can be recombined into advanced bio-composites with properties comparable to, and in some cases surpassing, petrochemical benchmarks. Beyond this example, economic modeling and life cycle assessment demonstrate the potential of the Cross Economy to deliver near-zero waste, market competitiveness, and alignment with United Nations Sustainable Development Goals (UN SDGs). By shifting the narrative from recycling to regeneration and multiplication of value, the Cross Economy provides a replicable blueprint for inclusive green growth and resilient post-petroleum industrial ecosystems.

1 | Introduction

Throughout history, materials have not merely served as tools but have acted as fundamental drivers of human society. Major transitions in civilization, from the Stone Age to the information technology era, have been closely tied to advances in how materials are discovered, processed, and applied. Stone, bronze, and iron enabled survival and warfare; glass and paper facilitated the spread of science and knowledge; and plastics and semiconductors laid the foundation for mass production and modern electronics [1]. These examples reveal that materials are not passive substrates but active agents that shape innovation, societal values, and the relationship between humanity, nature, and technology. In this sense, creativity and technological advancement have been alternately constrained or accelerated, depending on how material potentials are rediscovered and redefined [2]. Accordingly, the future of society will depend not only on the development of new technologies but also on how materials are utilized and transformed to unlock their latent possibilities [3]. However, recent critiques have highlighted aplateau in material-based innovation [4]. These constraints arise in part from current industrial paradigms, which limit how we perceive and harness the vast potential of materials [5]. At the same time, escalating global crises such as climate change [6] and environmental degradation [7] are placing systemic limits on existing models of technological progress [8]. From a sustainability perspective, it is increasingly clear that innovation driven solely by “new technologies” is inadequate; a more fundamental redesign of the economic and societal systems that underlie them is required.

Since the late twentieth century, the fundamental flaws of the linear “take-make-waste” economic model have become increasingly apparent [9]. This system, which prioritizes throughput over regeneration, drives resource depletion, environmental degradation, and the unsustainable accumulation of waste [10]. These mounting ecological pressures have intensified global urgency for a shift towards sustainable development.

The circular economy (CE) originated in the 1970s as a solution to the linear "take-make-dispose" model, initially focusing on reactive waste management like landfill regulation amid growing resource scarcity. This first phase, termed CE 1.0 by Reike et al. (2018) [11], was driven by environmental compliance. The concept later evolved into CE 2.0, gaining momentum in the 1990s and 2000s. Influenced by reports like the Brundtland Report [12], this new phase shifted the focus from mere compliance to seeing economic opportunity in environmental challenges. CE 2.0 integrated market-based, efficiency-driven practices into core business operations, emphasizing cost reduction, risk management, and product value retention [11, 13].

Despite promoting regenerative principles, early CE frameworks have been critiqued for significant theoretical and practical limitations. A primary objection lies in their disregard for thermodynamic constraints, as the inherent degradation of material quality over recycling cycles renders perpetual circularity unattainable [14]. A second concern is that the CE paradigm may impose unjust economic constraints on developing nations by discouraging reliance on proven, low-cost raw material sectors [13, 15].

These limitations are compounded by severe environmental consequences, as improperly managed waste pollutes ecosystems and exacerbates greenhouse gas emissions and biodiversity loss [16]. Within industrial systems that remain structurally linear, isolated interventions such as standalone recycling initiatives fail to resolve underlying inefficiencies. This has led scholars to conclude that the CE, in its present form, functions less as a catalyst for genuine industrial transformation and more as an optimization strategy for a flawed system, leaving its potential environmental benefits largely unrealized [17, 18].

Of particular concern is the disproportionate energy consumption and greenhouse gas emissions linked to both resource extraction and waste disposal [17]. These impacts pose severe long-term risks to the viability of the global economic system, with some projections warning of systemic instability within decades if current trends continue [19].

Beyond these technical and environmental limitations are governance challenges that further exacerbate the problem. Inconsistent waste classification and regulatory frameworks across regions facilitate transnational waste flows, allowing high-income countries to externalize the environmental costs of disposal onto less-developed nations [20].

In response to these shortcomings, alternative and complementary frameworks have emerged under the rubric of CE 3.0, which incorporates the notion of transformational CE [11, 13]. Unlike earlier iterations that emphasized technical fixes or business efficiencies, this perspective frames CE as a broader political and socio-cultural project aimed at addressing the root causes of unsustainability. It prioritizes systemic change, including shifts in values, institutions, and governance structures. Within this context, the Cross Economy closely aligns with the transformational CE vision, yet extends it further by centering material transformation as a pathway to create and multiply value across the economy and society. The Cross Economy advances beyond material circularity to emphasize the cross-pollination of knowledge, practices, and governance mechanisms, elements essential for enabling deep sustainability transitions. By introducing a clearer conceptual foundation under the term "Cross Economy," this framework avoids the ambiguity of conventional CE interpretations and explicitly highlights how material innovation can "cross up" into higher dimensions of economic growth.

The Cross Economy model reconceptualizes previously untapped materials, overlooked due to technological or perceptual limitations, as *latent assets to be redirected into entirely new industrial applications or value chains through the integration of emerging technologies* [2]. The model redefines the concept of a resource, broadening the term to include all potential materials, moving beyond circular economy's loop-based logic toward systemic innovation in material development and industrial creation. The Cross Economy thus enables intersectoral and cross-dimensional convergence, facilitating near-zero-waste systems through the integration of surplus and post-use materials into new, high-value applications. By reimagining resource use, it can provide a blueprint for inclusive green growth and advance specific Sustainable Development Goals (SDGs) including, but not limited to, responsible consumption and production (SDG 12) and sustainable economic growth and decent work (SDG 8).

This perspective begins by outlining the structural limitations inherent in both linear and circular economy models, and subsequently articulates the theoretical and empirical foundations of the Cross Economy framework. Moving beyond a singular focus, we present spent coffee grounds (SCGs) as a model case alongside a range of representative waste streams to illustrate the versatility and scalability of the Cross Economy approach. Through meta-synthesis analysis, we evaluate the anticipated economic, environmental, and social impacts of the Cross Economy integration across diverse sectors, underscoring its potential to enable regenerative, post-linear industrial systems. By doing so, this study aims to offer a sustainable and scalable pathway for overcoming the unresolved challenges of resource depletion and environmental harm.

2 | Methodology

2.1 | From Linear to Cross Economy

The Cross Economy model addresses the limitations of both the traditional linear economy ("take–make–waste") and the circular economy (focused on "reduce–reuse–recycle") by converting undervalued or waste materials into high-value, high-dimensional products through innovations in materials science and sustainable processing technologies. Figure 1 illustrates the distinctive characteristics of the Linear–Circular–Cross Economy. Beyond recycling, the Cross Economy aims to achieve an "up-valuation" of materials via morphological and functional transformation, thereby enhancing region-specific industries by transforming currently undervalued regional products and overall environmental resilience.

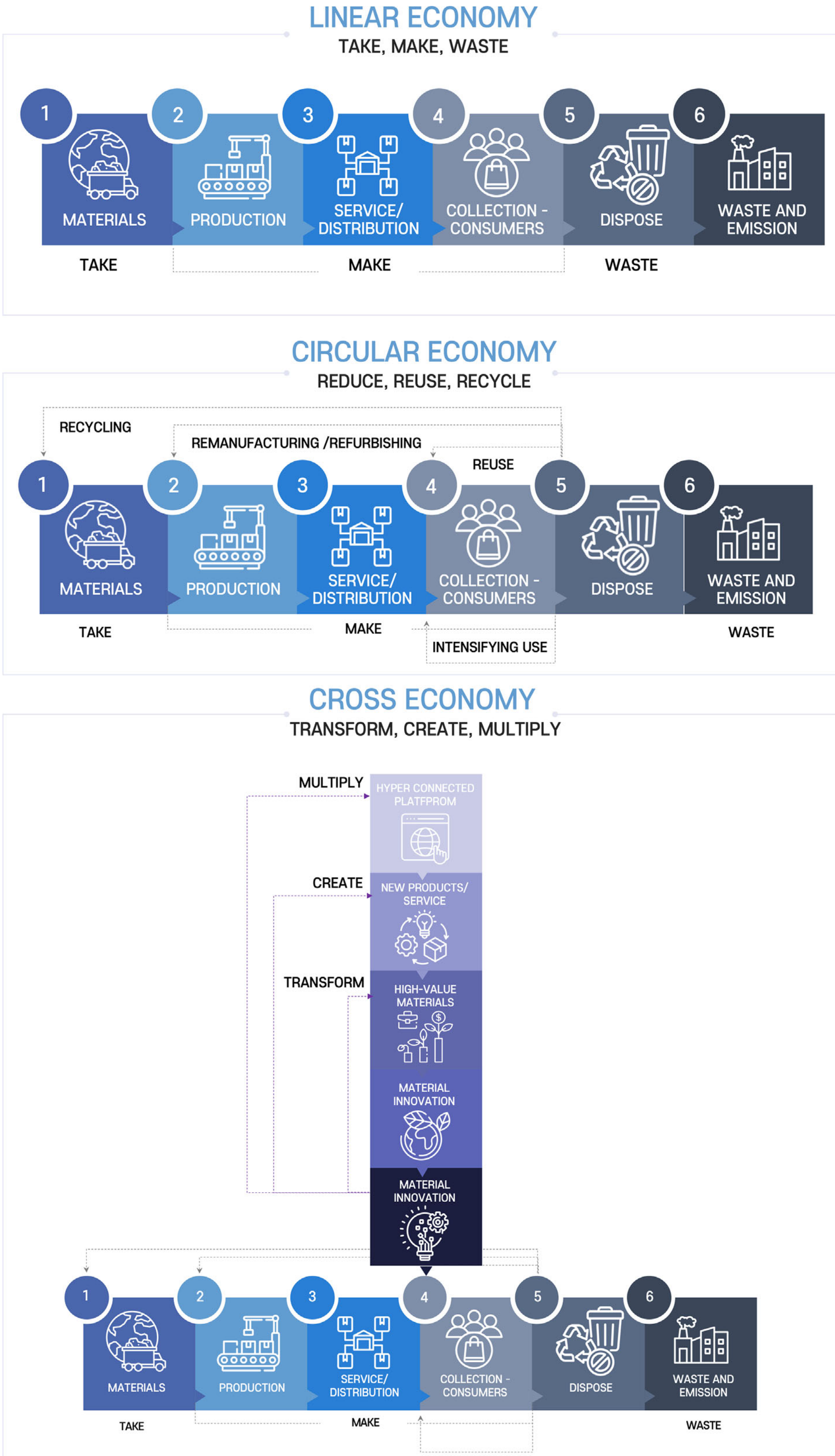

FIGURE 1 | A conceptual model illustrating the evolution of economic paradigms—from the resource-consumptive Linear Economy to the restorative Circular Economy, and ultimately to the transformative Cross Economy—adapted from [2, 21]: (a) Linear Economy; (b) Circular Economy; (c) Cross Economy. Unlike the Linear Economy's "Take—Make—Waste" and the Circular Economy's "Reduce—Reuse—Recycle", the fundamental strategy of the Cross Economy is encapsulated in "Transform—Create—Multiply". The primary expected outcome of this model is the achievement of "beyond-sustainability", defined as ethical growth enhancing economic prosperity, sustainability, and well-being of people through material value-creating innovation. The impact can reach broader economic, environmental, and social domains, unlocking growth potential while improving resource efficiency and social equity.

Moreover, the Cross Economy not only pursues sustainability objectives but places "resilience" at the core of economic development. The resilience envisioned by the Cross Economy through the rediscovery of material potential extends beyond simply overcoming the environmental and economic challenges that arise when reusable natural resources are underutilized. It lies in cultivating region-specific environmental and economic resilience competitiveness by valorizing locally embedded, indigenous resources [22].[1] For example, by strategically identifying and valorizing "locally abundant" yet "underutilized" resources through technological innovation, small and mid-sized towns worldwide, grappling with both resource depletion and economic decline, can revitalize their regional economies and develop globally competitive industrial bases [23]. This process redefines materials once dismissed as waste or environmental burdens into high-value economic resources, thereby unlocking new industrial pathways and expanding economic potential [24]. In doing so, the Cross Economy offers a transformative strategic framework: one that uncovers latent material value, catalyzes a synergistic relationship between sustainability and economic development, and facilitates the inclusion of local communities within globally distributed value chains, aligning with current industrial ecosystems as well.

A salient example is the valorization of SCGs, a globally abundant waste stream, into advanced functional materials through precision fractionation, targeted purification, and integrative materials engineering strategies. Over 90% of SCGs collected by cafés and instant-coffee plants are disposed in municipal landfills [25], yet it contains cellulose, lignin, polyphenols, lipids, and caffeine, all of which can serve as precursors for high-value materials [26, 27]. This resource transformation underscores the potential to secure both sustainability and innovation across industries through applications such as biodegradable packaging, activated carbon, polymer films, or even energy-storage materials [28–30].

Thus, the Cross Economy transcends the constraints of linear and circular models by coupling undervalued or waste resources with advanced materials science technologies and process engineering to generate high-value outputs, ultimately conferring resilience to both regional economies and global markets. This study demonstrates the "Transform—Create—Multiply" sequence of the Cross Economy model using SCGs as a case study, elucidating its synergies among innovation, sustainability, and regional development. Given the central role of scientific and technological innovation in enabling the Cross Economy, Figure 2 illustrates how material science–driven mechanisms interact with industrial and economic systems to activate latent material potential and generate new value pathways.

2.2 | Analytical Framework: Cross Economy's "Transform–Create–Multiply"

To assess the industrial relevance of the Cross Economy concept, this perspective proposes a three-phase framework—Transform, Create, Multiply—that clearly maps how resources can be redefined and scaled into sustainable, value-generating systems [2]. In the Transform phase, materials once considered waste undergo targeted physical and chemical modifications to unlock new functionalities. The Create phase focuses on generating industrial value through advanced material design and engineering. Finally, the Multiply phase drives the widespread adoption of these innovations across economic, environmental, and societal domains, enabling widespread real-world application and impact.

A striking example of material transformation is quartz. primarily composed of silicon dioxide (SiO_2), once viewed as an abundant, low-value mineral found in ordinary sand. This perception changed in 1916, when Jan Czochralski developed a method to grow single-crystal silicon using a quartz crucible [31], making a pivotal moment that transformed quartz from a common raw material into the foundation of the modern semiconductor industry [31, 32]. Before the invention of the Czochralski process, quartz, now a foundational material underpinning semiconductor-driven advanced industrial empires, no more valuable than common street stone. Its uses were largely confined to low-value applications such as window glass, with little to no strategic or industrial significance. In other words, what was once considered an inconsequential material was redefined through scientific and technological innovation into a high-value platform underpinning modern industries such as computing, artificial intelligence, telecommunications, and electric mobility [33–35]. This case illustrates how materials can evolve from waste (long regarded as devoid of value) to wealth (reborn as a driver of transformative innovation), by unlocking latent potential and converting one form of material into another through deliberate, knowledge-driven transformation. This process encapsulates the central tenet of the Cross Economy: that materials are not static end-products, but dynamic value reservoirs waiting to be activated through scientific insight and creative engineering. The marked contract, the circular economy remains primarily concerned with closing resource loops within production and consumption systems, relying on physical recycling and incremental efficiency improvements rather than systemic redesign [36, 37]. The Cross Economy, however, moves beyond the expansion of value chains to build new ecosystems of transformation, enabling a strategic transition toward industrial sustainability that couples technological advancement with institutional evolution.

2.2.1 | Phase 1: Transform

The transform phase marks the scientific redefinition of materials traditionally regarded as waste or of negligible value. Through targeted physical, chemical, or biological modification, enabled by advances in materials science, nanotechnology, and sustainable processing, these substances are converted into entirely new material forms with expanded functionality. This stage goes beyond conventional purification and separation; it seeks to uncover latent potential within raw or discarded matter and to transform it into a functional resource. Typical examples include the conversion of biomass and industrial byproducts into nanocellulose, biopolymers, or functional composites through biochemical fractionation, nanoscale machining, and surface modification. Success in this value-up phase is essential, as it defines both the technical feasibility and economic viability of the subsequent Create and Multiply phases.

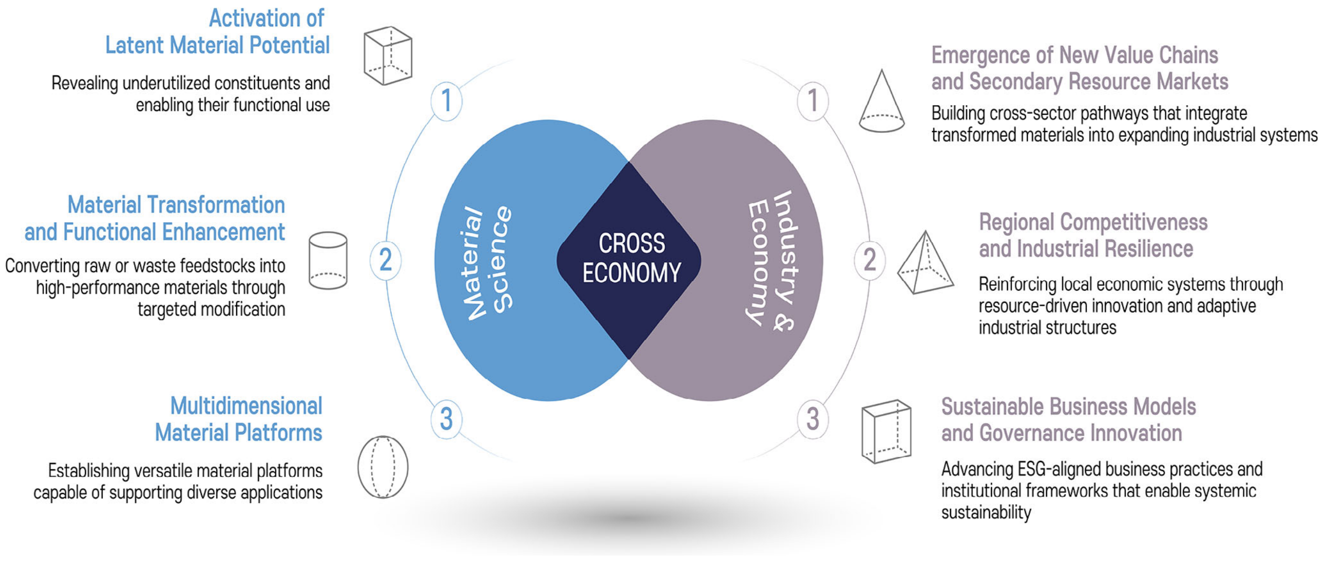

FIGURE 2 | Integrated science–industry framework underpinning the Cross Economy. The figure presents the integrative framework of the Cross Economy, showing how materials science converges with industrial and economic systems to generate new value through the Cross Economy. The interaction of these domains enables materials, new value-chain formation, and resilience-driven sustainable growth.

2.2.2 | Phase 2: Create

In the Create phase, transformed materials serve as the foundation for designing and fabricating new products, devices, or services that demonstrate tangible industrial and societal value. This stage transcends the replication of existing goods by imparting novel functionalities and pioneering entirely new use cases. It requires close integration of functional materials engineering, product design, certification, and early commercialization frameworks to validate laboratory-scale innovations under real-world operating conditions [38]. The Create phase thus serves as a bridge between R&D and industrial deployment, assessing performance, scalability, and competitiveness while catalyzing regional innovation, supply chain evolution, and investment attraction [39]. A paradigmatic example is the transformation of quartz into high-purity silicon wafers, the foundation of semiconductor chips and a technological breakthrough that not only gave rise to modern electronics but also propelled successive industrial revolutions in computing, telecommunications, and advanced manufacturing [40].

2.2.3 | Phase 3: Multiply

The Multiply phase represents the diffusion and amplification of high-value innovations born in the Create phase into broader industrial and economic ecosystems. Here, the transformation of waste into new functional materials evolves into systemic industrial renewal, reshaping value chains and spawning new markets. Unlike conventional recycling, which circulates value within existing loops, the Multiply phase creates new loops altogether, driving the emergence of novel industries and cross-sector applications that sustain long-term growth. Achieving this requires not only technological dissemination but also institutionalization, standardization, and multi-sector partnerships aligned with global sustainability frameworks such as the UN Sustainable Development Goals.

A defining historical example is the global proliferation of semiconductor technology after the 1970s, which triggered the ICT revolution and underpins a 2024 global market valued at US$8.92 trillion [41]. This evolution, from low-value quartz to a cornerstone of the digital economy, demonstrates the multiplicative power of material innovation, culminating in Industry 4.0 and reaffirming how foundational discoveries can reconfigure entire economic and industrial systems [42]. To further demonstrate how the Transform–Create–Multiply logic extends and operates across multiple resource streams, Figure 3 presents an expanded set of representative materials and their corresponding valorization pathway.

2.3 | Cross Economy Goes to Multiple Sectors

To demonstrate how the Transform—Create—Multiply framework operates across industries, Table 1 maps a range of underutilized or waste feedstocks to their progressively higher-value material and economic functions [43–74]. Each trajectory begins with the Transform phase, in which intrinsic chemical constituents, such as collagen in fish waste [44, 74] or polyphenolics in fruit peels [52, 53, 56], are extracted and refined into valuable molecular building blocks. In the Create phase, these intermediates are engineered into market-ready materials and devices, including algae-derived bioplastics [47, 48] or cellulose nanofibers [71]. Finally, during the Multiply phase, these innovations integrate across sectors, forming new industrial ecosystems that catalyze value creation in medicine, energy, construction, and beyond.

By uniting such diverse feedstocks, ranging from seafood byproducts to spent coffee grounds, within a single comparative matrix, Table 1 highlights the versatility, scalability, and systemic applicability of theCross Economy strategies. It provides a reference framework for evaluating technological readiness, cross-sector spillover potential, and industrial

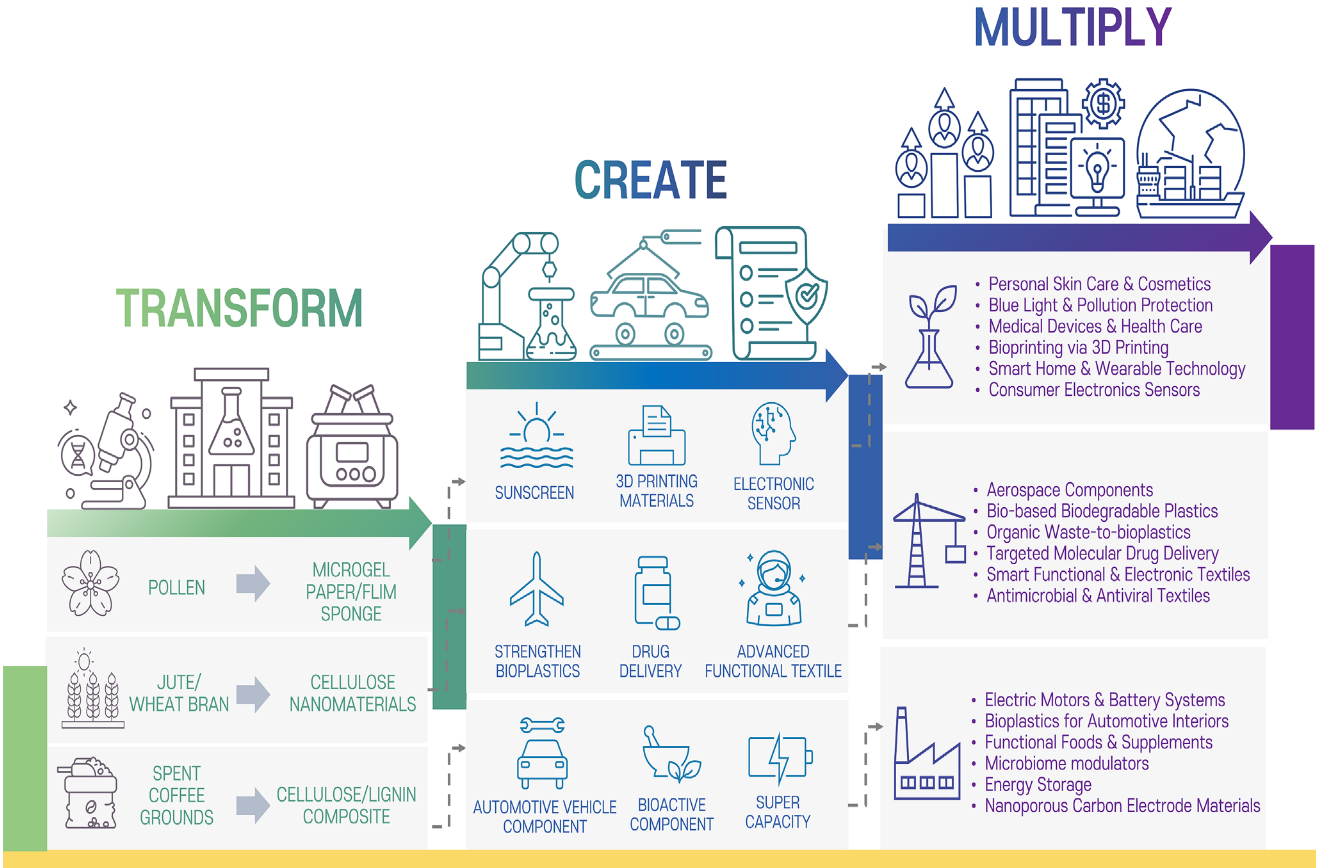

FIGURE 3 | Representative real-world examples illustrating the Cross Economy's "Transformation–Create–Multiply" framework using multiple locally abundant and underutilized resources, including pollen, jute, wheat bran, and spent coffee grounds. The figure demonstrates how diverse bio-based materials can be systematically transformed into high-value products and subsequently expanded into broad industrial applications through the Multiply phase.

transformation pathways explored in subsequent sections of this study.

2.4 | Turning Waste Into Wealth: SCGs in the Cross Economy Paradigm

In this section, spent coffee grounds (SCGs) are presented as a model system to demonstrate how an abundant yet underutilized biomass can be strategically valorized within the Cross Economy framework. Through precision fractionation, SCGs are systematically deconstructed into high-purity molecular components, which are subsequently engineered into high-performance materials and integrated across interconnected industrial and economic ecosystems. This case exemplifies how the Cross Economy framework can translate theoretical principles into practical, scalable pathways for sustainable innovation, transforming waste into enduring sources of value and resilience. Coffee consumption is a deeply ingrained global phenomenon, with an estimated 10 million metric tonnes in the 2020/2021 cycle [89]. Throughout history, coffee has symbolized wakefulness, reason, and social exchange: fueling Enlightenment-era discourse in European coffeehouses [90]; resistance against colonial labor systems [91]; and modern movements like fair trade [92]. As both a powerful cultural icon and economic driver, it is considered one of the most beloved beverages of modern society, still remains the second-most traded commodity after crude oil [91]. However, while the global coffee industry has long served as a vital engine of socio-economic and cultural exchange, it also generates vast quantities of organic waste. Case studies from Europe and North America reveal that 90–95% of SCGs are still disposed of in landfills, with only 5–10% diverted to organic recovery pathways such as composting [93].

Especially, when landfilled or improperly managed, SCGs pose significant environmental risks. Anaerobic decomposition of SCGs in landfills produces methane, a greenhouse gas with a global warming potential approximately 28 times greater than CO_2 [93]. Additionally, wastewater generated during SCG washing or processing exhibits high chemical oxygen demand (COD), which can severely deplete dissolved oxygen in aquatic environments and disrupt ecological balance [94]. Furthermore, SCGs contain bioactive compounds such as caffeine, chlorogenic acids, and polyphenols that contribute to soil phytotoxicity by inhibiting plant growth and diminishing microbial biodiversity [93]. In the context of international coffee trade, the transboundary movement and disposal of SCGs in regions lacking robust waste management systems exacerbate cross-border pollution leakage, perpetuating global environmental inequities [93].

Likewise, as it is regarded as a waste and also a cause of environmental pollution, SCGs exemplifies the kind of overlooked resource that the Cross Economy seeks to reimagine, not simply as waste, but as a feedstock for regenerative material systems. In this context, SCGs are particularly well-suited as a representative model for the Cross Economy framework for following reasons: global abundance [89]; molecular richness (e.g., cellulose, lignin, lipids, polyphenols [95]; and a pronounced gap between potential availability and current levels of valorization [93]. These characteristics allow SCGs to serve as a scalable and transferable template for demonstrating the Transform–Create–Multiply phases of the Cross Economy.

Also, only around 30% of the coffee bean's mass is extracted into the beverage, meaning that the remaining 70% ends up as SCGs, resulting in nearly 7 million tonnes of SCGs generated each year [89]. This highlights the vast scale of underutilized biomass. The conversion efficiency from green beans to SCGs varies by method, but a broadly accepted estimate is that 0.65–0.91 g of SCG is produced per gram of green beans, depending on roasting and brewing practices [89]. Given this scale and conversion ratio, SCGs represent a globally abundant, underexploited, and compositionally rich feedstock with significant potential for sustainable upcycling.

As of 2024, the global coffee industry was valued at USD 138.37 billion, supported by rising consumption in both developed and emerging markets. Ranking among the world's most traded commodities, coffee exports exceeded 130 million 60-kg bags per year, reaching a record trade value of USD 28.5 billion in 2021/22. Understanding this value chain provides critical context for identifying opportunities to transform coffee waste into new economic and material value [89]. Within the global value chain (GVC), a high degree of asymmetry persists: while production is heavily concentrated in a few efficient origins, value creation and profit margins remain skewed toward downstream actors in importing countries, underscoring systemic inequities in global coffee trade dynamics [89]. The conventional coffee value chain is composed of sequential stages including cultivation, primary processing (green coffee production), secondary processing (roasting and grinding), retailing, and consumption, ultimately ending with disposal [96]. Each stage aggregates economic value, with roasters historically capturing the largest share, 30% of the total retail price, due to the capital-intensive nature of roasting and the strategic role of brand value creation through blending and flavors engineering [96]. Retailers, international traders, local intermediaries, and farmers capture progressively smaller shares, highlighting a systemic imbalance in value distribution [96].

Applying the Cross Economy model establishes an innovative secondary value chain atop the existing coffee industry. This SCG-based chain comprises three interconnected phases:

- Transform: Precision fractionation of SCGs to extract cellulose, lignin, oils, and polyphenols [95].
- Create: Development of high-performance products such as biocomposites [97], bioactive ingredients [98], and renewable energy carriers [99].
- Multiply: Deployment of decentralized SCG biorefineries near urban consumption hubs, fostering multi-stakeholder networks for feedstock collection, processing, and market integration [100, 101].

This regenerative pathway fundamentally redefines the endpoint of the conventional coffee value chain. Instead of concluding with consumption and disposal, spent coffee grounds (SCGs) are recast as inputs for new cycles of material innovation, adding successive layers of economic and environmental value. By leveraging existing coffee logistics, retail, and consumer networks, SCG valorization within the Cross Economy framework enables rapid, low-friction scalability.

Overall, the SCG case study exemplifies the transformative power of the Cross Economy paradigm, demonstrating how reimagining waste as a regenerative resource can simultaneously alleviate environmental pressures and catalyze new high-value industries grounded in sustainability, resilience, and systemic renewal.

3 | Analysis

3.1 | Transform, Waste to Wealth: From Agricultural Waste to Regenerative Resources

In the first phase of the Cross Economy model, Transform, redefines SCGs not as residual biomass, but as a strategic regenerative input with high techno-economic and ecological value. Through systematic upstream interventions, SCGs are repositioned within a bioresource inventory that includes coffee cherry pulp, parchment, silverskin, husk, spent grounds and other coffee processing residues [102]. This inventory enables the foundation for industrial symbiosis and regenerative manufacturing.

Notably among other residual streams, the chemical components of SCGs are rich in lignocellulosic and bioactive compounds, including cellulose (30.2 wt%), hemicellulose (25.0 wt%), lignin (12.0 wt%), lipids (13–15 wt%), proteins (17.44 wt%), and total phenolic compounds (0.437 wt%) [103–107]. These multifunctional constituents can be valorized through tailored processing methods to produce a spectrum of materials, ranging from nanocellulose and bioplastics to bio-oils and antioxidants. Table 2 presents selected examples of functional compounds derived from SCG transformation processes.

Among notable examples, nanocellulose has been successfully extracted from the cellulose- and hemicellulose-rich fractions of SCGs, producing nanofibers with nanoscale diameters and high aspect ratios, depending on the extraction technique [71]. The resulting material exhibits high specific strength and excellent gas barrier properties, enabling its application in sustainable food packaging films and bioresorbable medical scaffolds [109] [110–113]. This approach converts coffee waste into regenerative nanomaterials that rival petroleum-based barrier films without additional land or fertilizer use.

Another pathway integrates SCG-derived cellulose and lignin as bio-fillers in biodegradable polymers such as poly(butylene succinate) (PBS) and poly(lactic acid) (PLA), enhancing crystallinity, stiffness, thermal stability, and melt-flow characteristics [114, 115]. Incorporating SCG-derived lignin and cellulose into PBS biocomposites significantly improves thermo-mechanical performance, including enhanced crystallization behavior and an increase in heat deflection temperature of 11C at 20 wt.% SCGs, meeting potential suitability for interior automotive applications [115].

TABLE 1 | Potential Transform–Create–Multiply applications of underutilized biomass and waste materials across industrial sectors. This table illustrates representative pathways through which diverse underutilized or waste feedstocks, ranging from seafood byproducts and agricultural residues to algae and spent coffee grounds, can progress through the three phases of the Cross Economy model. Each entry traces how specific molecular or compositional constituents are transformed into high-value intermediates, created into advanced materials or functional products, and ultimately multiplied across multiple industries to form new value chains. By mapping these trajectories, the table highlights the scalability, versatility, and systemic potential of the Cross Economy framework to drive regenerative innovation beyond the limits of recycling and upcycling.

Raw material (Waste)	Component transform	High-value products & examples create	Industry sector multiply	Refs.
Seafood Byproducts	Collagen/Gelatin Chitosan Hydroxyapatite	Biomedical polymer Sludge stabilization & water treatment Hydroxyapatite–chitosan–gelatin scaffolds	Regenerative medicine Tissue engineering Biomedical devices Dental biomaterials Food packaging Nutraceuticals Cosmeceuticals & Nutricosmetics	[44, 75]
Tea Leaves	Polyphenols Alkaloids Proteins, fibers	Bio-based antioxidants Antimicrobial additives Active food-packaging films	Functional biomedical materials Advanced drug-delivery systems Cosmeceuticals & Nutricosmetics Sustainable food & nutraceutical packaging Smart bio interfaces & responsive coatings	[45, 76]
Algae	Algal biomass	Algae-based bioplastics Algae-based biofuels	Bioenergy & Renewable Fuels Carbon-capture & biorefinery systems Waste-treatment processes Green packaging & sustainable manufacturing	[47, 48, 77]
Crops Straws	Cellulose Hemicellulose Lignin Lipids Fatty acids n-alkanes Sterols Tocopherols Fatty alcohols Acyl glycerides	Biofuels (Biodiesel, bioethanol, bio-oils, biochar) Activated carbons/porous carbons	Bioenergy & Renewable Fuels Nutraceuticals & functional-food ingredients Green chemistry & bioprocess engineering Cosmeceuticals & Dermatological actives	[50, 73, 78, 79]
Corncob	Silica-rich ash Biosilica	Silica/silicon nanomaterials (Silica nanoparticles, Mesoporous silica, Silicon quantum dots)	Bio composite & Aggregates Bioenergy & Renewable Fuels Solar Cells, Energy Storage Device LEDs, EMI Functional foods & nutraceuticals Pharmaceuticals Waste-treatment processes	[80, 81]
Fruit Peels	Phenols Flavonoids Terpenes Proteins Vitamins Organic acids Limonene Linalool	Antioxidant actives Antimicrobial actives Anti-inflammatory actives Biodegradable & bioplastic films Antibacterial	Barrier & functional-coating technologies Cosmeceuticals & Natural skincare Smart packaging & active coatings Bioactive-ingredient engineering Chronic-disease-preventive supplements Neuroprotective agents Anti-aging pharmaceuticals Nano-antioxidants for therapeutics Green solvents & eco-friendly cleaners	[52, 53, 55]

(Continues)

Raw material (Waste)	Component transform	High-value products & examples create	Industry sector multiply	Refs.
Cinnamon	Eugenol (essential oil)	Antibacterial & anti-biofilm Perfumery Nutraceuticals Cosmeceuticals Oral-care	Luxury perfumery & functional fragrance Cosmeceuticals & Bioactive skincare Clean-beauty cosmetics Natural preservatives & antimicrobial systems	[57, 82]
Cassava	Cassava starch	Bioenergy (bioethanol, biogas) Bioplastics Starch nanomaterials Adsorbents Wastewater remediation Organic acids Antimicrobial agents	High-quality carbon credits Biorefinery & platform chemicals Bio-based polymers & materials Renewable energy & biofuels Environmental remediation & sorbents	[60, 83]
Jute	Cellulose-rich bast fibre	Natural-fibre composite Jute-PLA bio composite	Bioplastics manufacturing Lightweight automotive components Aerospace composites Green building materials Electronics housings	[84–86]
Brewer's Spent Grain	Protein-lignin Celluloes Hemicellulos	Adsorbents Soil remediation Biocatalyst Active packaging Coating Film Bioenergy (bioethanol, biogas, pyrolytic bio-oil/char)	Tissue engineering Regenerative medicine 3-D cell-culture biotechnology High-throughput drug screening	[63, 64]
Pollen	Sporopollenin exine capsules Microgels	3D-printable materials (soft matter) Flexible electronics Soft robotics Drug delivery Biosensing materials	Wound dressings Biosensors Flexible electronics Soft robotics	[66, 67]
Wheat Bran	Cellulose Lignin Starch Proteins, Polyphenols, Vitamins Minerals	Protein-polyphenol films Protein-polyphenol antioxidant coating Dietary fiber supplements Cellulose Nanocrystal & Cellulose Nanofiber	Functional foods & nutraceuticals Cosmeceuticals & Nutricosmetics Active packaging & edible films Personalized wellness & clinical nutrition Bioactive materials & coatings Prebiotic products	[69, 87]
Cereal Byproduct	Dietary fibers Simple sugars Polyphenols Phytosterols Amino acids Vitamins	Nutraceutical precursors Biopolymer films Activated-carbon adsorbents	Gas/water/wastewater treatment Skincare products Fermented foods Pharmaceutical products Sustainable & anti-fungal food packaging	[73, 88]

These SCG composites are compatible with conventional extrusion and injection molding processes, enabling cost-effective manufacturing. In particular, SCG-filled PHBV biocomposites can contribute to cost reduction and require lower processing temperatures at higher SCG contents, which could indirectly reduce energy input [116].

Taken together, these examples demonstrate that the Transform phase extends beyond waste diversion—it strategically redefines SCGs as feedstocks for high-margin, technology-driven markets, establishing the foundation for the Create and Multiply phases of the Cross Economy. Additional valorization pathways include energy recovery through biodiesel and bioethanol production, further broadening the resource potential of SCGs [117, 118].

SCG-derived cellulose and lignin can be blended with biodegradable polymers such as PLA or TPS to create biocomposites

TABLE 2 | Compositional profile, functional roles, and material-derived applications of spent coffee grounds (SCGs). This table summarizes the key biochemical constituents of SCGs, their corresponding functional properties, and representative applications across material, chemical, and energy domains. By linking compositional characteristics to potential end uses, it highlights how SCGs serve as multifunctional precursors for high-value products within the Cross Economy framework.

Component	Composition (wt%)	Functional role	Applications	Materials derived	Refs.
Cellulose	30.2	Structural polysaccharide; rigidity; nanocellulose precursor	Pulp/paper, nanocellulose, biocomposite reinforcement, bioethanol	Nanocellulose films, aerogels, reinforcement fibers	[103]
Hemicellulose (galacto-/ arabinomannans)	25.0	Amorphous polysaccharide; viscosity; film forming; dietary fiber	Edible/biodegradable films, bioethanol, prebiotics	Biodegradable films, hydrogel matrices	[103, 104]
Lignin	12.0	Phenolic polymer; UV barrier; antioxidant	Antioxidant extracts, phenolic adhesives, carbon precursors	Lignin-based resins, carbon fibers, biochar	[103, 104]
Dietary Fiber	60.49	Insoluble + soluble fiber; digestion modulator; prebiotic	Dietary supplements, functional foods	Fiber reinforced biocomposites, encapsulation matrices	[26, 104]
Proteins	17.44	Amino acid source; nutritional value	Protein hydrolysates, fermentation substrates, animal feed	Protein-based adhesives, nutrient films, bioplastics	[104]
Lipids (Linoleic acid/ Palmitic acid)	13-15	Energy storage, unsaturated fatty acid, Saturated fatty acid	Biodiesel, Functional Oil, Nutraceutical oil, Biodiesel feedstock		[105]
Caffeine	0.147 – 0.35	CNS stimulant; pharmacologically active	Pharma recovery, food/beverage additives	Caffeine sensing films, stimulatory patches	[104, 106, 108]
Total Phenolics	0.437	Antioxidant; radical scavenging	Food/cosmetic/pharma antioxidants	Polyphenol coatings, antioxidant nanoparticles	[106, 107]
Chlorogenic Acids	0.16	Major phenolic; antioxidant, antimicrobial	Nutraceuticals, functional foods	Antimicrobial packaging, encapsulated antioxidants	[104, 106]

with improved properties. Incorporating 15 wt.% SCGS into PLA increases ductility, lowers processing temperature, and enhances thermal stability [119]. The lignin and carbon content of SCGs also improves thermal resistance in starch blends [120]. These enhancements make SCG-based biocomposites suitable for automotive applications by boosting mechanical strength and heat tolerance [117]. Compared to traditional petrochemical-based interior panels, these bio-composites present superior environmental credentials and mechanical properties tailored to vehicle manufacturing standards.

Furthermore, such SCG-based materials are compatible with scalable, industry-standard processes like twin-screw extrusion and injection molding [121, 122]. This compatibility allows seamless integration into existing automotive manufacturing without costly retooling.

In this context, the Transform phase elevates SCGs from agricultural residue to a regenerative material class, strategically positioning them within high-growth sectors seeking sustainable alternatives.

3.2 | Create: Cross-Dimensional Product Development and Sectoral Innovation

The Create phase differentiates low-value uses of SCGs from high-value material innovations that position them as enablers of next-generation industries. Conventional applications support waste reduction but underutilize SCGs' chemical and functional potential, yielding limited economic value [123].

High-value applications of SCGs harness their biochemical and structural properties to create advanced materials for technology-driven industries. The automotive sector exemplifies this potential. Although about 81% of SCG research focuses on bioenergy, their high lignocellulosic, lipid, and polyphenolic content makes them effective bioplastic additives that enhance mechanical strength and thermal stability. SCG-based bioplastics meet industry standards for structural integrity and heat resistance while remaining compatible with existing manufacturing methods, such as extrusion, injection molding, and thermo-pressing, allowing adoption without major retooling. This alignment supports the automotive industry's transition toward ESG goals and carbon-neutral supply chains, reinforcing the broader pursuit of sustainable innovation. Notably, SCG-derived biocomposites are now being developed for diverse automotive interior and structural components, enabled by the selective conversion of SCG-derived cellulose, lignin, and lipids into application-specific composite matrices [100, 124].

1) Door-trim and interior side-panel substrates

Micronized SCG fibers dispersed in bio-polypropylene or PLA form a lightweight yet rigid composite that readily substitutes the talc-filled PP traditionally molded into Class-A door panels. The SCG lignocellulose network stiffens the polymer matrix, allowing a thinner wall section and therefore lower mass, while its dark hue masks scuffing without additional pigment. Because these panels account for a large wetted area inside the cabin, replacing petro-plastics with SCG biocomposite tangibly lowers the vehicle's embedded CO_2 and showcases visible "green" content, satisfying both OEM life-cycle targets and consumer expectations for sustainable interiors [121, 125, 126].

2) Instrument-panel (IP) fascia and dashboard skins

SCG-reinforced bio-polytrimethylene terephthalate (PTT) composites deliver dimensional stability, heat-cycle durability, and surface gloss required for premium instrument-panel fascia and dashboard skins while replacing petrochemical feedstocks. Incorporation of SCGs has been shown to enhance mechanical strength and thermal stability, suppressing warpage through improved interfacial adhesion [127, 128] and enables "mold-in-color" processing that eliminates secondary painting and streamlines production for Tier-1 suppliers aiming to decarbonize visible touch-points.

3) Seat-back shells and headliner substrates

SCG fibers blended into biopolymer matrices like polypropylene (PP) enhance mechanical strength and acoustic damping, making them viable for interior automotive parts. SCGs' porous structure reduces vibration and noise, while composites show over 40% tensile strength improvement and noise reduction coefficients up to 0.61, indicating strong potential for lightweight, moldable NVH components such as seat-backs and headliners [129, 130].

4) Engine covers and under-hood acoustic shields

Castor oil-derived long-chain bio-polyamides, such as PA 4.10, are recognized for their high-temperature resistance and chemical stability, making them suitable for under-hood automotive applications [131]. Integrating carbonized SCGs into these bio-polyamides has been explored to enhance thermal and mechanical properties while maintaining a lower density compared to traditional materials like aluminum. This approach not only utilizes non-edible, post-consumer biomass but also aligns with sustainable manufacturing practices by potentially enabling the use of existing tooling for composite molding processes [132].

5) Fuel- and brake-line tubing / quick connectors

Castor oil-derived polyamide 11 (PA11) is recognized for its flexibility and chemical resistance, making it suitable for automotive fuel and brake line applications. Incorporating cellulose nanofibers (CNF) derived from SCGs into PA11 matrices has been explored to enhance mechanical strength and barrier properties. These CNF-reinforced composites exhibit improved stiffness and reduced fuel permeation rates, while maintaining the ductility necessary for complex routing in automotive systems. This suggests the potential of utilizing SCGs-derived CNF in producing sustainable and high-performance fuel and brake line components [133].

Through these highly targeted conversions, SCGs serve not merely as fillers but as functional materials that replace petrochemical-based compounds, reduce vehicle mass, and improve the life-cycle carbon footprint of vehicle components [134]. These strategies demonstrate the depth of SCGs' versatility and the transformative effect of aligning waste valorization with high-performance material innovation. For example, reducing component weight by approximately 15–20% can improve the energy efficiency of battery electric vehicles, potentially extending their driving range by up to 6–7% under urban conditions, though the effect is more limited (~2%) during highway driving [135–137].

The advantages of SCG-based automotive biocomposites span across economic, industrial, social, and environmental dimensions. Utilizing SCGs, a widely available post-consumer waste, as a filler in polymer composites such as PLA reduces dependence on virgin petrochemical feedstocks, minimizes additional raw material processing steps, and contributes to significant cost reductions [122]. This sustainable approach mitigates risks associated with price volatility and supply disruptions of crude oil, and in oil-importing countries, enhances national economic resilience through import substitution. Moreover, the establishment of localized SCG supply chains may enable inclusive, regionally distributed value creation.

From an industrial perspective, the SCG-derived composites are compatible with existing processing methods such as twin-screw extrusion and injection molding [117, 118]. Their ease of integration allows automotive manufacturers to adopt sustainable materials without major equipment overhauls. The SCG-reinforced polypropylene biocomposites demonstrated mechanical performance comparable to conventional polypropylene, with a tensile strength reaching 30.6 MPa and a Young's modulus of up to 1549 MPa when compatibilized with SEBS-g-MA and bleached SCG fillers [138]. These values meet baseline performance ranges for certain non-structural automotive components, although formal certification to ISO 527-1 and VDA 230-201 standards would require application-specific testing.

On the social front, SCG valorization encourages community-based supply chains involving urban coffee vendors, biomass collectors, and rural processors. This model promotes SME development, green job creation, and local entrepreneurship, while also engaging the public in sustainable waste management and cross economic practices.

From an environmental standpoint, the substitution of fossil-based materials with SCG-derived composites contributes to a reduction in greenhouse gas emissions, plastic waste, and environmental persistence through improved biodegradability.

TABLE 3 | Automotive Applications of SCG-Based Biocomposites: Materials, Functional Properties, and Sustainability Value.

Automotive component	SCG-based material system	Functional and performance advantages	Sustainability and industrial implications
Door trim and interior side panels	Micronized SCG fibers dispersed in bio-PP or PLA	Lightweight and rigid; allows thinner wall sections and lower mass; SCGs' dark hue masks scuffing without extra pigments	Replaces talc-filled PP; reduces embedded CO_2; supports OEM life-cycle targets and sustainable interior branding
Instrument panel fascia and dashboard skins	SCG-reinforced bio-PTT composites	High dimensional stability under heat cycle; improved mechanical strength and thermal stability; mold-in-color processing eliminates need for secondary painting	Replaces petrochemical feedstocks; facilitates decarbonization of visible interior surfaces; compatible with Tier-1 production
Seat-back shells and headliner substrates	SCG fibers blended into biopolymer matrices like PP	>40% improvement in tensile strength; porous structure enhances acoustic damping; noise reduction coefficient up to 0.61	Enables lightweight NVH (Noise, Vibration, Harshness) parts; improves interior sound quality and vibration control
Engine covers and under-hood acoustic shields	Carbonized SCGs integrated into castor oil-derived long-chain bio-polyamides	High thermal and chemical resistance; lower density compared to aluminum while maintaining mechanical integrity	Utilizes non-edible post-consumer biomass; enables sustainable under-hood applications without tooling changes
Fuel and brake line tubing/quick connectors	SCG-derived cellulose nanofibers (CNF) embedded in bio-PA11	Improved stiffness and barrier properties; reduced fuel permeation rates; maintains ductility needed for complex routing	Provides sustainable, high-performance alternatives for fuel and brake line components

By utilizing zero-burden, post-consumer waste streams, these composites facilitate alignment with major sustainability initiatives, including the EU Green Deal, through decreased lifecycle emissions. Notably, SCG-based poly(butylene succinate) (PBS) composites have demonstrated the potential to significantly mitigate Scope 3 emissions related to upstream raw material extraction and downstream disposal [139]. This positions SCG composites as strategic enablers in advancing corporate ESG objectives and meeting carbon accounting benchmarks established under the Greenhouse Gas Protocol framework.

The examples in Table 3 highlight the cross-dimensional design of the Create phase, where one waste stream (SCGs) supports multiple high-value sectors through integrated material science. The automotive use case encapsulates the holistic promise of the Cross Economy model, i.e. decarbonization, localization, and regeneration.

3.3 | Multiply: Systemic Scaling and Policy-Driven Impact

In the Multiply phase, the Cross Economy model advances beyond pilot-scale SCG valorization to systemic deployment, integrating high-value materials into global supply chains, policy frameworks, and socio-economic systems. This phase unfolds across three domains, (i) economic scaling, (ii) social impact, and (iii) environmental benefit, driven by stakeholder collaboration, modular biorefinery networks, ESG alignment, and digital traceability to ensure sustainable, scalable growth [140]. By aligning with global sustainability frameworks (e.g., UN Sustainable Development Goals), regional strategies (e.g., ASEAN Network on Bio-Circular-Green Economy), and innovative finance (e.g., green bonds, blended finance), Multiply not only amplifies economic returns but also secures policy legitimacy and societal buy-in [141, 142].

3.3.1 | Economic Scaling and Market Potential

Economically, SCGs represent a massive, under-utilized feedstock. Figure 2 illustrates how the Cross Economy model applied to SCGs multiplies once transformed and created values, focusing specifically on the automotive sector as a representative case. As analyzed earlier, SCGs can be converted into valuable feedstocks such as cellulose and lignin ($0.05–0.75/kg) [143, 144], and further utilized in the Create phase to produce bioplastic composites ($2.00–7.00/kg) [145] which can substitute conventional plastic materials including automotive components. For instance, the dashboard panel of a BMW 330i is priced at $335.00 per unit [146]. The Multiply phase highlights the market potential of this model, projecting multi-billion-dollar growth across industries including automotive, electric vehicles, and bioplastics by 2030, thereby emphasizing how waste can yield scalable industrial wealth as below as shown in Figure 4.

Taken together, SCG-based bioplastic composites can simultaneously address the automobile industry's fastest-growing submarkets unlocking a combined opportunity measured in the tens of billions of U.S. dollars by 2030, and positioning coffee-waste valorization as a flagship use-case within the

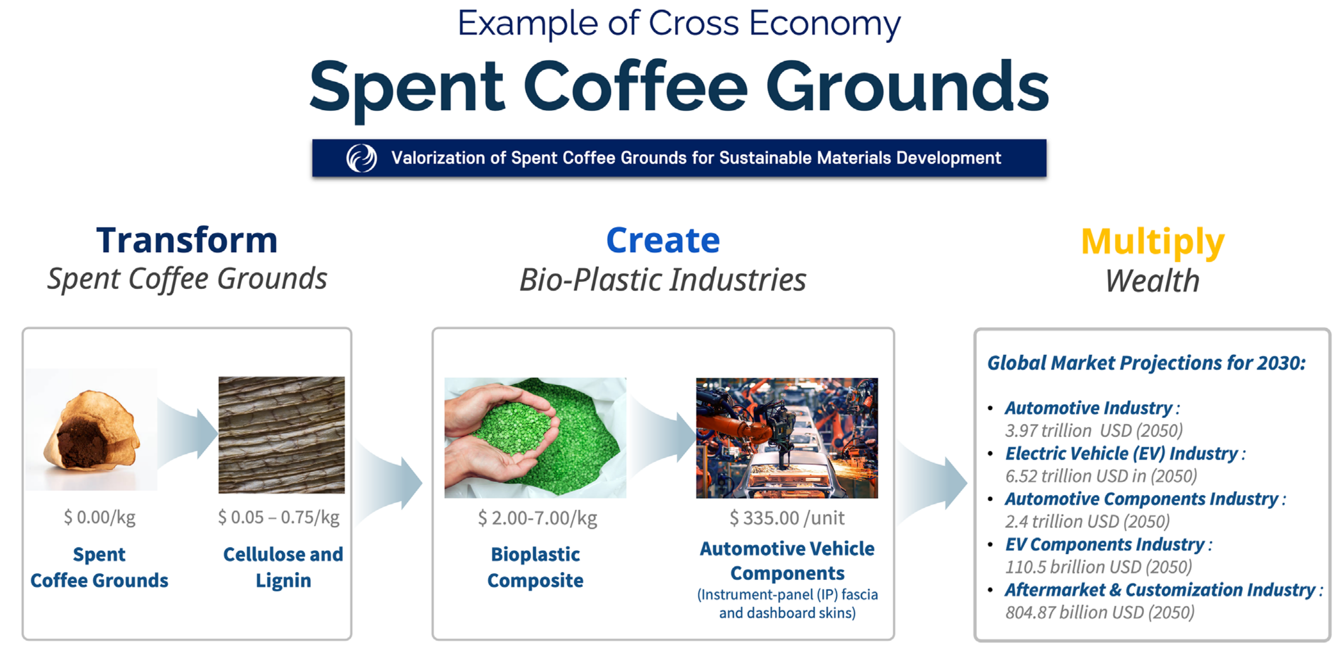

FIGURE 4 | Example of the Cross Economy: Spent Coffee Grounds.

circular-economy transition of global mobility. Additionally, beyond the automotive sector, the economic benefits of SCGs valorization can be scaled across various industrial sectors, as summarized in Table 4.

3.3.2 | Social Impact and SCGs Alignment

The impact of the Cross Economy model is not confined to the economic realm; it multiplies across social and environmental domains as well, amplifying value and transformation at every level. In the social dimension, the commercialization of high-value vehicle components fabricated from SCGs delivers transformative benefits by directly advancing multiple United Nations Sustainable Development Goals (SDGs). First, SDG 12 (responsible consumption and production) is addressed by converting a waste stream into high-performance materials, reducing reliance on virgin petrochemicals. In the Netherlands, pilot initiatives involving SCG-derived composites have demonstrated the potential to divert SCGs from landfill while fostering sustainable collaboration among cafés, waste collectors, and logistics providers [162, 163]. These projects not only mitigate CO_2-equivalent emissions by replacing petrochemical materials but also contribute to the growth of green enterprises engaged in sustainable automotive innovation.

Under SDG 9 (Industry, Innovation and Infrastructure), the establishment of regional SCGs biorefineries and composite-manufacturing workshops creates resilient industrial clusters. For example, pilot-scale facilities converting SCGs into bio-carbon fillers and biocomposite panels have the potential to create localized employment across the green manufacturing value chain. These include processing and quality assurance, as well as indirect opportunities in logistics, supply, and maintenance supporting cross economic industrial ecosystems while valorizing urban biowaste [134]. These operations not only diversify local economies but also build specialized technical capacity in sustainable materials manufacturing, enabling formerly agrarian or waste-management communities to participate in advanced industrial value chains [164].

Under SDG 8 (decent work and economic growth) and SDG 1 (no poverty), shifting SCGs from low-value uses to high-value applications such as electric-vehicle components can potentially enhance revenue streams for small enterprises [133]. The development of SCG-derived composites aligns with the goals of promoting sustainable economic growth and poverty reduction by creating new market opportunities and employment in the green manufacturing sector [165]. In coffee-consuming urban environment, micro and small enterprises that collect and preprocess SCGs have achieved measurable gains in household incomes and fostered inclusive employment: green productivity initiatives leveraging SCGs valorization have generated new jobs, particularly for women and youth, thereby advancing poverty alleviation and economic growth [166].

Using SCGs to create bioplastic products contributes directly to SDG 11 (sustainable cities and communities) by helping cities manage organic waste more effectively and build greener local economies. Instead of sending SCGs to landfills, cities can support small businesses that collect and process this material into useful products like biodegradable packaging or consumer goods. This reduces municipal waste, lowers pollution, and supports local jobs. A study highlights how SCG-based bioplastics can be sustainably produced and integrated into local production systems, reinforcing urban sustainable economy models [114]. These efforts make cities cleaner, more resource-efficient, and economically inclusive.

TABLE 4 | Valorization Pathways of Spent Coffee Grounds into High-Value Materials under the Cross Economy Model.

SCG component	Material	High-value products & examples	Industry sector	Refs.
transform	**create**		**multiply**	
Lipids	Coffee oil	ASTM D6751 compliant biodiesel Potential lubricant blending stock	Energy & Fuels Renewable Biofuels Solid Bioenergy Bioenergy Platforms	[117, 147, 148]
Cellulose & hemicellulose sugars	Hydrolyzed polysaccharides (glucose, mannose, xylose) Enzymatic saccharification after acid pretreatment	Fuel ethanol blends (E10–E85) Chemical feedstocks (acetic acid, ethylamine)		[26, 149]
Residual solids	Anaerobic digestible organics	Combined heat & power (CHP) methane fuel		[26]
Lignin & carbon framework	Biochar Bio-oil mix	Renewable heating oil substitute Soil amendment Carbon sequestration agent		[150, 151]
Lignin & carbon framework	Activated Carbon	Water/air-purification filters (MB, phenols) Pharmaceutical purification adsorbent	Environmental Remediation & Catalysis Water Treatment Air Purification Catalyst Carriers	[117, 152]
Cellulose & starch	PLA/TPS/SCG biocomposites	Compostable food packaging Single-use tableware	Biopolymers & Composites Bioplastics Green Packaging Materials Automotive Bio-composites Construction-Grade Composite Panels	[153]
Cellulose & hemicellulose	PBS/SCG composites	Agricultural mulch films Biodegradable nursery pots		[114]
Lipid-derived polyol	Transamidated/epoxidized polyol	Building insulation Automotive seating & cushion foam		[154]
Residual–clay composites	Bricks & Ceramics	Sound-insulating bricks Sustainable interior tiles	Construction & Civil Engineering Sustainable Concrete Additives Eco-ceramics & Bricks Geopolymer Binders Modified Asphalt and Rejuvenators	[155–157]
Alkali-activated residues	Geopolymers	Low-carbon subgrade fillers Road-base panels		[158]
Bio-oil + biochar	Composite rejuvenator	Pavement maintenance rejuvenator		[151]
Whole SCGs or ash	SCG-biochar modifiers	Sustainable modified asphalt		[150]
Proteins & dietary fibers	Soil Amendment, Biofertilizer	Premium organic compost Slow-release NPK biofertilizer	Agriculture & Horticulture Organic Soil Amendments Biochar-Based Fertilizers Controlled-Release Nutrients	[159]
Phenolic compounds	Polyphenolic Extracts	Antioxidant nutraceuticals Anti-aging cosmetic serums	Food, Cosmetics & Nutraceuticals Nutraceuticals Functional Food Ingredients Cosmetic Ingredients Natural Colorants	[26, 160]
Polysaccharides	Oligosaccharides	Prebiotic syrups Infant formula supplements		[161]
Lignin & carbon framework	Lignin-based activated carbon; oxygen functionalization	High-capacitance energy storage devices Electrochemical sensors	Electronics & Energy Storage Carbon Electrode Materials Green Electrodes for Sensors	[152]
Cellulose	Microcrystalline cellulose Cellulose Nanofiber Cellulose Nanocrystal	Packaging films Biomedical membranes Oxygen/moisture barrier films Reinforcement for bioplastics Tablet binder Stabilizer	Nanomaterials & Advanced Composites Cellulose Nanofibers (CNF) Cellulose Nanocrystal (CNC) Bio-inspired Nano-structured Barriers	[27, 149]

TABLE 5 | Comparison between Upcycling and the Cross Economy Model Using Spent Coffee Grounds.

Category	Upcycling	Cross economy	Refs.
Definition of Waste	Post-consumer or post-industrial products with diminished utility	Technologically unexploited or undervalued natural resources (e.g., SCGs, pollen, silverskin, etc.)	[167–169]
Application Scope and Scalability	Product-level reuse, localized or artisanal scale / Limited scalability due to small-batch or manual production constraints	Systemic, industrial-level, cross-sector applicability, globally scalable / Industrial deployment enabled by the Transform–Create–Multiply framework	[167–171]
Depth of Transformation	Retains the material's original chemical identity; structural or performance enhancements are minimal	Achieves fundamental transformation via advanced technologies (e.g., nanotechnology, bioengineering), resulting in novel material properties and functions	[167, 168]
Technological Requirements	Low to moderate; primarily based on design or craftsmanship	High; requires integrated applications of nanotechnology, biotechnology, and digital manufacturing platforms	[170, 171]
Material Quality Outcome	Typically similar to or lower than the original material; difficult to exceed the base material's performance limitations	Produces materials with superior mechanical, thermal, or barrier performance, often surpassing petroleum-based equivalents	[167, 168]
Economic Value Creation	Generates limited economic value; mostly constrained to niche sectors such as fashion or furniture	Creates high-value products applicable across sectors such as automotive, biopharmaceuticals, and construction; supports technology exports and industrial diversification	[167, 168, 170, 171]
Environmental Impact	May involve hidden environmental costs due to added energy use, logistics, or equipment for non-thermal extraction and processing	Minimizes greenhouse gas emissions and pollution through lifecycle-optimized processes and resource circularity	[167–169]

Finally, SDG 17 (partnerships for the goals) is exemplified by multi-stakeholder collaborations linking municipal governments, academic research centers, coffee cooperatives, and EV manufacturers to co-develop certification standards, shared R&D platforms, and revenue-sharing agreements. These partnerships ensure that social benefits are equitably distributed and that the SCG-based composite sector scales in a manner that is both economically viable and socially inclusive. The key differences between upcycling and the Cross Economy are summarized in Table 5.

3.3.3 | Environmental Benefits and Lifecycle Assessment

SCG-based composites and bioplastics offer significant environmental advantages over conventional petrochemical resins and neat polypropylene (PP) across their full life cycle. Classified as *zero-burden biowaste* under ISO 14044, spent coffee grounds (SCGs) arise as by-products of coffee brewing, carrying no upstream cultivation or fossil-fuel emissions [172]. Each kilogram of SCGs replacing fossil-derived polymer therefore adds "zero" feedstock global warming potential (GWP), enabling 15–25% lower GWP in PP composites containing 20 wt% SCGs [173]. Similarly, SCG/PBS and SCG/PLA biocompounds achieve 7–10% lower cumulative energy demand (CED) and carbon footprint (CF) per kilogram of material; at 60 wt% SCG loading, total CED and CF decrease by about 8% compared to neat PBS [97]. These reductions stem from eliminating polymer-synthesis burdens, lowering virgin polymer mass, and stabilizing SCGs' intrinsic carbon within the solid matrix.

Life cycle assessments identify two main process hotspots: drying and transport. Open-air drying is energy-intensive due to SCGs' high initial moisture (≈ 62 wt%), accounting for ~30% of site electricity use. A GAIA-type rotary dryer at 175°C removes 1.15 kg H_2O h^{-1} from 50 kg wet SCGs per cycle [174]. Studies show that carbon savings diminish beyond 100 km haul distances [162], emphasizing the need for localized collection hubs (< 50 km radius) and solar-assisted or waste-heat drying to minimize energy demand [174].

During disposal, SCG-reinforced PP retains > 88% of neat PP's mechanical strength after re-extrusion, achieves > 5% higher energy-recovery efficiency on incineration, and preserves 23–28% of original carbon as stable biochar [99]. Socio-economically, SCG valorization supports decentralized waste collection, local job creation, and landfill cost reduction. Industrial initiatives such as *Coffee from* (Italy) and EU-funded projects *LIFE ECOFFEED* and *WaysTUP!* are already integrating SCGs into injection-moldable thermoplastics and regional supply chains, aligning with the EU Green Deal's "waste-to-resource" agenda [175–177].

In summary, SCG-derived materials deliver:

- Up to 8.4% reductions in GWP and CED via zero-burden feedstocks and partial bio-based polymer substitution;
- Stable carbon retention in durable matrices, extending carbon residence time;
- Improved recyclability and energy recovery potential through mechanical or chemical reprocessing;
- Regional economic benefits by converting coffee waste into high-value industrial feedstocks.

To scale sustainably, future work should optimize logistics and drying efficiency—targeting $\geq$ 20% energy reduction—and incorporate cradle-to-cradle LCA models to capture full circularity [97]. With these advancements, SCG-based composites and bioplastics represent a promising driver of the Cross Economy transition toward regenerative materials innovation.

4 | Discussion

This case study demonstrates how the Cross Economy model enables new pathways for material innovation and sustainability. By linking agricultural waste, specifically spent coffee grounds (SCGs), to advanced manufacturing sectors like automotive production, it converts a low-value residue into a high-value resource, creating a novel cross-sector value stream. The following discussion explores (i) how the Cross Economy fundamentally differs from conventional upcycling approaches and (ii) the policy and institutional frameworks required to scale such innovations from concept to industrial adoption.

4.1 | The Difference Between Upcycling and the Cross Economy

The term upcycling is commonly understood as the creative reuse of post-consumer or post-industrial waste to produce items of equal or greater apparent value, yet without fundamentally altering the material's intrinsic structure or chemistry [178]. Upcycling processes typically involve only physical transformations, for example, cutting, reshaping, or surface embellishment, that leave polymer chains, fiber chemistries, or bulk properties essentially unchanged. Much like melting and resolidifying a plastic without breaking its covalent backbone, upcycled goods retain the original feedstock's molecular architecture and thus cannot exceed its inherent performance limits. As a result, although upcycling diverts waste from landfills and can foster local resilient practices, the resulting products (e.g., fashion accessories, furniture, or decorative items) rarely outperform their virgin counterparts in strength, durability, or functional lifetime [178].

Moreover, upcycling can incur hidden environmental costs. Non-thermal, "green" extraction techniques (e.g., enzymatic or ultrasonic treatments) may improve bioactive yields from food wastes such as agricultural byproducts, but they also demand additional energy inputs, specialized equipment, and logistics, which are factors that can offset modest waste-diversion benefits and lead to debates over whether certain upcycled goods truly qualify as "environmentally friendly" [179].

By contrast, the Cross Economy model begins by redefining "waste" itself. Instead of restricting the concept to end-of-life consumer products, the Cross Economy recognizes any under-utilized or undervalued natural resource, whether SCGs, silverskins, pollen, or mineral fines, as a potential feedstock for advanced materials innovation. This paradigm shift elevates formerly discarded streams into a bioresource inventory, unlocking techno-economic potential through systematic upstream valorization.

Crucially, the Cross Economy operates at a systemic, industrial scale and follows a "Transform–Create–Multiply" framework:

- Transform: Reorganize atoms into entirely new molecular architectures with emergent properties, analogous to a chemical reaction where covalent bonds break and re-form [180]. For example, isolating nanocellulose from SCGs cellulose involves deconstructing and reconstructing the polysaccharide chains to yield high-strength fibrils.
- Create: Engineer entirely new material functionalities—such as SCG-derived bioplastics exhibiting tailored mechanical, thermal, or barrier properties—that surpass petrochemical benchmarks.
- Multiply: Deploy these innovations across multiple sectors—automotive, packaging, construction—thereby amplifying economic, social, and environmental impact.

Unlike upcycling's design-focused reuse, the Cross Economy leverages advanced processing technologies (nanotechnology, bioengineering, cross-dimensional material science) to fundamentally alter feedstock properties, producing high-performance materials that exceed the limitations of their original sources. This deeper level of transformation not only minimizes waste and pollution but also catalyzes new high-value industries, drives import substitution and fosters inclusive growth in emerging markets. Figure 5 illustrates extended applications within the Cross Economy framework, specifically highlighting advanced valorization pathways of SCGs.

In summary, while upcycling offers meaningful contributions within consumer and artisanal contexts, the Cross Economy provides a comprehensive, technology-driven framework for sustainable industrial innovation delivering systemic environmental benefits, unlocking substantial economic value, and laying the groundwork for truly regenerative industrial ecosystems.

4.2 | Policy Recommendations for Scaling Cross Economy Innovations

To transition the Cross Economy from a conceptual model to a widely adopted industrial paradigm, an integrated suite of policy interventions is required. These policies must address both upstream enablers such as resource redefinition and technological valorization, and downstream barriers related to market adoption, certification, and infrastructure. The following policy recommendations provide a strategic roadmap for

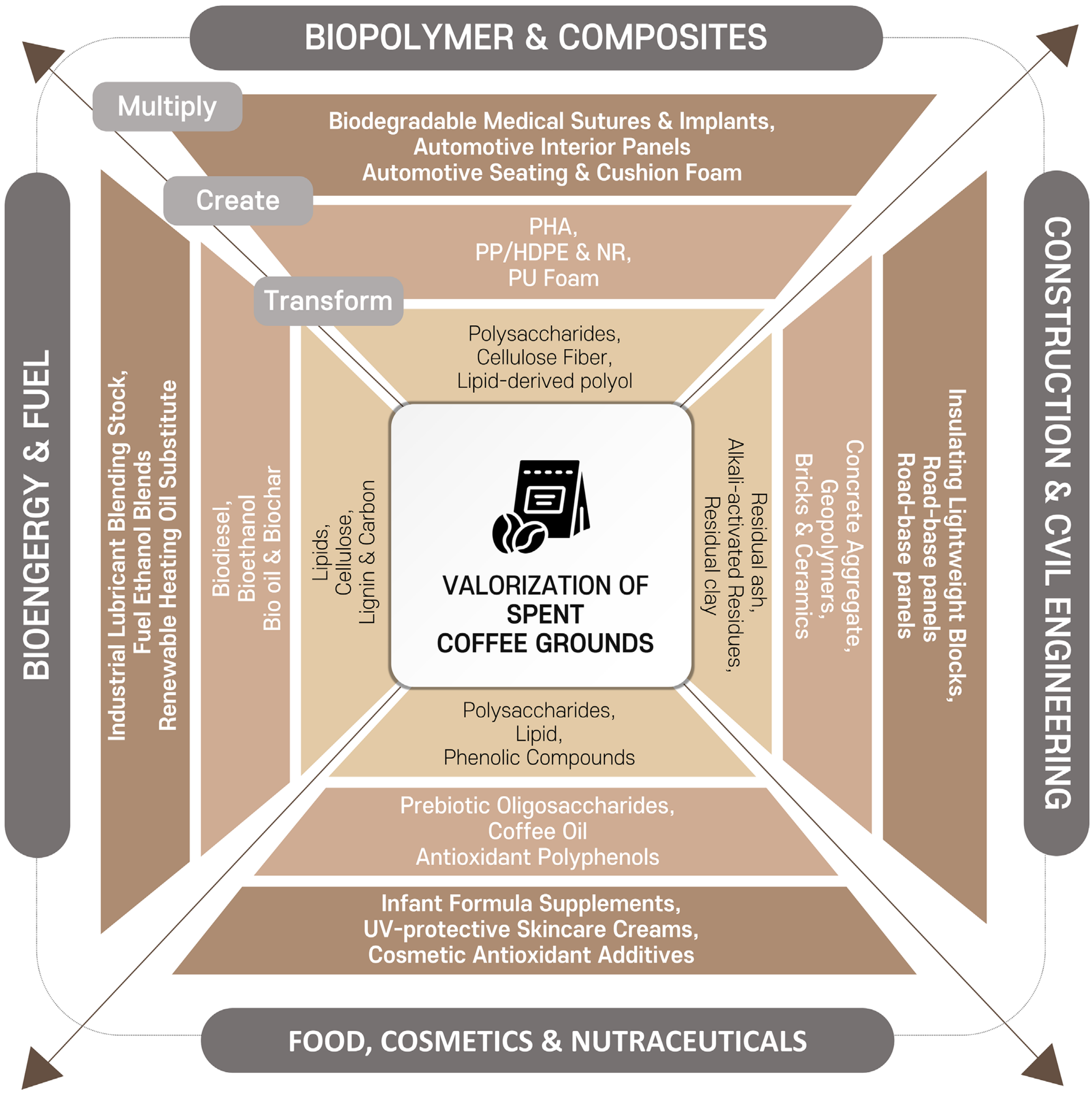

FIGURE 5 | Further Applications of Spent Coffee Grounds in the Cross Economy.

institutionalizing the Cross Economy across diverse material streams and sectors.

1) Deploy targeted financial instruments to reduce capital risk and promote innovation

Targeted fiscal instruments such as research subsidies, public–private matching grants, and accelerated depreciation for green equipment can lower the entry barrier for companies engaging in cross-economy processing. By reducing the capital risk of building decentralized biorefinery hubs or investing in advanced processing technologies (e.g., nanocellulose extraction, enzymatic fractionation, or digital additive manufacturing), these incentives stimulate innovation while supporting regional industrial diversification. Successful case studies, such as Brazil's *RenovaBio* program for biofuels [181] or Korea's *Green New Deal* initiatives [182], demonstrate the effectiveness of performance-based financial mechanisms in scaling bio-based industries and aligning industrial policy with climate goals.

2) Leverage public procurement to catalyze demand and de-risk adoption

Public procurement policies should be strategically leveraged to accelerate market uptake of cross-economy products. Governments can act as anchor buyers by integrating certified cross-economy materials into infrastructure, transportation, and public service sectors. For example, using upcycled biocomposites in public vehicle interiors or construction projects can both validate material performance and drive cost reduction through volume purchasing [183, 184]. When guided by clearly defined sustainability criteria and life cycle assessment (LCA) benchmarks, green public procurement (GPP) reduces the perceived risk associated with adopting eco-innovations, while simultaneously strengthening market signals that indicate long-term demand reliability to private investors [185].

3) Establish mandatory biobased content regulations across key manufacturing sectors

The establishment of mandatory biobased content regulations across sectors such as automotive, construction, textiles, and consumer packaging can create baseline market demand for cross-economy materials. Drawing from precedents such as the European Union's *Renewable Energy Directive* or *Single-Use Plastics Directive*, such mandates can require minimum percentages of renewable, biodegradable, or bio-sourced inputs in product lines [184]. This approach incentivizes upstream investment in material innovation and ensures a stable demand environment that supports economies of scale. Importantly, the regulations must be tailored to sector-specific performance requirements to prevent greenwashing and promote genuine sustainability outcomes.

4) Invest in digital logistics and smart waste infrastructure

Investments in data-driven waste logistics and digital infrastructure are necessary to support feedstock aggregation and value chain integration. Smart bin networks, sensor-based sorting systems, and blockchain-enabled traceability platforms can optimize material collection, reduce contamination, and support dynamic supply–demand coordination. Municipalities and private operators alike can benefit from such digital tools, which enhance the efficiency of cross-economy processing systems and provide real-time analytics for policy refinement. Empirical studies indicate that integrated digital infrastructure can reduce waste management costs by up to 20–30% while improving resource recovery yields and enabling more equitable participation among small-scale suppliers [186].

5) Develop an eco-labelling framework harmonized with existing national/international standards or regulations

Creating a harmonized eco-labeling framework is critical for ensuring market transparency and consumer trust. It will serve as a communication bridge between producers that valorize undervalued materials and audiences that wish to demonstrate environmental responsibility. It should evaluate how well a material, once treated as waste, has been transformed into a high-value resource through environmental indicators such as carbon footprint, biodegradability, and toxicity, and acknowledge the producers of their sustainability-first actions. Alignment with national regulation or global standards (such as ISO 14040 for life cycle assessment or ASTM standards for bio-based polymers) will facilitate product dissemination and international trade and prevent regulatory fragmentation [187]. In this way, the label becomes not merely a quality mark for environmental friendliness, but a catalyst for mainstream consumer recognition of the Cross Economy model and environmental benefits embedded in the material innovation.

Collectively, these policy recommendations serve as foundational pillars for mainstreaming the Cross Economy across materials, sectors, and geographies. They not only enhance the economic viability of waste valorization but also contribute to broader public policy goals, including climate mitigation, sustainable industrialization, and inclusive employment. As the challenges of resource scarcity, environmental degradation, and supply chain volatility intensify, the Cross Economy supported by coherent and forward-looking policy instruments offers a resilient, regenerative pathway for sustainable development.

5 | Conclusion and Outlook

The Cross Economy marks a pivotal shift in our approach to materials, value, and sustainability. It asks us to see not "waste," but latent resources waiting to be transformed. Through its "Transform-Create-Multiply" logic, this model provides the blueprint for a new industrial revolution, one that is decentralized, resilient, and regenerative by design.

Our work with spent coffee grounds is just the beginning. It proves we can create superior, bio-based materials for complex industries like automotive manufacturing, simultaneously building local jobs and cutting our carbon footprint. This is the Cross Economy in action: turning a common residue into a cornerstone of a new bio-industrial network.

The horizon for this paradigm is vast. Imagine applying this same thinking to every major industrial and agricultural byproduct, unlocking novel solutions in medicine, construction, and nanotechnology. This is not mere recycling; it is a fundamental re-imagining of our material world. By fostering collaboration through smart policy and targeted investment, the Cross Economy can position materials science as the engine of a truly sustainable and prosperous future, creating value that crosses sectors, communities, and generations.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The authors have nothing to report.

Endnote

[1] Around 27% of surveyed households reported earning income through the collection, processing, and sale of non-timber forest products (NTFPs), which accounted for roughly 19% of their annual net household income. This indicates that local communities can directly strengthen their economic resilience and competitiveness by utilizing resources readily available in their surrounding environments.

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