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Toward sustainable industry: integrating industrial symbiosis, biorefineries, and circular economy for SDG alignment

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The global transition toward sustainability requires connected and system wide approaches that go beyond traditional industry boundaries. This review explores how industrial symbiosis, biorefineries, circular economy, and sustainability frameworks are linked and probable ways these could together support the shift to cleaner and low carbon industrial systems. Industrial symbiosis allows industries to share resources like energy and materials, which helps reduce waste and encourages cooperation. Biorefineries turn biomass and organic waste into valuable products, and the circular economy focuses on designing systems that reduce waste by keeping products and materials in use for longer. When combined, these frameworks could create strong synergies that support environmental protection, economic development, and social well-being, while also helping to achieve global goals like clean energy, climate action, and sustainable production. This review also explores new tools and approaches such as artificial intelligence, blockchain, nature-based solutions, and regenerative design that help bring these systems together more effectively. Even with these promising developments, there are still challenges, such as the lack of models that work across different industries, their scales, limited attention to fairness and equity, and a need for more practical examples in developing countries. To address these, a roadmap is proposed that includes shared digital platforms, living labs, and collaboration across different fields. This paper offers a clear framework to support decision makers in policy, research, and industry in building inclusive, resilient, and sustainable industrial systems for the future.

1. Introduction

The global pursuit of sustainable development is facing mounting challenges driven by escalating climate change, environmental degradation, resource depletion, and rising socio-economic inequalities. Traditional linear economic models characterized by the extraction, consumption, and disposal of resources are no longer viable in the realm of these interconnected global crises. As a result, there is a growing urgency to transition toward more sustainable, regenerative, and resource efficient systems. In this context, the convergence of industrial symbiosis, biorefinery, circular economy, and sustainability presents a transformative opportunity. These frameworks, when integrated, provide a systemic approach to minimizing waste, valorizing byproducts, and nurturing closed loop industrial practices. This integrated paradigm not only contributes to reducing greenhouse gas (GHG) emissions and pollution but also enhances economic resilience and raises innovation across sectors.[1]

Furthermore, the integration of these systems directly supports a wide range of United Nations Sustainable Development Goals (SDGs), notably SDG 3 (Good Health and Well Being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).[4] The increasing relevance of this integrated approach is underscored by growing policy support and industrial interest worldwide. It represents not just an environmental imperative, but also an economic opportunity to decouple growth from resource consumption, promote technological advancement, and enhance global sustainability transitions.[5]

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The convergence of industrial symbiosis, biorefinery and circular economy, and sustainability reflects a shift toward integrated and regenerative systems thinking (a holistic approach that integrates feedstock, processes, products, energy, economics, and environmental impacts to optimize the entire biorefinery value chain rather than individual units). Industrial symbiosis refers to a collaborative model in which industries exchange byproducts, energy, water, and materials in ways that generate mutual environmental and economic benefits by turning waste from one entity into resources for another.[1] A biorefinery converts biomass into fuels, chemicals, and materials through biochemical, thermochemical, or hybrid platforms, serving as the backbone of the bioeconomy and reducing fossil fuel dependency.[3,5] Integrated with circular economy and industrial symbiosis principles, biorefineries act as central hubs that transform diverse biomass and organic waste into valuable products, advancing sustainable production and consumption.

The circular economy is an economic paradigm that seeks to maintain the value of products and resources in the economy for as long as possible by promoting strategies such as reuse, repair, recycling, and closed loop material flows. It aims to reduce waste and improve the environmental footprint of production and consumption systems.[4] Sustainability, while often conflated with sustainable development, denotes the desired state of balance among environmental, economic, and social dimensions. In contrast, sustainable development is the

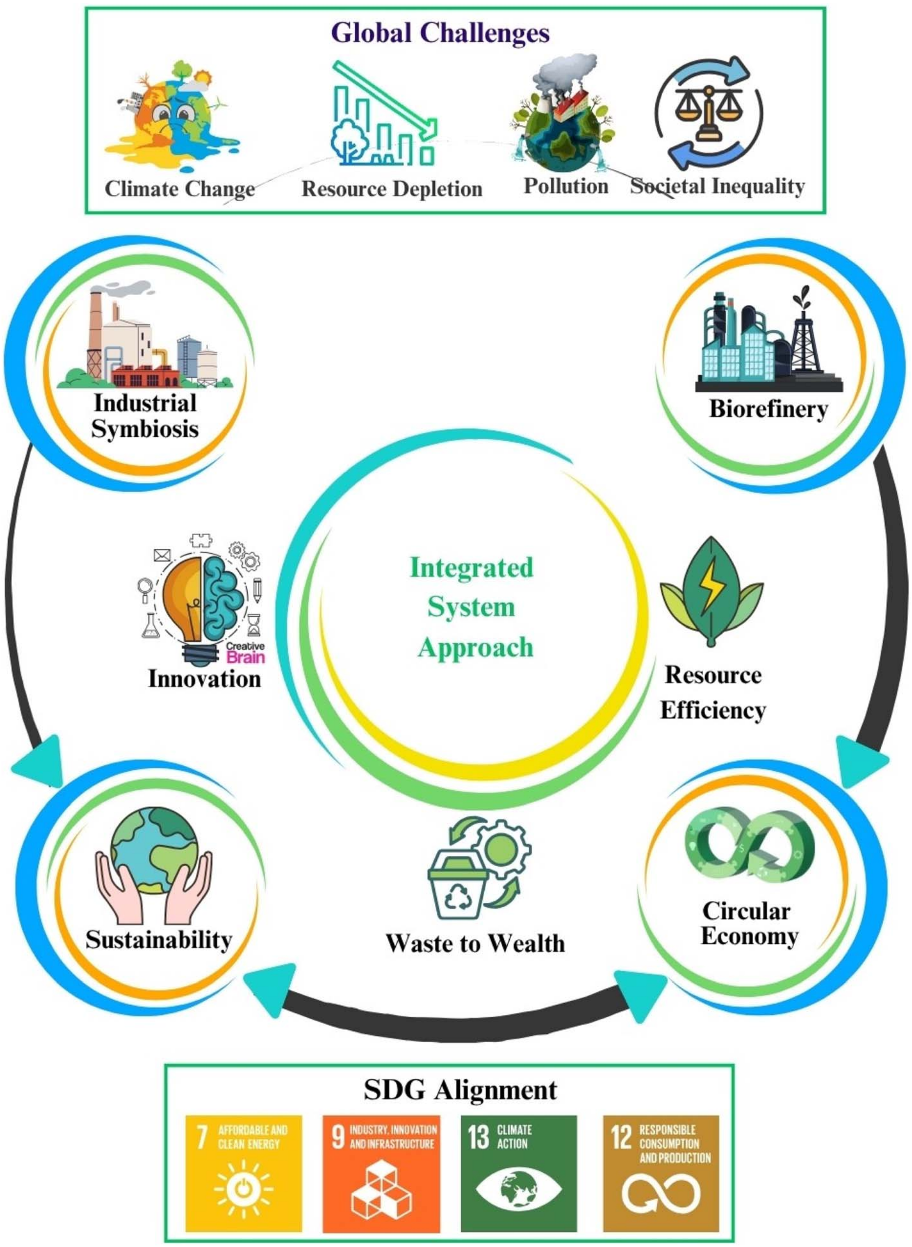

Fig. 1 A conceptual framework illustrating the convergence of industrial symbiosis, biorefinery, circular economy, and sustainability as an integrated response to global sustainability challenges.

ongoing process aimed at achieving that state. Together, these concepts provide a framework for designing industrial systems that are not only efficient but also resilient, equitable, and environmentally sound.[2]

Global megatrends such as population growth, industrialisation, and technological advancements have continuously shaped economic and environmental systems. Over the past two centuries, global industrialisation has been driven by mechanisation, energy advancements, and technological progress. The mechanisation of production processes, the advent of steam and electricity, and later developments in information and communication technologies have drastically increased productivity and reshaped labour markets. In recent decades, the rise of automation, artificial intelligence (AI), and digital platforms has further accelerated innovation and economic interdependence. Technological megatrends such as digitalisation, automation, and Industry 4.0 are reshaping industrial systems, enabling real-time monitoring, data-driven optimisation, and improved resource efficiency within circular and symbiotic industrial networks.[6] The concept of planetary boundaries provides a scientific framework for defining the environmental limits within which human activities can safely operate. Current industrial systems often exceed these thresholds through intensive resource extraction, high carbon emissions, and waste generation. This alignment directly supports SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 7 (Affordable and Clean Energy).[7]

Addressing the escalating challenges of climate change, resource depletion, and unsustainable consumption patterns requires a systems level transition that goes beyond isolated solutions. The integration of industrial symbiosis, biorefinery and circular economy principles represents a powerful strategy to enhance resource efficiency while advancing the broader goals of sustainable development. These integrated approaches minimize waste, close material and energy loops, and maximize resource value, reducing environmental footprints.[1,3] When biorefineries operate within industrial symbiosis networks, they utilize nearby organic residues and waste streams as feedstocks, lowering input costs and environmental burdens.[4] Such synergies drive technological innovation and competitiveness while supporting SDGs related to clean energy, responsible consumption, climate action, and inclusive growth.[2] Overall, this holistic integration decouples economic progress from environmental degradation and aligns industrial development with long-term sustainability. This integrated perspective is illustrated in Fig. 1, which conceptually maps the convergence of industrial symbiosis, biorefinery, circular economy and sustainability.

This review aims to critically explore and synthesize the interrelationships among industrial symbiosis, biorefinery and circular economy principles, and sustainability frameworks. Although these concepts have been discussed extensively in individual contexts, their integrated application remains underexplored in the academic literature. By bridging these domains, the review seeks to highlight the synergistic potential of combining material and energy efficiency (through industrial symbiosis), biomass valorization (through biorefineries), resource regeneration (through circular economy strategies), and the pursuit of social, environmental, and economic balance (through sustainability). Specifically, this comprehensive review examines technological developments, systemic challenges, policy mechanisms, and real-world case studies that illustrate successful integration. Additionally, it outlines emerging trends such as digitalization, life cycle thinking, and policy innovation that can enable more effective deployment of these models. This review is motivated by the need for a holistic perspective that integrates these strategies to guide sustainable industry transitions. Its novelty lies in synthesizing these concepts under the lens of planetary boundaries, global megatrends, and SDGs, providing a comprehensive framework for aligning industrial operations with environmental, economic, and societal objectives. The scope encompasses both developed and developing economies and considers multiple sectors including agriculture, manufacturing, and energy. Ultimately, this review endeavours to provide researchers, policymakers, and industry stakeholders with a comprehensive framework to guide the design and implementation of low carbon, resource efficient, and resilient industrial systems aligned with the SDGs.

2. Conceptual frameworks underpinning the nexus

2.1 Industrial symbiosis

2.1.1. Concept, principles, and global exemplars of industrial symbiosis. Industrial symbiosis is a central concept within industrial ecology, emphasizing collaboration among distinct industries to exchange materials, water, energy, by-products, and knowledge in order to achieve mutual environmental and economic benefits. Drawing inspiration from biological symbiosis, it operates through networks where waste or surplus from one facility becomes a resource for another, enabling more efficient and sustainable resource utilization.[8] Chertow[9] defines industrial symbiosis as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products". This framework promotes interconnected industrial systems that emulate ecological cycles, thereby reducing dependence on virgin resources and minimizing environmental impacts.[10] The core principles of industrial symbiosis include resource sharing, geographical or operational proximity (though not always required), transparency, trust, and cooperation, which together enable long-term collaboration among stakeholders.[11] Several global case studies demonstrate the practical implementation of these principles. The Kalundborg Symbiosis in Denmark remains one of the earliest and most cited examples, involving energy production, pharmaceutical, and waste management sectors. Through exchanges of steam, cooling water, flue gas, and gypsum, the network has achieved substantial reductions in water use and GHG emissions while improving operational efficiency. Comparable outcomes have been reported in the Guiyang urban industrial symbiosis in China and the Sotenäs Symbiosis Centre in Sweden, including job creation, emission mitigation, and circular resource flows.[8,11]

Further integration of industrial and urban symbiosis has been demonstrated in Yongcheng, China, a resource-dependent city facing environmental pressures from industrial activity. Material flow and energy analyses identified 39 symbiotic activities, leading to savings of 2.37 million tons of slag, reductions of 0.43 million tons of municipal waste, conservation of 1.07 million tons of coal, and avoidance of 4.88 million tons of CO_2 emissions. Urban symbiosis additionally contributed to 11% CO_2 reduction and 7% energy savings, highlighting the potential of combined approaches for low-carbon and resource-efficient development.[12] These examples illustrate that industrial symbiosis is adaptable across regions and sectors, offering a scalable pathway toward circular industrial systems. Quantitatively, the field has expanded rapidly, with a systematic review of 584 publications showing exponential growth since 2007. China leads in documented studies and case examples, followed by the United States, with manufacturing emerging as the dominant sector and impact quantification and network analysis as the most common analytical methods.[8]

2.1.2. Role in resource and energy efficiency. Industrial symbiosis enhances resource and energy efficiency by enabling coordinated exchanges of materials, utilities, and by-products among interconnected industries. By reusing waste streams and sharing energy, steam, water, and chemicals, participating facilities reduce reliance on virgin inputs and shift from linear to circular operational models, delivering both environmental and economic benefits.[8,10] Energy efficiency gains are a key outcome of these collaborations. Excess heat from power plants can be utilized by neighbouring industries, while shared water and steam systems lower energy-intensive treatment requirements.[11] Such strategies generate operational cost savings, reduced emissions, and improved environmental performance, as demonstrated in established networks such as Kalundborg (Denmark) and Guiyang (China), where coordinated exchanges have resulted in measurable CO_2 reductions and financial benefits.[8]

Beyond efficiency improvements, industrial symbiosis strengthens industrial resilience by creating localized resource loops, reducing vulnerability to supply disruptions, and supporting adaptive capacity under regulatory and market pressures. As industries increasingly pursue decarbonization and alignment with SDGs, industrial symbiosis provides a practical pathway to improve eco-efficiency without compromising competitiveness. Fig. 2 illustrates the key principles, resource exchanges, and real-world examples of industrial symbiosis. Mortensen and Kørnøv[11] describe three developmental stages and five influencing factor groups that facilitate industrial symbiosis formation, though their work focuses primarily on process dynamics rather than quantified efficiency outcomes. Wadström *et al.*[10] proposed an assessment framework applied to 56 case studies, revealing that material exchanges dominate reported synergies, while energy and water integration receive less attention and economic and social impacts remain weakly quantified. Together, these studies highlight that although industrial symbiosis formation and evaluation are well explored, standardized and outcome-oriented assessments of resource and energy efficiency gains remain limited, underscoring the need for more comparative and performance-focused research.[10,11]

2.2 Biorefinery systems

2.2.1. Biorefinery typologies and technological platforms. Biorefineries represent the cornerstone of the circular bioeconomy, offering a sustainable and versatile platform for converting biomass and organic residues into a diverse range of marketable products, including biofuels, chemicals, bioplastics, and energy. These systems are broadly classified into thermochemical, biochemical, and hybrid platforms, each with unique operational principles and advantages.

2.2.1.1. Thermochemical, biochemical, and hybrid platforms. Thermochemical biorefineries use high temperature processes such as pyrolysis, gasification, and hydrothermal carbonization, to decompose biomass into syngas, bio-oil, and biochar, and are particularly well suited for dry lignocellulosic feedstocks and heterogeneous municipal waste.[13,14] In contrast, biochemical biorefineries rely on the metabolic activities of microorganisms and enzymes to convert organic matter through fermentation, anaerobic digestion, or enzymatic hydrolysis into products like bioalcohols, biogas, organic acids, *etc.* These processes are energy efficient and environmentally friendly but often require careful feedstock pretreatment and process optimization.[15,16] Hybrid biorefineries integrate both thermochemical and biochemical approaches to enhance system efficiency and maximize biomass valorization. For example, residues from fermentation can be subjected to pyrolysis to produce biochar, which can then be recycled as a catalyst or soil amendment, thereby closing the material loop and supporting near zero waste targets.[14,17] Thermochemical (400–900 °C; 60–75% efficiency) and biochemical (30–60 °C; 70–90% conversion) biorefinery platforms are frequently presented with favourable performance metrics, while hybrid systems are reported to improve carbon utilization by 10–25%. However, these values are largely reported in isolation, with limited scrutiny of integration losses, scale-up challenges, or economic uncertainty.[13,16]

2.2.1.2. Smart biorefineries and emerging technologies. The selection of biorefinery pathways depends on multiple factors, including feedstock type, technology readiness, and end product demand. According to the International Energy Agency Bioenergy Task 42 classification framework, biorefineries should be evaluated based on the feedstock, process, platform products, and final applications to ensure alignment with sustainability goals.[16] As the sector evolves, emerging smart biorefinery models are leveraging digital tools such as machine learning, process integration, and digital twins to optimize resource use, reduce emissions, and support economic viability. Smart biorefineries are digitally enabled, adaptive systems that use real-time monitoring, data analytics, automation, and predictive modelling to optimize feedstock use, process control, energy integration, and product recovery across the value chain.[1] Emphasizing flexibility, resilience to feedstock variability, and closed-loop decision support, they align material

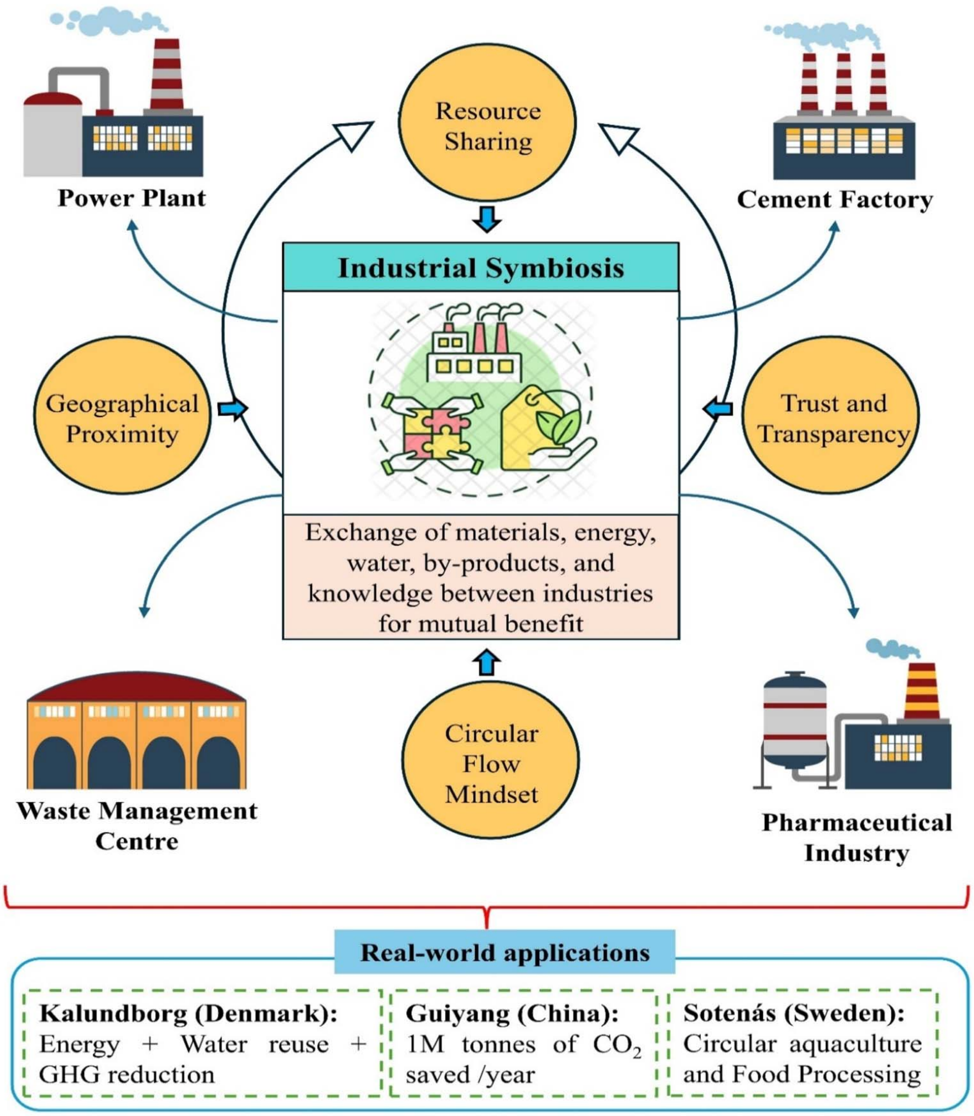

Fig. 2 A model of industrial symbiosis, illustrating the exchange of materials, energy, and byproducts across industries.

and energy flows with circular economy principles and support low-carbon industrial transitions. Reported benefits include 10–25% gains in resource efficiency and 15–30% waste reduction; however, these outcomes remain largely theoretical or lab-scale, with limited industrial validation and insufficient assessment of technology readiness, data robustness, and economic risk. The classification and interconnection between feedstocks, processing technologies, and product outputs in biorefineries is visually represented in Fig. 3.

2.2.2. Feedstock diversity and biorefinery outputs. Biorefineries rely on a wide spectrum of biowaste feedstocks, including agricultural residues, food and aquatic waste, and industrial organic by-products.[18] These resources differ in their biochemical composition. Lignocellulosic residues such as rice straw, sugarcane bagasse, and coir pith are rich in cellulose (30–50%), hemicellulose (15–30%), and lignin (10–25%), while food and industrial waste contains high levels of carbohydrates, proteins, and lipids suitable for anaerobic or fermentative processes.[19] Aquatic biomass such as algae provides low-lignin, high-carbohydrate feedstock for sustainable fuel and material production.[20] Depending on feedstock characteristics, biorefineries can generate diverse outputs including bioenergy (biogas, bioethanol, and biohydrogen), biochemicals (organic acids and enzymes), and biomaterials (bioplastics and fibers). Valorizing such diverse waste streams enhances process flexibility, minimizes environmental burdens, and supports circular economy objectives by transforming waste into valuable co-products aligned with the SDGs.[21]

Biorefineries are highly versatile systems that utilize a broad spectrum of biomass feedstocks, which can be classified into four major categories: lignocellulosic biomass, organic solid waste, aquatic biomass, and industrial or agricultural residues. Lignocellulosic biomass including crop residues, forestry by-products, and dedicated energy crops is among the most widely used feedstocks due to its abundance and high carbon content, making it suitable for the production of bioethanol,

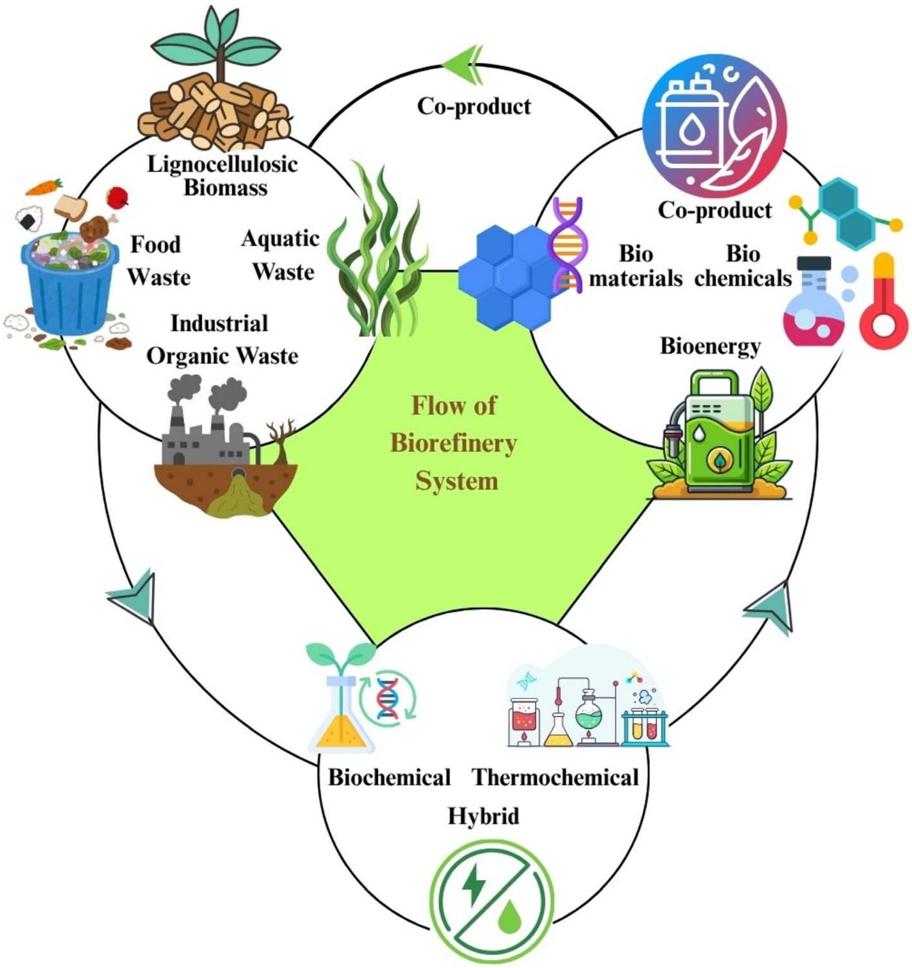

Fig. 3 Overview of biorefinery system classifications and process product pathways.

biogas, biochar, and platform chemicals such as furfural and levulinic acid.[13,15] Organic solid waste from municipal and domestic sources, such as food scraps and garden waste, serves as an ideal substrate for anaerobic digestion and fermentation, leading to the generation of biogas, organic acids, biohydrogen, and compost.[16] Aquatic feedstocks such as algae and aquatic plants offer high lipid and carbohydrate content and are being increasingly explored for biodiesel, bioethanol, and protein extraction.[17] Additionally, industrial and agricultural residues like dairy waste, fruit peels, bagasse, and slaughterhouse waste can be valorized into high value bioproducts such as enzymes, bioplastics, and biosurfactants.[14,15] The end products of biorefineries span multiple sectors and value chains. Energy products include bioethanol, biodiesel, biogas, biocrude and syngas which serve as renewable substitutes for fossil fuels. Non-energy outputs comprise a wide range of bio-based chemicals, materials, and polymers, including lactic acid, polyhydroxyalkanoates, biochar, fertilizers, adhesives, nutraceuticals and active pharmaceutical ingredients. Advanced integrated biorefineries are also capable of producing multipurpose co-products like nutrient enriched digestate and biofertilizers that enhance soil health and carbon sequestration. The diversity of feedstock options and product flexibility underscores the adaptability of biorefinery systems and their critical role in closing biomass loops within the circular bioeconomy.[14,16]

A case study on fatty acid production demonstrated how feedstock diversity significantly influences biorefinery outputs and product quality. Using a systematic multivariate analysis approach, researchers examined two key operations oil hydrolysis and fatty acid distillation to identify how variations in raw materials and process conditions affect outcomes. The study revealed that the type of oil used, such as canola or palm oil, strongly impacts the quality of the final fatty acids due to differences in composition. However, when a single oil type is used, process parameters like the feed flow rate and reflux ratio become the main factors affecting product variability. This analysis highlights the importance of understanding feedstock variability and process control to achieve consistent and optimized biorefinery performance.[22] Studies report that diverse feedstocks such as agricultural residues, energy crops, and organic waste can yield 50–80% fermentable sugars after pretreatment, enabling production of fuels, chemicals, and biopolymers. However, conversion efficiencies and product yields vary widely depending on feedstock composition, with lignin rich materials often reducing overall process efficiency by

Table 1 Classification of biorefinery systems, feedstocks, processes, end products, and references

Biorefinery type	Conversion process	Typical feedstocks	Major end products	Remarks	References
Thermochemical	Pyrolysis, gasification, combustion, hydrothermal and carbonization	Lignocellulosic biomass, municipal solid waste, and agricultural residues	Syngas, bio-oil, biochar, and electricity	High temperature; suitable for dry and mixed feedstocks	13, 14 and 16
Biochemical	Fermentation, anaerobic digestion, and enzymatic hydrolysis	Food waste, manure, crop residues, and organic industrial waste	Bioethanol, biogas, organic acids, and enzymes	Environmentally friendly; requires pretreatment for some substrates	15–17
Hybrid	Integration of thermochemical & biochemical	Any combination of the above	Multiple outputs including energy, chemicals, and fertilizers	Supports cascading resource use; maximizes waste valorization	13 and 14
Advanced/smart	AI optimization, multipathway, and digital twins	Mixed feedstocks and co-streams	Tailored products, circular flows, nutrient recovery, and energy	High resource efficiency; aligned with smart industry and circular economy	14

20–40%. While recent reviews emphasize feedstock flexibility and multiple output streams, most studies still report isolated yields rather than critically comparing feedstocks in terms of scalability, consistency, and economic performance, limiting reliable feedstock selection for integrated biorefineries.[19–21] A comparative overview of biorefinery types, associated feedstocks, conversion routes, and product outputs is summarized in Table 1.

2.2.3. Biorefineries in waste valorization and the bioeconomy. Biorefineries play a transformative role in advancing both waste valorization and the bioeconomy by enabling the efficient conversion of organic residues and biomass into high value products, thereby addressing the global challenges of waste management, fossil fuel dependence, and environmental degradation. Through integrated processing technologies, biorefineries are capable of transforming diverse waste streams such as agricultural residues, food waste, industrial effluents, and municipal solid waste into a wide range of renewable fuels, chemicals, and materials that substitute for fossil derived counterparts.[14,15] This approach not only diverts significant volumes of biodegradable waste from landfills and incineration, reducing methane and CO_2 emissions, but also promotes circular material flows by reintegrating by-products into production cycles. For example, lignocellulosic waste can be fermented into ethanol or converted into biochar for carbon sequestration and soil enhancement, while food and dairy waste can be processed into biogas, organic acids, and bioplastics.[13,17] As such, biorefineries represent a core operational model within the circular and bio-based economy, where biological resources are sustainably utilized, waste is minimized, and value is maximized across the supply chain. Moreover, they support the decoupling of economic growth from resource extraction by generating employment, reducing environmental burdens, and encouraging regional resource self-sufficiency. By integrating renewable feedstocks, clean technologies, and smart design principles, biorefineries foster innovation while aligning with multiple SDGs, including SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 7 (Affordable and Clean Energy).[14,16] Ultimately, biorefineries serve not only as technological platforms but also as systemic enablers of the sustainable transition toward a regenerative, low carbon future. Waste based biorefineries are reported in the literature to convert approximately 40–70% of organic waste carbon into fuels, chemicals, or materials, with 15–30% reductions in landfill disposal and 10–25% reductions in GHG emissions, depending on waste type and system boundaries. However, these values are largely derived from scenario analysis, pilot scale studies, and system level assessments, with limited evidence from long term industrial operation, leaving scalability and economic robustness insufficiently demonstrated.[14–16]

2.3 Circular economy

2.3.1. Circular economy: global strategies and inclusive transition. The circular economy is a regenerative economic model that aims to retain the value of materials, products, and resources in the economy for as long as possible, minimizing waste and adverse environmental impacts. In contrast to the conventional linear economy of "take–make–dispose," the circular economy promotes a paradigm shift toward reuse, recycling, remanufacturing, ecodesign, and product life extension. This model, rooted in industrial ecology and ecological economics, is increasingly regarded as a strategic response to global challenges such as climate change, resource depletion, and unsustainable consumption.[23,24] At the global policy level, the European Union (EU) has taken a leading role through its circular economy action plans (2015, 2020), embedded within the European Green Deal, with key objectives that include sustainable product design, circular procurement, eco-labelling, and Extended Producer Responsibility. These policies contribute significantly to SDGs 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action) by promoting decoupling of economic growth from environmental degradation.[25] The EU estimates that such strategies could lead to material savings of over USD 380 billion annually and generate half a million new jobs through recycling and remanufacturing.[23,26]

In emerging economies like India, the circular economy has gained momentum through flagship programs such as the Swachh Bharat Mission, Smart Cities Mission, and the Lifestyle for Environment initiative. According to a recent G20 backed report, India's circular transition could increase Gross Domestic Product (GDP) by USD 45 billion by 2030, create 4.4 million clean jobs, and reduce carbon emissions by 126 million tonnes, approximately 9% of current levels.[24,27] India's circular economy strategy spans seven key sectors, including batteries, solar panels, steel, construction and demolition waste, wastewater, organic waste, and agriculture. Yet, the country faces systemic challenges such as fragmented policy enforcement, underdeveloped secondary markets, poor infrastructure, and limited public awareness. At the firm level, circular economy business models play a transformative role in enabling circular transitions. These include models based on circular supply chains, product as a service, resource recovery, and life cycle extension. Such business models are increasingly integrated with Environmental Social Governance (ESG) indicators to enhance sustainability performance and accountability.[23]

Case studies such as Contarina SpA in Italy demonstrate how circular business models in the waste management sector can contribute directly to several SDGs, including SDG 4 (Quality Education), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production), through innovative recycling, decentralised processing, and inclusive employment practices.[25] Furthermore, digital technologies such as the Internet of Things (IoT), blockchain, AI, and digital twins are accelerating circular economy transitions by improving traceability, enabling life cycle analysis (LCA), and optimizing waste management systems. These digital innovations are critical for creating resilient, transparent, and adaptive supply chains.[28]

However, in the Global South, circular economy transitions often suffer from top down, techno centric approaches that risk excluding informal sectors and marginalized communities. Scholars advocate for participatory and location-based approaches that integrate local knowledge, empower informal actors, and ensure social justice alongside environmental and economic goals. Therefore, the circular economy must be seen not only as a technical fix but also as a social and political project requiring systemic redesign, policy coherence, and multi-stakeholder collaboration to realize its full potential in advancing a sustainable and inclusive economy.

Global circular economy strategies increasingly emphasize multi-level governance, stakeholder coordination, and policy coherence, with national and regional roadmaps typically structured around 3–5 priority action areas such as waste reduction, resource efficiency, and social inclusion. However, while strategic frameworks acknowledge inclusivity as a core principle, quantitative indicators for social outcomes are largely absent or weakly defined, and empirical validation is often limited to selected case regions.[23–25]

2.3.2. Circular economy business models and value creation pathways. Circular Economy Business Models (CEBMs) represent a fundamental departure from the traditional linear "take–make–dispose" model by prioritizing regenerative processes that maximize the utility of resources, extend product life cycles, and internalize environmental and social externalities. These models aim to decouple economic growth from resource consumption through a range of strategies such as material substitution, product life extension, waste valorization, and service-based access. Value creation within this framework is not solely focused on profit generation but is equally concerned with environmental performance and social inclusivity. As Fatimah *et al.*[23] noted, circular economy models support a multi-dimensional value proposition by integrating ESG indicators directly into business operations. Circular supply models that replace virgin inputs with renewable or recycled alternatives reduce exposure to resource scarcity and volatility, while product life extension strategies such as repair, refurbishment, and remanufacturing prolong the economic utility of goods and reduce demand for new materials.[16] Similarly, resource recovery models that extract value from waste streams contribute to a closed loop system, as illustrated by biogas and compost production from organic waste in urban ecosystems.[24]

Furthermore, product as service models allow users to access products through leasing or subscription schemes, incentivizing firms to invest in product durability and service innovation. Sharing platforms, enabled by digital tools and consumer networks, increase asset utilization efficiency while reducing environmental footprints.[15] The five core circular economy business model archetypes, along with their applications and associated value streams, are summarized in Table 2.

The role of digitalization is increasingly critical, as technologies such as the IoT, blockchain, and AI facilitate real time tracking of resource flows, predictive maintenance, and data driven lifecycle assessments.[28] These capabilities not only enhance operational efficiency but also build consumer trust and regulatory compliance by increasing transparency. CEBMs create economic value by lowering raw material dependency, opening secondary markets, and reducing operational costs,

Table 2 Circular economy business model archetypes, examples, and value streams[23–25]

Circular economy model archetype	Description	Example applications	Value streams
Circular supply	Use of renewable, recycled, or bio-based inputs instead of virgin materials	Recycled aluminum in auto manufacturing	Environmental: reduced raw material extraction and emissions
		Bio-based packaging	Economic: lower input costs
		Secondary steel in construction	Social: reduced dependency on extractive industries
Product life extension	Extending product use through repair, refurbishment, and remanufacturing	Refurbished electronics	Environmental: less landfill and resource use
		Reused construction equipment	Economic: revenue from aftermarket services
		Remanufactured vehicle parts	Social: local job creation in repair sectors
Resource recovery	Recovering usable materials or energy from waste or byproducts	Biogas from organic waste	Environmental: closed loop material flows
		E-waste recycling	Economic: monetization of waste streams
		Industrial byproduct utilization	Social: formalizing informal waste sectors
Product as a service	Customers pay for product access rather than ownership	Tool leasing	Environmental: product longevity and reuse
		EV battery as a service	Economic: recurring revenue models
		Furniture rental	Social: affordable access to premium goods
Sharing platforms	Increased utilization of underused products or assets *via* shared access	Ride sharing (*e.g.*, Uber and Ola)	Environmental: reduced total product demand
		Co-working spaces	Economic: platform revenue and efficiency
		Peer to peer tool sharing platforms	Social: community based asset access

while also generating environmental value by mitigating GHG emissions and minimizing waste. Social value is created through green job generation, particularly in labor intensive sectors like waste collection, recycling, and repair, where India alone is projected to create over 4.4 million clean jobs by 2030.[27]

Nevertheless, the implementation of CEBMs remains constrained by several systemic barriers. These include fragmented regulations, limited infrastructure, low consumer awareness, and a lack of standardized metrics that adequately capture the long-term benefits of circularity.[24] Traditional financial indicators such as return on investment or payback period often fail to reflect the broader value circular economy models deliver, necessitating the integration of sustainability-oriented performance frameworks. In emerging economies, challenges are further amplified by institutional fragmentation and the dominance of informal sectors in key areas like waste management. As Hadfield *et al.*[28] emphasized, circular economy transitions in the Global South require a transformative approach that combines systems thinking with participatory governance and socio-cultural sensitivity. Successful circular economy implementation depends on the alignment of business strategy with enabling policy instruments, public private partnerships, and inclusive innovation systems. In this regard, business models must evolve not only to deliver economic returns but also to generate ecological resilience and social equity. When implemented effectively, CEBMs offer a comprehensive redefinition of value creation balancing profitability with sustainability and enabling businesses to thrive within planetary boundaries. The relationship between circular economy principles, enabling policies, strategic models, and sustainability outcomes is depicted in Fig. 4. The model illustrates how global (*e.g.*, the EU Green Deal) and national (*e.g.*, India's circular economy strategy) policies drive business model innovation, supported by digital enablers, ultimately contributing to resource efficiency, job creation, and SDG alignment.

A case study on pineapple processing demonstrates how industrial fruit by-products can be managed through a circular economy approach. Instead of discarding peels, cores, and other residues as waste, these by-products were identified as a rich source of polyphenols with high antioxidant activity. Using biotechnological extraction methods, these compounds can be recovered and converted into high-value antioxidant products for industrial applications. This approach not only reduces landfill waste and environmental impact but also creates economic value by turning waste into marketable products. The study highlights how shifting from a linear "produce–consume–dispose" model to an integrated circular valorisation strategy can benefit both industry and the environment.[29]

Circular economy business models are commonly framed around product service systems, closed loop supply chains, and collaborative value networks, with firms often adopting 2–4 simultaneous value creation pathways such as cost reduction, risk mitigation, and reputational gains. However, the literature largely prioritizes conceptual classification of business models over quantified value capture, with limited evidence on long

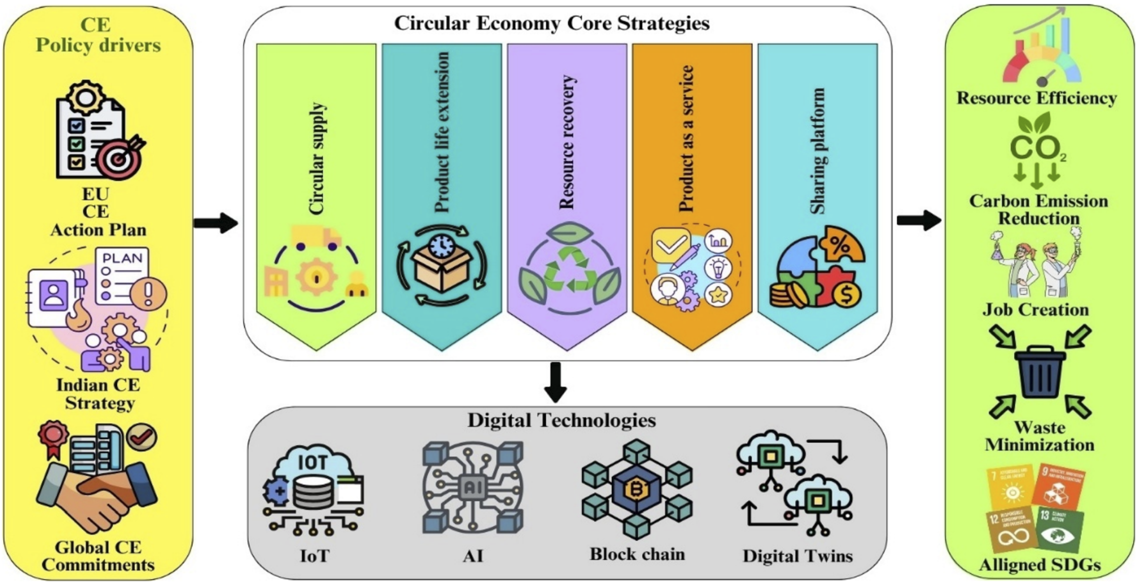

Fig. 4 Conceptual framework showing the interaction between circular economy policies, strategic models, enabling technologies, and sustainability outcomes aligned with SDGs.

term profitability, revenue stability, or distribution of value across supply chain actors. Moreover, social and environmental value creation is frequently asserted rather than measured, leading to an imbalance between strategic ambition and demonstrated economic performance, particularly for small and medium enterprises.

2.4 Sustainability

2.4.1. Environmental, economic, and social dimensions. Sustainability, as a multidimensional and dynamic concept, is grounded in the integration of environmental health, economic viability, and social equity. In the context of industrial symbiosis, biorefineries, and circular economy systems, these dimensions offer a framework for evaluating the performance and long-term impact of industrial processes and policy interventions. Sustainability is not a static state but a continuous journey toward balancing ecological integrity, economic development, and societal well-being.[2]

From an environmental perspective, sustainability seeks to reduce human pressure on ecosystems, limit GHG emissions, and conserve biodiversity. Industrial and circular models like biorefineries and industrial symbiosis play a key role here by transforming waste into resources, thus reducing landfill, energy consumption, and pollution. For instance, biorefineries convert agricultural residues, municipal solid waste, or food industry byproducts into fuels, bioplastics, or platform chemicals directly reducing the environmental footprint of fossil dependent systems.[30] However, using biomass does not automatically ensure sustainability. Factors such as land use change, water consumption, and nutrient cycles must be considered, highlighting the importance of full LCA.[2,31]

The economic dimension focuses on the long-term viability and efficiency of systems, ensuring that industries remain productive while minimizing resource input and maximizing value creation. Sustainability driven models like green finance, circular supply chains, and industrial symbiosis reduce operational costs, mitigate supply risks, and foster innovation.[32] For instance, companies implementing circular practices report reduced input costs and improved productivity through the reuse of waste materials or sharing of heat and water *via* symbiotic networks.[33] Moreover, the bioeconomy sector is increasingly viewed as an engine of economic revitalization, especially in rural and underdeveloped regions, offering diversified job opportunities, stimulating investment, and promoting technological advancement.[30,34]

The social dimension of sustainability ensures equity, inclusivity, and improved quality of life for all. It includes access to clean energy and water, decent employment, social justice, and participatory governance. The shift to sustainable production and consumption must actively involve marginalized communities and ensure that benefits are equitably distributed. Biorefineries can support social development by generating local employment, promoting farmer cooperatives, and encouraging gender inclusive value chains.[2] However, if poorly planned, such systems may lead to land conflicts, food security concerns, or social exclusion especially in regions where resource governance is weak.[31] Hence, sustainability assessments must integrate social impact indicators such as job quality, education access, and public health.

An integrated understanding of sustainability must also acknowledge interdependence and trade-off. For example, maximizing biomass use may conflict with food security if agricultural land is diverted from food to fuel. Similarly, prioritizing economic returns may result in poor environmental performance unless regulatory checks or incentives are in place. Therefore, systems thinking, participatory decision making, and adaptive governance are essential to avoid isolated, technocentric solutions and foster long term sustainability across all dimensions.[30]

Sustainability assessments increasingly adopt a triple dimension framework with environmental indicators often outnumbering economic and social metrics by a factor of two to three in empirical studies. While environmental gains such as emission reduction and resource efficiency are commonly quantified, economic resilience and social equity remain weakly operationalized, frequently relying on qualitative proxies. This imbalance limits cross dimensional comparability and risks overstating sustainability performance, as trade-offs between environmental benefits and economic or social outcomes are rarely examined in an integrated manner.[30,31]

2.4.2. Relevance to SDGs. The transition to circular and sustainable production systems through industrial symbiosis, biorefineries, circular economy models, and the bioeconomy directly supports a wide range of SDGs. These frameworks not only align with global environmental and economic objectives but also serve as enablers for integrated action across multiple development targets.

2.4.2.1. SDG 3 – good health and well being. Sustainable industrial practices such as biorefineries, industrial symbiosis, and circular economy strategies contribute significantly to SDG 3 by addressing pollution, occupational hazards, and environmental exposure that affect public health. Specifically, these models help achieve Target 3.9, which aims to substantially reduce deaths and illnesses from hazardous chemicals and air, water, and soil pollution.

Promoting mental health and psychological well-being is a core aspect of SDG 3, particularly under Target 3.4 (focuses on cutting early deaths from NCDs by 33% by 2030 while strengthening mental health and well-being). For instance, a study by Abdelnaeim *et al.*[35] examined the role of service quality in enhancing students' psychological well-being within Egyptian higher education institutions. By demonstrating how functional and technical service quality dimensions affect various aspects of student well-being, this study highlights the broader social and psychological dimensions of sustainability. Such research underscores that achieving SDG 3 extends beyond physical health to encompass emotional and mental wellness, aligning with the holistic concept of well-being promoted by the United Nations.

One of the key pathways through which these frameworks promote health is by reducing air pollution. Traditional fossil fuel-based systems release substantial amounts of particulate matter, volatile organic compounds, and other harmful emissions. In contrast, biorefineries utilizing biomass or organic waste for energy production and material conversion produce fewer air pollutants, particularly when paired with clean combustion or anaerobic digestion technologies.[2] For instance, converting agricultural waste into biofuels reduces open field burning, a major source of respiratory illnesses in rural communities. Industrial symbiosis networks further enhance air and water quality by integrating waste treatment, energy exchange, and resource sharing between facilities. This reduces the need for offsite disposal, untreated discharge, and long-distance waste transport, each of which poses public health risks. Co-existence of industries in eco-industrial parks often includes shared effluent treatment plants and emission control systems, which collectively reduce environmental exposure and health burdens in adjacent communities.[33]

In addition, circular economy principles encourage safer product design, reduction in toxic inputs, and longer product life cycles, all of which reduce health risks across the supply chain. Material substitution with bio-based and biodegradable alternatives in packaging, textiles, and consumer goods further minimizes human exposure to microplastics, persistent chemicals, and heavy metals.[30] Beyond pollution control, these systems can indirectly improve health outcomes by addressing social determinants of health, such as access to clean energy, improved livelihoods, and safer working conditions. For example, decentralized biorefineries can provide clean cooking fuels to off grid communities, reducing indoor air pollution and the incidence of respiratory diseases among women and children. Thus, the alignment of industrial sustainability models with SDG 3 ensures a multidimensional impact addressing both environmental pathways of disease and the broader systemic conditions that shape human health.

Although SDG 3 is frequently referenced in sustainability strategies, its implementation is largely symbiotic, with health impacts assessed through self-reported or managerial indicators rather than measurable health outcomes. This gap between commitment and evidence limits the ability to verify whether SDG-aligned actions deliver real improvements in well-being, weakening their credibility and policy relevance.[35]

2.4.2.2. SDG 6 – clean water and sanitation. The integrated application of biorefineries, industrial symbiosis, and circular economy strategies contributes meaningfully to SDG 6, particularly addressing Target 6.3 (improve water quality by reducing pollution and minimizing the release of hazardous chemicals) and Target 6.4 (substantially increase water use efficiency across all sectors). Pakistan, a rapidly developing nation with a large population and expanding industrial sector, continues to face significant challenges in achieving SDG 6. Although access to improved water sources increased during the Millennium Development Goals era with official statistics indicating that over 90% of the population has access to basic drinking water the quality and long-term sustainability of these supplies remain major concerns. A substantial proportion of Pakistan's water sources are contaminated with biological and chemical pollutants, and only about half of the population has access to safely managed water services that are reliable, safe, and available on-premises.[36]

Biorefineries are increasingly being designed to be water resilient by integrating water recycling, anaerobic treatment, and effluent polishing systems. Many biorefinery processes, such as fermentation and hydrolysis, rely on large water inputs, yet their effluent streams can be treated and reused internally, minimizing freshwater withdrawals. Moreover, residues from wastewater treatment in biorefineries, such as biosolids, can be further processed into bioenergy or soil amendments, creating value from waste and aligning with circular economy principles.[2] Circular economy models promote water stewardship through systemic redesign of industrial and municipal processes. For instance, the recovery of nutrients (*e.g.*, nitrogen and phosphorus) and energy from wastewater *via* struvite crystallization or anaerobic digestion helps not only in pollution prevention but also in resource recovery, a key principle of SDG 6. Cities and industries adopting circular economy strategies are increasingly implementing Nature-based Solutions (NbSs) such as constructed wetlands and biofiltration systems, which serve both treatment and ecological restoration functions.[30]

Additionally, these integrated systems contribute indirectly to SDG 6.1 (achieving universal access to safe and affordable drinking water) by reducing contamination sources in surface and groundwater, especially in regions where industrial effluents compromise drinking water quality. By promoting clean production and waste valorization, industrial symbiosis and circular bioeconomy frameworks offer scalable, sustainable solutions to water scarcity and pollution challenges. The synergy between sustainable industrial systems and water management strategies is critical for achieving SDG 6. When applied holistically, these models reduce water footprints, prevent waterborne pollution, and ensure long term water security in both urban and industrial landscapes.

The Pakistan Council of Research in Water Resources SDG-6 baseline report indicates that less than half of the population has access to safely managed drinking water and sanitation services, with strong urban-rural disparities and declining groundwater quality. Although the national coverage figure often exceeds 70% for basic water access, advanced indicators such as water safety, wastewater treatment, and reuse remain below 40% in many regions. This gap between nominal access and service quality highlights a systemic failure in SDG-6 implementation, where infrastructure expansion has not translated into safe, equitable, and sustainable water and sanitation outcomes.[36]

2.4.2.3. SDG 7 – affordable and clean energy. The development and integration of biorefineries, industrial symbiosis, and circular economy strategies play a crucial role in advancing SDG 7, which aims to ensure access to reliable, sustainable, and modern energy for all. These frameworks contribute especially to Target 7.2 (increase the share of renewable energy in the global energy mix) and Target 7.3 (enhance energy efficiency).

A recent study by Frimpong *et al.*[37] in Ghana assessed strategies for enhancing energy sustainability, identifying renewable energy utilization, emission reduction, and efficient energy policies as key indicators. The findings emphasize that the integration of strong policy frameworks, sustainable energy indicators, and strategic communication is essential to accelerate progress toward clean energy access. These insights reinforce the global relevance of SDG 7, underscoring that achieving affordable and clean energy is both an environmental necessity and a foundation for inclusive development.

Biorefineries are at the core of bioenergy innovation. By converting biomass and organic waste into bioethanol, biodiesel, biogas, and advanced biofuels, biorefineries provide decentralized, low emission energy alternatives to fossil fuels.[2] The use of lignocellulosic residues, food waste, animal manure, and municipal solid waste as feedstocks not only promotes energy diversification but also addresses waste management and rural development. Moreover, the production of biomethane through anaerobic digestion provides a flexible, storable, and grid compatible renewable energy source, especially relevant for countries with agricultural economies.[30] Industrial symbiosis further enhances energy sustainability by enabling waste heat recovery, cogeneration, and shared energy infrastructure among industrial actors. For instance, excess heat from a power plant can be supplied to neighboring industries or used in district heating systems, significantly improving overall energy efficiency and reducing total energy demand.[33] These cooperative arrangements align closely with energy cascading principles, where energy flows are optimized from high grade to low grade uses, reducing both energy waste and operating costs.

The circular economy promotes energy efficiency across product life cycles through reuse, remanufacturing, and design for energy efficiency. Reducing material extraction and increasing product longevity reduces the energy embedded in manufacturing processes. In addition, circular economy driven innovations in sectors like construction (*e.g.*, modular design) and manufacturing (*e.g.*, low carbon materials) could reduce energy consumption per unit of GDP, thereby supporting national progress toward SDG 7 indicators.[34] These models contribute to energy access in underserved regions. Decentralized biorefineries, for example, can deliver bioenergy in rural and peri-urban areas that lack reliable grid access, enhancing energy equity. The deployment of small-scale biomass digesters, gasifiers, and ethanol microdistilleries supports inclusive energy transitions by reducing dependence on costly and polluting fossil fuels. The implementation of circular bioeconomy models and symbiotic industrial networks represents a dual strategy to improve energy access and reduce the carbon intensity of energy systems. By integrating renewable energy generation, energy recovery, and efficiency optimization, these systems directly support the transition to sustainable energy in line with the targets of SDG 7.

The SDGs Report 2025 highlights continued progress toward SDG 7. Global electricity access rose to 92% by 2023, and renewable energy is expected to become the primary power source by 2025. Despite this, Sub-Saharan Africa remains the most affected region, with the majority of people without electricity and only 21% having access to clean cooking fuels. Although global use of clean cooking solutions improved to 74%, around 2.1 billion people still rely on polluting energy sources. Renewable energy's share in total consumption increased to 17.9% in 2022, driven mainly by growth in solar and wind power. The report emphasizes that greater investment and stronger policies are vital for achieving universal access to sustainable energy.

The transition toward affordable and clean energy is closely linked to sustainable resource management and forest-based livelihoods. According to Jagger *et al.*,[38] traditional wood fuels currently play a major role in energy provision across low- and middle-income countries, but their dominance is expected to decline as modern energy technologies expand. However, energy stacking where households rely on both modern and traditional fuels will likely persist. The study further highlights that innovations in bio-based energy systems, such as forest-derived biofuels and biopower, can support SDG 7 if balanced with sustainable forest management. Conversely, large-scale reliance on agriculture-derived biofuels or hydropower without proper safeguards may threaten forests and rural livelihoods. Thus, biorefineries and circular bioeconomy strategies must integrate both energy and ecological sustainability to ensure net positive outcomes across SDGs. Despite policy commitments to SDG 7, access to affordable and reliable clean energy remains uneven, with renewable energy contributing less than one third of total final energy consumption in many developing regions. While decentralized and renewable energy systems are promoted as solutions, affordability, grid integration, and financing constraints continue to limit adoption, particularly for low-income households.[37]

2.4.2.4. SDG 8 – decent work and economic growth. The implementation of biorefineries, industrial symbiosis, circular economy, and bioeconomy frameworks significantly contributes to SDG 8, which promotes sustained, inclusive economic growth, full and productive employment, and decent work for all. These sustainable industrial systems support Target 8.2 (achieve higher levels of economic productivity through diversification, technological upgrading, and innovation) and Target 8.4 (improve global resource efficiency in consumption and production). One of the most notable contributions of these frameworks lies in the creation of green jobs across sectors such as waste management, bio-based manufacturing, eco-industrial operations, and clean energy. The circular bioeconomy has emerged as a driver of rural employment by creating opportunities in biomass collection, processing, and transformation. These jobs are typically more decentralized and inclusive than those in fossil-based industries, helping to reduce rural to urban migration and regional economic disparities.[30]

These systems support economic diversification (Target 8.2) while reducing environmental degradation. As discussed in the book Achieving UN SDG 8: Economic Growth and Decent Work for All (2023), the challenge lies in fostering economic growth without compromising environmental integrity or social equity. The publication emphasizes that achieving SDG 8 requires integrated policies promoting sustainable industry, fair labour practices, and inclusive education principles that align with the operational and policy frameworks of bio-based and circular economy models.[39]

Biorefineries, particularly when established in agro-industrial zones, stimulate local micro-economies by integrating farmers, cooperatives, and small and medium sized enterprises (SMEs) into biomass supply chains. These systems offer new revenue streams to agricultural communities through the sale of crop residues, livestock manure, and organic waste, aligning economic growth with rural development.[2] Additionally, the by-products generated such as biofertilizers, bioplastics, and animal feed could support further local industries and markets, expanding the circular economy's economic multiplier effect. Industrial symbiosis enhances economic efficiency by lowering raw material and waste management costs, creating synergistic business models that can boost competitiveness. Companies involved in resource exchange often benefit from cost savings, innovation spillovers, and new partnership opportunities. These networks also encourage knowledge sharing, skill development, and long-term resilience among industrial candidates, making them more attractive to investment and human capital.[33]

Moreover, circular economy initiatives foster innovation in product design, materials science, logistics, and business strategy. Design thinking leads to innovation-based startups and enterprises focused on repair, reuse, remanufacturing, and digital platforms for sharing and redistribution. These sectors are expected to grow rapidly in the coming decades, contributing to job creation and diversified economic activity, especially in urban centers.[32] It is also important to note the emphasis on "decent work" jobs that are safe, fair, and inclusive. Circular and bio-based sectors provide a platform for promoting gender equality, youth employment, and upskilling, though this requires proactive policies to ensure labor rights, occupational safety, and equitable access to emerging opportunities.[34] The synergy between environmental sustainability and economic vitality in industrial symbiosis, circular economy, and biorefinery systems exemplifies the core ethos of SDG 8: creating inclusive growth pathways that decouple development from environmental degradation while ensuring dignified, future fit employment. Despite sustained economic growth in many regions, over 60% of global employment remains informal, with limited job security, social protection, or labor rights. While GDP growth rates of 3–5% are frequently reported, indicators of decent work such as safe working conditions, fair wages, and employment stability show far slower improvement, particularly in low- and middle-income economies. This imbalance demonstrates that SDG 8 implementation largely equates growth with progress, while structural deficits in job quality and worker protection remain insufficient addressed.[39]

2.4.2.5. SDG 9 – industry, innovation, and infrastructure. The transformation of industrial systems through biorefineries, industrial symbiosis, the circular economy, and the bioeconomy significantly advances SDG 9. This goal promotes the development of sustainable, resilient, and inclusive industrialization, along with developing innovation and modern infrastructure. These frameworks contribute especially to Target 9.2 (promote inclusive and sustainable industrialization), Target 9.4 (upgrade infrastructure for sustainability), and Target 9.5 (enhance scientific research and technological capability).

Industrial symbiosis plays a central role in advancing sustainable industry by shifting production systems from linear, siloed models to integrated, resource efficient networks. Industrial symbiosis facilitates inter firm collaboration where waste, heat, water, and byproducts from one industry become inputs for another, thus reducing raw material use and improving system wide efficiency. These industrial networks often form within eco-industrial parks, where physical infrastructure (*e.g.*, pipelines, cogeneration units, and water loops) supports closed loop processes, thereby embodying upgraded and climate resilient industrial systems.[33]

Biorefineries represent next generation industrial infrastructure, merging biotechnology, chemistry, and process engineering to convert biomass into a diverse range of energy and material products. These facilities are inherently modular, scalable, and adaptable to different feedstocks ranging from lignocellulosic residues to municipal solid waste making them especially suited for distributed manufacturing models that enhance regional industrial capabilities.[2] Biorefineries also promote technological spillovers into adjacent sectors such as agriculture, pharmaceuticals, and energy, reinforcing innovative ecosystems. Circular economy models stimulate industrial innovation by encouraging sustainable design, materials substitution, and digital technologies such as the IoT and blockchain for tracking resource flows. These innovations not only improve environmental performance but also create competitive advantages in global markets. The circular economy supports industries in transitioning from product ownership to service-based models (*e.g.*, product as a service), which demand rethinking value chains and customer relationships, hallmarks of industrial modernization.[32] The bioeconomy, as an innovation intensive domain, fosters cross sectoral R&D, including synthetic biology, advanced fermentation, enzymatic processing, and smart logistics. It creates incentives for public private partnerships, university industry collaborations, and startups focused on zero waste technologies. These developments align with the need to increase research intensity (Target 9.5) and develop regional industrial capacity in developing economies (Target 9.2), especially in agriculture linked sectors where biomass is abundant but underutilized.[30]

Digitalization in Industry 5.0, which merges automation with human centric design, offers a new paradigm for building resilient and inclusive infrastructure. Coupling digital tools with circular economy and bio-based solutions enhances transparency, system integration, and adaptive control, making industrial systems more responsive to resource availability and climate change risks.[33] Through technological modernization, value chain re-design, and cross disciplinary innovation, industrial symbiosis, biorefineries, and circular bioeconomy systems contribute comprehensively to achieving SDG 9, ensuring that the next wave of industrial development is not only productive and innovative but also regenerative and inclusive.

A recent study by Edbais and Hossain[40] examining SDG 9 implementation in Kuwait highlights the need to diversify industrial sectors, advance renewable energy, and encourage innovation and R&D activities. The study emphasizes that supporting SMEs, fostering technology adoption, and promoting public–private partnerships are key to building sustainable industrial infrastructure. These insights align with the principles of circular and bio-based industrial models, demonstrating how technological innovation and sustainable industrialization can drive economic growth while minimizing environmental impacts. Even with increased investment in innovation and infrastructure, over 40% of industrial activity in developing economies still relies on outdated or low-efficiency technologies. While research and innovation expenditure often remains below 1–2% of GDP in many regions, infrastructure development tends to prioritize expansion over resilience and sustainability. This imbalance indicates that SDG 9 progress is investment-driven rather than innovation effective, limiting long-term industrial competitiveness and inclusive infrastructure development.[40]

2.4.2.6. SDG 12 – responsible consumption and production. SDG 12 aims to "ensure sustainable consumption and production patterns" by promoting resource efficiency, reducing waste, and decoupling economic growth from environmental degradation. It is arguably the most directly supported SDG by frameworks such as industrial symbiosis, biorefineries, the circular economy, and the bioeconomy. These systems actively align with Targets 12.2 (sustainable management and efficient use of natural resources), 12.3 (halving food waste), 12.4 (environmentally sound management of chemicals and wastes), and 12.5 (substantially reduce waste generation).

Circular economy principles are foundational to achieving SDG 12. It encourages the redesign of products and processes to extend life cycles, enable reuse and remanufacturing, and ensure that materials are kept in use as long as possible. This reduces the need for virgin resource extraction and lowers the environmental impact of production systems.[40] Circular economy driven innovations such as product as service models, reverse logistics, and modular product design have redefined consumption patterns across industries, from electronics to packaging. Biorefineries embody circular economy strategies by converting various waste streams including agricultural residues, food waste, and municipal solid waste into high value products such as biofuels, bioplastics, enzymes, and organic fertilizers. This approach not only reduces environmental impacts but also supports food energy water nexus objectives. For example, food processing byproducts can be transformed into energy or feed ingredients, helping reduce both upstream food loss and downstream organic waste.[2] This contributes significantly to Target 12.3, which focuses on reducing global food waste at the retail and consumer levels and along production and supply chains. Industrial symbiosis is a key enabler of resource efficiency and waste reduction across industries. Industrial symbiosis allows the by-products, waste energy, and secondary materials of one industry to be used as inputs in another, significantly reducing waste sent to landfills and lowering raw material demand. These systems not only improve materials circularity but also reduce emissions and costs, contributing to Target 12.5 (substantial reduction of waste generation through prevention, reduction, and reuse).[33] Furthermore, industrial symbiosis aligns with Target 12.4, which advocates environmentally sound management of chemicals and waste throughout their life cycles. In addition, circular economy and bioeconomy strategies support sustainable public procurement (Target 12.7) by promoting LCA (evaluates energy use, emissions, and environmental burdens across all stages of a system to support sustainable decision-making), eco-labeling, and cradle to cradle certification in the sourcing of bio-based and recyclable materials.[30] Governments and corporations adopting circular procurement practices stimulate demand for sustainable goods and services, thereby encouraging innovation and market transformation.

Crucially, these systems also contribute to raising awareness and education for sustainable consumption (Target 12.8). The adoption of circular economy and industrial symbiosis requires stakeholder engagement and behavior change among industries, consumers, and regulators. Many circular economy initiatives include consumer facing campaigns, zero waste platforms, and digital tools that track product footprints, encouraging more conscious consumption habits. SDG 12 represents a central axis around which industrial sustainability revolves. Biorefineries, industrial symbiosis, and circular economy systems not only enable cleaner production but also actively reshape consumption paradigms, making production and lifestyle choices more efficient, restorative, and equitable.

A recent study by Firoiu *et al.*[42] analyzed sustainable production and consumption practices in EU Member States, highlighting strategies for reducing material use, optimizing supply chains, and fostering circular economy approaches. These practices align with the principles of industrial symbiosis and biorefineries, where waste streams are valorized, energy and material efficiency are maximized, and environmental impacts are minimized. By integrating such strategies, industries can advance SDG 12 objectives while promoting economic and environmental sustainability. Regardless of policy commitments to SDG 12, global material consumption continues to increase, with resource use increasing by over 3% annually while waste generation grows faster than recycling capacity. Although circular and responsible production practices are promoted, less than 20% of material flows are effectively reused or recycled in many economies. This persistent gap between consumption growth and resource efficiency highlights that SDG 12 implementation remains policy oriented rather than outcome driven, with limited impact on absolute resource used reduction.[42]

2.4.2.7. SDG 13 – climate action. SDG 13 calls for urgent action to combat climate change and its impacts and is directly addressed by the implementation of biorefineries, industrial symbiosis, the circular economy, and the bioeconomy. These frameworks contribute significantly to Target 13.2 (integrate climate change measures into national policies and planning) and Target 13.3 (improve education and awareness for climate change mitigation and adaptation). At the core of climate mitigation strategies is the reduction of GHG emissions. Biorefineries, by producing renewable fuels and bio-based materials, offer lower carbon alternatives to fossil derived products. When designed with low emission technologies, such as anaerobic digestion or enzymatic hydrolysis, biorefineries can be nearly carbon neutral or even carbon negative when co-products like biochar are used for soil sequestration.[2] Bioenergy, especially from waste biomass, also reduces methane emissions from landfills and open burning, two major sources of short-lived climate pollutants.

Industrial symbiosis enhances climate action by facilitating shared resource use that optimizes energy efficiency and minimizes emissions. Waste heat recovery, steam sharing, and integrated renewable energy systems (*e.g.*, solar biogas hybrids) allow industrial clusters to significantly reduce their collective carbon footprint. These industrial symbiosis networks can also support carbon capture, utilization, and storage schemes where industrial CO_2 is reused in other production processes, such as algae cultivation or carbonation of construction materials.[33] Circular economy models reduce emissions by promoting product longevity, materials reuse, and process optimization, all of which decrease energy intensive resource extraction and manufacturing. For instance, using recycled aluminum instead of virgin aluminum reduces GHG emissions by up to 95%, and similar trends hold for paper, plastics, and textiles. By shifting focus from throughput to value retention, the circular economy aligns with decarbonization pathways necessary to meet climate targets under the Paris Agreement.[41] The bioeconomy further supports climate goals through biological carbon sinks and substitution effects. Biobased materials like bioplastics and composites can displace carbon intensive inputs, while bio-based processes often have lower life cycle emissions than conventional alternatives. Additionally, integrating forestry, agriculture, and industrial value chains under bioeconomy models can promote land use strategies that optimize both productivity and carbon sequestration.[30]

These frameworks also contribute to climate adaptation and resilience. For example, decentralized bioenergy systems can improve energy access in climate vulnerable regions, while water efficient biorefinery designs can enhance drought resilience. By localizing production and diversifying feedstock sources, these systems reduce supply chain vulnerabilities caused by climate disruptions. Finally, all these models support climate education and awareness. The implementation of circular economy and industrial symbiosis strategies involves multiple stakeholders' industries, governments, and communities working collaboratively on sustainability initiatives. This promotes a culture of climate responsibility, enhances transparency, and drives informed decision making.[34] Through emission reduction, resource efficiency, carbon sequestration, and climate conscious design, biorefineries, industrial symbiosis, and circular economy models are powerful tools for achieving SDG 13. Their implementation offers practical, scalable, and locally adaptable solutions to the climate crisis.

Climate action (SDG 13) is a cross-cutting goal that underpins sustainable industrial transformation. As highlighted by Leal Filho *et al.*,[43] SDG 13 interacts synergistically with several other goals including SDG 7 (Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production) forming the foundation for integrated climate-responsive strategies. In this context, industrial symbiosis and biorefinery systems represent practical pathways for achieving SDG 13, as they minimize greenhouse-gas emissions through resource efficiency, waste valorization, and renewable energy integration. By facilitating carbon-neutral production networks and valorizing organic residues into bioenergy or biochemicals, these circular systems contribute directly to climate-mitigation targets while advancing innovation-driven sustainability. Thus, the adoption of symbiotic industrial networks and bio-based processing platforms can operationalize the global vision of SDG 13 through localized, low-carbon technological frameworks. Despite widespread adoption of climate strategies, global GHG emissions have continued to increase by 1–2% annually, indicating a clear gap between commitment and impact. While climate action plans and targets are extensively reported, measurable emission reductions and adaptation outcomes remain limited, particularly outside pilot initiatives. This mismatch suggests that SDG 13 implementation is planning intensive but action deficient, undermining its effectiveness in addressing climate urgency.[43]

2.4.2.8. SDG 15 – life on land. SDG 15 aims to protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss. The frameworks of biorefineries, industrial symbiosis, the circular economy, and the bioeconomy play important roles in addressing Target 15.1 (conservation and sustainable use of terrestrial ecosystems) and Target 15.2 (sustainable management of forests and afforestation).

Biorefineries, when sustainably designed, reduce pressure on forests and land by utilizing agricultural residues, organic waste, and non-edible biomass instead of virgin wood or food crops. This helps prevent deforestation and avoids land degradation caused by unsustainable biomass harvesting. When combined with precision agriculture and integrated biomass planning, biorefineries can support sustainable land use and encourage the cultivation of marginal or degraded lands with perennial or cover crops like miscanthus, switchgrass, or agroforestry systems thereby aiding ecosystem restoration and carbon sequestration.[2] However, the scaling of bioeconomy strategies must be managed carefully to avoid negative land use impacts, such as monoculture expansion, land grabbing, and biodiversity loss. This requires robust land governance, transparent feedstock sourcing, and strong sustainability certification systems.[30] Circular economy and industrial symbiosis models contribute to SDG 15 by reducing the need for virgin resource extraction. The reuse of construction materials, metals, industrial byproducts, and packaging materials prevents habitat destruction associated with mining, quarrying, and logging. Circular economy strategies that promote material circularity inherently reduce the pressure on land ecosystems, while industrial symbiosis can turn organic waste into biocompost or soil conditioners, improving soil fertility and reducing the need for chemical fertilizers thereby mitigating soil degradation.[33] Furthermore, circular economy models that encourage Extended Producer Responsibility (EPR), eco-design, and end of life product recovery systems reduce illegal dumping and land-based pollution, especially of plastics and e-waste, which are major contributors to soil contamination and ecosystem disruption. Biochar, a by-product of certain biorefinery processes (*e.g.*, pyrolysis), provides a direct mechanism for soil enhancement and carbon sequestration. When applied to land, biochar improves water retention, nutrient availability, and microbial activity, while locking carbon in the soil for centuries, thereby aligning industrial development with land restoration goals.[34] In addition, by reducing food loss and organic waste through valorization in biorefineries, these models indirectly support biodiversity conservation, especially in regions where agricultural expansion into forested areas is driven by the demand for new cropland. Transforming waste into value reduces this pressure and promotes a more circular

Table 3 Relevance of industrial symbiosis, biorefineries, circular economy, and bioeconomy to the UN SDGs

SDG	Goal title	Relevant targets	Key contributions of industrial symbiosis, biorefineries, circular economy, and bioeconomy	References
SDG 3	Good health and well being	3.9	Reduced air, water, and soil pollution through cleaner production, biofuels, and waste management; improved occupational and community health	2 and 33
SDG 6	Clean water and sanitation	6.3 and 6.4	Water reuse and recycling in industrial systems; efficient wastewater management; circular water flows and effluent valorization	2
SDG 7	Affordable and clean energy	7.2 and 7.3	Bioenergy production from waste; waste heat recovery; enhanced energy efficiency through shared infrastructure and clean technologies	30 and 33
SDG 8	Decent work and economic growth	8.2 and 8.4	Creation of green jobs; rural development *via* biomass value chains; economic productivity through resource efficiency and innovation	2 and 32
SDG 9	Industry, innovation and infrastructure	9.2, 9.4, and 9.5	Sustainable industrialization; eco industrial parks; biorefinery and circular economy driven R&D; digital innovation in manufacturing	33 and 34
SDG 12	Responsible consumption and production	12.2, 12.3, 12.4, 12.5, and 12.7	Resource decoupling; food waste valorization; safe waste treatment; product redesign; sustainable procurement and circular material use	2 and 41
SDG 13	Climate action	13.2 and 13.3	Emission reduction through bio-based processes; carbon sequestration (*e.g.*, biochar); energy substitution; climate education and resilience	30 and 34
SDG 15	Life on land	15.1 and 15.2	Sustainable biomass sourcing; forest conservation; reduced land degradation; land restoration *via* compost and biochar use	2 and 33

and ecologically balanced bioeconomy. SDG 15 is supported through a range of mechanisms: sustainable biomass utilization, minimized land-based pollution, forest friendly value chains, and restoration enhancing co-products like compost and biochar. The integration of industrial symbiosis, circular economy, and biorefineries into regional land use planning is thus essential for safeguarding terrestrial ecosystems while advancing economic and environmental objectives. Table 3 summarizes the specific contributions of industrial symbiosis, biorefineries, the circular economy, and the bioeconomy toward relevant UN SDGs.

Gulseven and Ahmed[44] evaluated the United Arab Emirates' progress toward SDG 15, identifying both policy commitment and critical data gaps that constrain effective biodiversity management and terrestrial ecosystem protection. Their work highlights the need for robust indicators and integrated conservation frameworks to strengthen regional sustainability performance. Kerton[45] highlighted that sustainable chemistry plays a vital role in achieving SDG 15, as it offers innovative routes to minimize chemical pollution, conserve biodiversity, and promote the responsible use of natural resources. Industrial processes grounded in green chemistry principles including biorefineries and circular material use can mitigate harmful emissions, reduce soil and water contamination, and protect terrestrial ecosystems from degradation. In this regard, industrial symbiosis frameworks that transform waste streams into feedstocks align with SDG 15 objectives by supporting sustainable land use and biodiversity conservation. Thus, sustainable industrial practices not only advance environmental performance but also ensure that industrial growth remains compatible with ecological integrity.

Regardless of global conservation commitments, over 70% of terrestrial ecosystems are now degraded or under increasing human pressure, with biodiversity loss continuing at an accelerated rate. While protected land coverage has expanded to 15–17% globally, ecosystem fragmentation, land use change, and weak enforcement significantly undermine conservation outcomes. This disconnect shows that SDG 15 progress is area based rather than impact based, with limited success in halting biodiversity decline or restoring ecosystem integrity.[44,45]

These integrated frameworks contribute directly to at least nine SDGs namely, SDG 3, 6, 7, 8, 9, 12, 13, and 15 and support several additional targets indirectly. Their implementation is pivotal for delivering cross sectoral impacts that align with the 2030 Agenda for Sustainable Development. However, these contributions must be evaluated through robust sustainability metrics such as Life Cycle Sustainability Assessment to ensure long term effectiveness and avoid unintended tradeoffs.

3. Interlinkages and synergies

3.1 The nexus approach: how industrial symbiosis, biorefineries, circular economy, and SDGs reinforce each other?

The escalating urgency of climate change, biodiversity loss, and unsustainable resource exploitation has necessitated systemic approaches to industrial sustainability. Among these, the convergence of industrial symbiosis, biorefineries, the circular economy, and the SDGs presents a powerful and mutually reinforcing framework that addresses environmental, economic, and social imperatives. This integrated nexus approach offers more than the individual counterparts, enabling synergistic pathways toward regenerative industrial systems that align closely with the 2030 Agenda for Sustainable Development.

Industrial symbiosis plays a foundational role in enabling this nexus by promoting cooperation between industries through the physical exchange of resources such as energy, water, byproducts, and waste materials. Industrial symbiosis reduces raw material input, minimizes emissions, and enhances overall process efficiency by linking firms into symbiotic networks, thus promoting both circularity and economic viability.[46] At the same time, biorefineries act as operational hubs for the valorization of biomass and organic waste, converting them into a wide array of biofuels, biochemicals, and biomaterials. When integrated within industrial symbiosis networks, biorefineries can utilize waste from surrounding industries (*e.g.*, food waste, agricultural residues, and effluents) as feedstock, while simultaneously supplying bioenergy, steam, or nutrient rich digestate to neighboring facilities.[2,47]

The circular economy complements both industrial symbiosis and biorefineries by promoting the design and implementation of closed loop production systems. Circular economy principles emphasize waste prevention, product longevity, remanufacturing, and regenerative use of materials. The interlinkage between the circular economy and industrial symbiosis is particularly strong in the context of eco-industrial parks, where material reuse, shared infrastructure, and life cycle optimization are central strategies.[30] Circularity enhances the performance of biorefineries by supporting cascading use of biomass, maximizing the value extracted from feedstocks through integrated processing routes (*e.g.*, extracting essential oils before converting residues into bioenergy). Moreover, circular thinking drives the adoption of cleaner technologies and sustainable product design, which feed back into industrial symbiosis networks with higher quality recyclable materials.[33]

The integration of the circular economy, industrial symbiosis, biorefineries, and the broader bioeconomy offers a highly synergistic pathway for advancing multiple SDGs, particularly SDG 3, 6, 7, 8, 9, 12, 13, and 15 which are discussed briefly. For SDG 3 (Good Health and Well-Being), circular economy and biorefinery frameworks play vital roles by reducing pollution and hazardous waste. The substitution of fossil-based products with cleaner bio-based fuels and materials, along with improved waste management and reduced emissions from open burning and landfilling, directly contributes to healthier air and water quality.[2] Industrial symbiosis enhances this by promoting cleaner production through inter-industry resource sharing and pollution abatement technologies.[33] In relation to SDG 6 (Clean Water and Sanitation), the circular economy and industrial symbiosis promote water recycling and efficient use through shared treatment infrastructure and cascading water loops. Biorefinery and bioeconomy systems also contribute by integrating low water use technologies and converting wastewater into valuable products like biofertilizers or process water, thereby reducing contamination and improving resource recovery.[2,30] SDG 7 (Affordable and Clean Energy) is directly supported by biorefinery and BE through the production of renewable energy sources such as bioethanol, biodiesel, and biogas derived from organic waste and non-edible biomass. Industrial symbiosis complements this by facilitating waste heat recovery and energy exchange among firms, while the circular economy reduces embedded energy demand through reuse and recycling.[33,34] SDG 8 (Decent Work and Economic Growth) benefits from the circular economy and bioeconomy through green entrepreneurship, job creation in sustainable manufacturing and waste processing, and value chain expansion for bio-based products. Biorefinery facilities, especially in rural areas, enable decentralized employment and stimulate regional economic diversification. Industrial symbiosis further supports this goal by encouraging the formation of collaborative industrial networks that open new employment and innovation opportunities.[30,32] The integration of these frameworks significantly enhances SDG 9 (Industry, Innovation and Infrastructure). Industrial symbiosis fosters sustainable industrial development by enabling eco-industrial parks and symbiotic resource flows. Biorefinery and bioeconomy promote

Fig. 5 Conceptual illustration of the synergistic roles of industrial symbiosis, biorefineries, circular economy, and bioeconomy in advancing key SDGs, highlighting sustainability outcomes.

innovation in biomass conversion technologies, while the circular economy encourages the redesign of supply chains and infrastructure to accommodate circular business models and digital tracking tools.[33,34] For SDG 12 (Responsible Consumption and Production), all four frameworks reinforce each other. The circular economy leads the way through product life extension, material recovery, and closed loop systems. Industrial symbiosis ensures the reuse of by-products between industrial actors. Biorefinery processes organic residues into new products, reducing raw material demand. The bioeconomy supports systemic shifts toward low impact, renewable biological resources.[2,30]

In terms of SDG 13 (Climate Action), the bioeconomy and biorefinery contribute by replacing fossil-based processes with low carbon alternatives and promoting carbon negative technologies like biochar. Industrial symbiosis enhances GHG reductions through efficiency and energy cascading, and the circular economy contributes by minimizing emissions linked to extraction and production activities. Together, these approaches align strongly with national climate targets and the Paris Agreement.[2,34] Finally, SDG 15 (Life on Land) is addressed through reduced pressure on terrestrial ecosystems. Biorefinery and bioeconomy frameworks promote sustainable biomass cultivation, soil restoration *via* compost and digestate, and agroecological land use practices. The circular economy and industrial symbiosis reduce land-based pollution by diverting waste from landfills and minimizing virgin material extraction.[30,33] This nexus of circular economy, industrial symbiosis, biorefinery and bioeconomy forms a mutually reinforcing system capable of delivering multidimensional sustainability benefits while advancing critical global development targets. Recognizing and operationalizing these synergies is essential for achieving a regenerative, inclusive, and low carbon industrial future. These interconnections are further illustrated in Fig. 5, which highlights the synergistic roles of industrial symbiosis, biorefineries, circular economy, and bioeconomy in advancing key SDGs.

Furthermore, the integration of industrial symbiosis, biorefineries, and circular economy with SDG planning enables better alignment between national development policies and global environmental goals. Regional industrial ecosystems can be designed with built in SDG metrics, such as carbon intensity, resource productivity, and employment quality. Tools like LCSA and material flow analysis are instrumental in quantifying these linkages and identifying hotspots for circular interventions.[2,46] For instance, a well-functioning industrial symbiosis and biorefinery network reduce the environmental burden of biomass processing while enhancing local job creation and energy resilience. Simultaneously, circular design interventions can reduce end of life waste and enhance upstream value chain transparency. Adopting a nexus approach that integrates industrial symbiosis, biorefineries, and circular economy not only accelerates progress toward specific SDGs but also creates self-reinforcing cycles of innovation, investment, and impact. This synergistic model is especially valuable in emerging economies, where it can stimulate regional industrial development, optimize local resource use, and create inclusive green employment all while meeting environmental and climate targets. By moving beyond siloed approaches and recognizing the interdependencies between these frameworks, stakeholders can create a resilient, low carbon, and circular industrial future.

Nexus based assessments report that integrated industrial symbiosis and biorefinery systems can reduce material and energy losses by 15–30% and lower environmental impacts by 10–25% when aligned with circular economy and SDG objectives. However, these synergies are mostly demonstrated through model based or scenario driven analysis, with limited empirical validation at the industrial scale. The absence of standardized indicators across industrial symbiosis, circular economy, and SDGs weakens the claimed reinforcements, indicating that the nexus approach remains conceptually attractive but operationally underdeveloped.[46,47]

3.2 Systems thinking in resource recovery and process integration

The integration of systems thinking in resource recovery and process integration offers a transformative pathway toward achieving circularity and sustainability goals. This approach enables a holistic view of complex environmental, economic, and social interactions, especially when managing biomass residues and designing biorefinery systems. Systems thinking considers the entire lifecycle of materials from production to consumption and post use allowing stakeholders to understand feedback loops, trade-offs, and synergies within a system. It is particularly useful in managing “wicked problems” such as climate change, waste accumulation, and inefficient resource flows, where linear interventions fail to account for systemic interdependencies.[48]

At the core of systems thinking is the ability to recognize and model interconnections among different resource domains such as energy, water, and materials which often function in silos under traditional planning. For example, the water–energy–food–climate nexus illustrates the cascading effects a policy in one sector can have on others, emphasizing the need for integrated governance and modeling tools.[49] By using system dynamics models and visual tools such as Sankey diagrams or chord plots, researchers and policymakers can simulate interlinkages and identify critical resource bottlenecks and trade-offs. This capability enables the decoupling of economic growth from environmental degradation by optimizing resource loops and preventing fragmentation in decision making.

In the domain of biomass residue management, systems thinking facilitates the development of synergistic and multisectoral strategies. Rather than treating waste as an isolated problem, it views residues as resources within interconnected cycles. Biorefinery systems, for instance, benefit from this perspective by integrating energy recovery, nutrient recycling, and material valorization into a closed loop model, thus enhancing both environmental performance and economic resilience.[48,50] Household level studies demonstrate that embedding energy and waste flows into a unified system leads to reduced emissions, greater material circularity, and improved sustainability metrics across the board.[50]

Furthermore, systemic frameworks also help identify challenges in achieving circularity. Iacovidou *et al.*[51] argued that despite the increasing enthusiasm for circular economy models, many resource recovery efforts remain "linear in disguise" such as energy recovery methods that degrade material value. A true systems approach moves beyond mere recycling to consider design for sustainability, infrastructure adaptability, consumer behavior, and policy environments. Systems thinking enables a shift from reductionist solutions to transformative, multi-level interventions involving governance, innovation, and cultural change.

The application of systems thinking in resource recovery and process integration strengthens the circular economy by aligning technological capabilities with socio-economic priorities and environmental constraints. It advances sustainability science by connecting actors, values, and material flows into a unified framework that is essential for addressing both immediate and long-term sustainability challenges. System based studies report 10–30% gains in resource recovery through process integration, but these results are largely model-driven and weakly validated at the industrial scale. Simplified assumption and limited treatment of uncertainty make systems thinking conceptually strong yet operationally fragile.[48–50]

3.3 Case studies

Case studies of industrial symbiosis, biorefineries, and circular bioeconomy systems provide concrete evidence of how these frameworks are implemented across diverse sectors and geographies. The Gujiao mining industrial park in China provides an illustrative example of early-stage industrial symbiosis. Song *et al.*[52] applied social network analysis to examine inter-firm collaborations, revealing that industrial symbiosis in the park is still in its infancy and anchor firms have limited influence on resource exchanges. The study highlights the importance of social relationships in enhancing industrial symbiosis, showing that technical exchanges alone are insufficient. To improve collaboration, the authors recommend establishing an information platform, providing economic incentives, investing in R&D, and promoting broad stakeholder engagement. This case underscores that successful industrial symbiosis requires both technical coordination and active social collaboration, offering insights for designing more effective eco-industrial parks.

Grimmel *et al.*[53] developed an urban industrial symbiosis recommendation platform that leverages historical material exchange data to identify potential symbiotic partnerships among urban factories. Using case studies in Braunschweig (Germany) and Singapore, the system demonstrated how data-driven tools can enhance circularity by matching waste and resource streams across diverse industries in dense urban regions. The hierarchical matching model integrates multiple criteria such as material compatibility, geographic proximity, and economic feasibility to recommend feasible exchanges. This real-world application illustrates how digitalization and knowledge-based systems can support the practical implementation of industrial symbiosis in urban contexts, promoting resource efficiency and advancing SDG 12 (Responsible Consumption and Production).

In emerging economies such as Saudi Arabia, significant industrial symbiosis potential has been identified in sectors like oil and gas, desalination, cement, and steel. However, technological, institutional, and regulatory gaps remain barriers to full scale implementation.[54,55] In the agrifood sector, the integration of industrial symbiosis principles offers vast potential for the valorization of biomass residues and by-products. For instance, Hamam *et al.*[56] illustrated how closed loop systems can be adopted in agro-food clusters to convert waste streams into valuable resources such as compost, bioenergy, and animal feed. Despite this potential, many agro-food industrial symbiosis initiatives are constrained by fragmented supply chains and insufficient stakeholder collaboration. Facilitated cooperation and digital tools for resource mapping could significantly enhance symbiotic exchanges and systemic efficiency in such contexts.

González-García *et al.*[57] evaluated a brewery waste-based biorefinery designed for the co-production of bioethanol and xylo oligosaccharides using LCA. The system utilized lignocellulosic residues such as barley straw and brewer's spent grains and was structured into five key process areas: reconditioning, autohydrolysis pretreatment, XOS purification, fermentation, and bioethanol purification. The LCA identified major environmental hotspots associated with steam generation for autohydrolysis and enzyme production for fermentation, which significantly contributed to global warming and ecotoxicity potentials. To mitigate these impacts, the study proposed replacing natural gas with wood chips as a renewable fuel, achieving 44–72% reductions in several impact categories. This case demonstrates how integrating waste valorization within biorefineries can promote circular economy principles while highlighting the importance of optimizing energy inputs and enzyme production for sustainable bio-based industries.

Lignocellulosic biorefineries offer another promising example. As outlined by Leong *et al.*,[58] these facilities are designed to process a wide variety of plant-based residues including forestry waste, rice and wheat straw, pulp industry byproducts, *etc.*, into biofuels, biopolymers, and high value chemicals. Case studies have shown that integrating waste biorefinery processes with wastewater treatment or anaerobic digestion units significantly improves overall energy efficiency and reduces GHG emissions. For instance, polyhydroxyalkanoates and bio-lipids can be derived from food and municipal waste, which are then converted into biofuels or biodegradable plastics, advancing both waste valorization and circular bioeconomy goals.

A global synthesis of circular bioeconomy implementation reveals diverse models adapted to local contexts. Hartwell and Macmillan[59] studied how building façades can be designed and managed using circular economy principles. They found that materials like aluminium and glass can be reused effectively, but challenges such as complex designs and lack of reuse systems limit circular practices. Some successful projects used modular designs and material tracking to allow easy disassembly and reuse. This example shows that a circular economy in the construction sector is possible when buildings are designed for recovery, reuse, and long-term sustainability. Tsolakis *et al.*[60] developed a Circular Economy 4.0 decision-making system that integrates digital technologies such as the IoT, data analytics, and digital twins into supply network design to enhance resource circularity and efficiency. The framework was tested through real industrial case studies in manufacturing and logistics sectors, where companies applied digital tools to map product life cycles, monitor resource flows, and optimize reuse and remanufacturing operations. The results demonstrated that digitalization enables data-driven circular strategies, improving material traceability, reducing waste, and supporting closed-loop supply chains. This real-world example highlights how Industry 4.0 technologies can operationalize the circular economy by transforming traditional linear supply networks into intelligent, connected, and sustainable systems.

Venkatesh[61] reviewed over 385 studies from 50 countries and identified trends in agriculture, forestry, aquaculture, and municipal solid waste sectors. Notably, integrated systems that combine anaerobic digestion, gasification, and microbial fermentation to upcycle waste into biochemicals and bioenergy are gaining traction. These decentralized models are especially relevant in rural or resource constrained regions and represent a vital step toward low carbon, resilient economies.

Real world case studies affirm the feasibility of industrial symbiosis, biorefinery integration, and circular bioeconomy principles. They highlight not only the technological but also the socio-institutional requirements such as policy alignment, infrastructure support, and multi-stakeholder collaboration necessary for successful implementation and scaling. These insights provide a roadmap for regions aiming to leverage local resource synergies for sustainable development.

Empirical case studies report material efficiency improvements of 15–45% and energy savings of 10–35% through industrial symbiosis and circular integration. However, most gains are context specific, with replication barriers linked to high coordination costs, data asymmetry, and policy dependency. Lifecycle based case analysis indicates GHG reductions of 20–40%, yet several studies rely on static LCA assumptions, underestimating rebound effects and system leakage. Socio-economic assessments show 5–18% cost savings, but benefits disproportionately favor large firms, limiting inclusivity. Food and bio-based system case studies highlight waste valorization rates up to 60%, but scalability is constrained by feedstock variability and market volatility, questioning long term resilience beyond pilot or regional scales.[52–56]

4. Benefits and opportunities

4.1 Emission reduction and waste minimization

One of the foremost benefits of transitioning to a circular economy and implementing symbiotic biorefinery models is the significant reduction in GHG emissions and overall waste generation. Unlike the linear economy, which relies heavily on virgin resource extraction and landfilling, circular economy systems retain materials in circulation, reducing the demand for energy intensive raw material processing. Biomass based energy systems, waste to energy technologies, and microbial fuel cells represent critical strategies that utilize agricultural residues, municipal solid waste, and industrial byproducts to generate renewable energy while diverting waste from landfills.[62] These technologies not only mitigate methane emissions from unmanaged organic waste but also reduce CO_2 emissions by replacing fossil-based energy sources.[63] The valorization of waste through circular practices, such as composting, anaerobic digestion, and fermentation, aligns closely with SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production) and directly contributes to creating a low carbon, resource efficient economy. Industrial symbiosis further complements these efforts by optimizing material and energy flows among firms, allowing waste from one entity to serve as input for another, effectively lowering system wide emissions and enhancing resource efficiency.[64] Integrated waste to resource and biorefinery systems report 20–40% reductions in GHG emissions and 30–60% decreases in solid waste disposal through material recovery and bioenergy generation. However, these benefits are often derived from controlled or pilot scale conditions, with limited assessment of rebound effects, feedstock variability, and long-term system stability.[62]

4.2 New value chains, job creation, and innovation

The integration of circular economy principles into industrial and agricultural systems opens new pathways for economic diversification, technological innovation, and employment. Circular bioeconomy business models such as those based on bio-based inputs, waste valorization, and service-oriented design generate new value chains by creating secondary markets for formerly discarded materials.[63] Waste biorefineries, for example, not only transform organic and industrial waste into biofuels, bioplastics, and biofertilizers but also catalyze the development of local, decentralized economies with reduced dependence on imports. These bioprocesses, often implemented at various scales from community-based setups to large scale industrial parks, offer opportunities for skilled and semi-skilled employment in sectors like waste logistics, R&D, bioproduct manufacturing, and maintenance. According to Islam *et al.*,[62] such systems also promote innovation through interdisciplinary collaboration across environmental science, biotechnology, process engineering, and digital analytics. Additionally, strategies involving microbial lipid production, bacterial cellulose synthesis, and the use of residual streams in fermentation processes have demonstrated scalable innovation potential that supports industrial competitiveness and sustainable entrepreneurship.[58] This transformation is not merely technological but socioeconomic, nurturing inclusive growth by creating green job opportunities and empowering SMEs.

Waste valorization and bio-based production systems are presented as drivers of new value chains and innovation led growth, with localized processing reported to generate 5–15% employment gains in emerging bioeconomy sectors. However, most evidence focuses on potential job creation rather than job quality, skill stability, or long-term market viability. Innovation outcomes are similarly framed in terms of technological novelty, while commercial adoption and diffusion remain weakly demonstrated, limiting the durability of these new value chains.[62,63]

4.3 Policy support and institutional frameworks

The effectiveness and scalability of circular economy and symbiotic biorefinery systems are significantly influenced by policy frameworks, regulatory instruments, and institutional coordination. In developed and developing countries alike, national circular economy strategies (such as India's G20 supported circular economy roadmap) and supranational efforts (such as the EU Green Deal and circular economy action plans) provide vital scaffolding for enabling systemic change. These policies often mandate EPR, promote eco-design standards, and support public–private partnerships for circular innovation.[62,64] Institutional mechanisms such as subsidies, tax incentives, and green procurement further facilitate circular investments. However, policy coherence across sectors and jurisdictions remains a challenge, particularly in emerging economies where institutional silos and fragmented waste governance hinder circular transitions. As Leiva *et al.*[64] highlighted, the techno economic viability of industrial symbiosis requires harmonized CAPEX–OPEX (capital expenses and operational expenses) accounting, lifecycle cost analysis, and material flow cost accounting approaches to guide investment and decision making. Creating enabling ecosystems where stakeholders' industries, academia, municipalities, and local communities collaborate across value chains is thus essential to advance circular economy initiatives. Institutional frameworks must also be inclusive, ensuring the participation of informal sector actors and marginalized communities in circular economy transitions to avoid techno-centric and inequitable outcomes. Policy frameworks are identified as key enablers of sustainability transitions, with coordinated regulations and incentives shown to improve project adoption rates by 20–30% in structured governance settings. However, institutional support remains fragmented and uneven, particularly in developing regions, where policy misalignment and weak enforcement limit long term impact.

5. Challenges and barriers

5.1 Technological, regulatory, financial, and behavioral barriers

Despite the momentum surrounding circular economy transitions and biorefinery innovations, multiple interconnected barriers hinder large scale implementation and commercialization. Technologically, the complexity of integrating diverse biomass feedstocks, process variability, and conversion inefficiencies make scaling up biorefineries and industrial symbiosis networks particularly challenging. These technical hurdles are often exacerbated by seasonal feedstock availability and the lack of standardized processing technologies.[65] Economically, many circular and biorefinery models face high upfront capital costs, limited access to finance, and difficulty achieving market competitiveness against well established, fossil-based alternatives. These financial concerns are especially acute in regions with underdeveloped bioeconomy infrastructures and uncertain investor confidence.[66,67] Regulatory uncertainties also play a critical role, particularly where environmental legislation is fragmented or lacks clarity on end-of-waste status, standardization, and quality benchmarks for circular and biobased products. Moreover, insufficient or misaligned policy incentives at times fail to effectively de-risk circular investments.

Behavioral and organizational barriers are equally significant. These include resistance to change within firms, insufficient management expertise on CEBMs, and a general lack of awareness or understanding among consumers regarding the benefits of circular products and services.[44] The misalignment between short term financial performance metrics and the long term environmental social returns of circular economy further impedes adoption. Cultural preferences for "new" over "reused" products and low public trust in waste-derived goods continue to be deterrents in many societies.[68] Despite technological progress, systemic barriers dominate. Around one third of projects fail to scale due to poor technological integration, while fragmented regulations extend implementation timelines by up to 25%. High capital costs and payback periods exceeding 8 years discourage investment, particularly for SMEs. Crucially, behavioral resistance and weak market demand, often overlooked, undermine adoption, indicating that technological innovation alone cannot deliver sustainability transitions without strong policy and social alignment.[66,67]

5.2 Lack of standardization and market incentives

A critical yet often overlooked barrier to circular economy adoption is the absence of standardized classification systems, quality specifications, and traceability frameworks for secondary raw materials and bio-based products. The lack of harmonized norms makes it difficult to ensure consistency, safety, and performance key concerns for industries, regulators, and consumers alike. Without these standards, recycled/repurposed products often struggle to compete in mainstream markets, leading to weak demand-pull effects.[65] Also, the insufficient development of marketplaces or procurement systems for waste-derived goods limits the scaling of circular bioeconomy product value chains.

Incentives for circular economy innovation such as tax breaks, green financing, or preferential procurement are sporadic or absent in many countries, further discouraging private sector investment. Additionally, existing subsidies for linear, resource intensive industries often distort market competitiveness, unintentionally undermining emerging circular solutions. The lack of consistent carbon pricing mechanisms, EPR enforcement, or eco-labelling schemes also restricts consumer uptake and industry motivation to innovate toward circularity. The studies show that non-standardized assessment methods (LCA, circularity indicators, and SDG metrics) prevent fair comparison and reduce industry confidence. At the same time, weak and inconsistent market incentives fail to compensate for the 20–40% higher upfront costs of circular and symbiotic systems. This combination keeps most initiatives at the pilot scale, limiting large scale adoption despite technical feasibility.[66]

5.3 Need for multi-stakeholder collaboration

Given the systemic and cross sectoral nature of circular economy transitions, isolated efforts are insufficient. However, achieving effective coordination among diverse stakeholders' governments, businesses, research institutions, non-governmental organizations, and consumers remains a major hurdle. Institutional bodies, fragmented governance structures, and competing policy priorities often lead to poor alignment of objectives and duplication of efforts. The absence of regional circular economy platforms or knowledge sharing hubs limits learning, joint ventures, and replicability of best practices across sectors or geographies.[69]

In industrial symbiosis and biorefinery networks, for example, collaboration is critical to ensuring reliable input output flows, shared infrastructure, and cost-effective logistics. Yet, mistrust among firms, lack of data transparency, and concerns about intellectual properties frequently obstruct cooperation. Additionally, SMEs often lack the resources or institutional support to participate meaningfully in circular economy partnerships. To overcome these barriers, it is essential to foster enabling ecosystems that prioritize co-design, capacity building, and inclusive innovation particularly in the Global South, where informal role players and local communities must be engaged to ensure socially justified transitions.

Industrial symbiosis and circular initiatives fail when firms, governments, financiers, and communities act in isolation. Case evidence indicates that projects with formal multi-stakeholder platforms achieve 25–40% higher resource exchange efficiency, while fragmented governance leads to delays exceeding 2–3 years and reduced trust. The study critically highlights that collaboration is often voluntary and informal, making outcomes unstable without institutionalized coordination mechanisms.

6. Sustainability assessment methodologies for industrial symbiosis and biorefineries

Recent studies emphasize the integration of Techno-Economic Analysis (TEA) (assessment of capital and operating costs to determine the economic feasibility and minimum selling price of biorefinery products) and LCA to holistically evaluate sustainability performance in biorefinery systems. Verma and Saini[70] highlighted that combining these methodologies helps determine both the economic feasibility and the environmental implications of industrial effluent treatment processes, thereby promoting sustainable process design and resource recovery.

6.1 Life cycle assessment

LCA is a well-established methodology for evaluating the environmental impacts of products and services throughout their entire life cycle. The LCA framework comprises four primary stages: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation.[71]

The application of LCA and related methodologies has gained considerable attention in corporate social responsibility and sustainability evaluation. However, limited research has explored the integration of LCA with quantitative approaches such as statistical analysis and AI.[72] Modern firms are increasingly adopting sustainability-oriented approaches to strengthen corporate social responsibility initiatives and assess the efficiency of procurement, production, and distribution processes. Life cycle methods enable organizations to systematically assess the environmental performance of their products and processes across the entire life cycle. LCA has been applied extensively in recent years to support sustainability practices across diverse sectors, extending beyond traditional industries. LCA, per ISO 14040:2006, is widely used for biorefineries and industrial symbiosis, but differences in boundaries and assumptions can shift results by 20–50%, limiting comparability. This makes LCA indicative rather than definite, reducing its reliability for decision making. LCA turns qualitative circularity ideas into quantitative design levers, identifies environmental hot-spots across interconnected processes, and prioritizes where material and energy exchanges will actually reduce impacts. By quantifying cradle-to-gate and cradle-to-grave effects, LCA helps site planners and biorefinery designers choose which waste streams to exchange, which valorization routes to scale, and which co-products deliver the largest net environmental gains avoiding well-intentioned but counterproductive substitutions.[56] For emerging biorefineries, prospective LCA supports scale-up decisions by comparing alternative processing pathways (*e.g.*, biochemical *vs.* thermochemical) and by revealing trade-offs between carbon, energy, and other impact categories; when combined with TEA it prioritizes symbiotic linkages that are both low-impact and economically viable.[73] Therefore, embedding LCA into industrial-symbiosis planning creates measurable evidence for regulators, investors, and community stakeholders accelerating approvals and financing by demonstrating verified environmental benefits. Dynamic and circularity-aware LCAs furthermore allow comparison of "symbiosis bundles" (sets of exchanges) rather than single exchanges, enabling system-level optimization of material cascading and energy recovery across industrial parks and regional biorefinery networks.

6.1.1. Social life cycle assessment. Social Life Cycle Assessment (S-LCA) provides insights into the social impacts associated with a product's life cycle. Although promising, S-LCA remains under development and lacks comprehensive detail in its current applications.[74] Integrating social considerations alongside environmental and economic metrics is essential for achieving a holistic sustainability evaluation. It extends conventional LCA to social impacts but suffers from inconsistent indicators, poor data availability, and subjective scoring, especially in industrial symbiosis and biorefinery contexts. Connecting S-LCA to industrial symbiosis and biorefineries strengthens sustainability planning by incorporating human and societal impacts alongside environmental and economic considerations. In systems where industries share resources and biorefineries transform biomass into fuels, chemicals, or materials, S-LCA highlights social outcomes such as job creation, worker health and safety, community well-being, and stakeholder equity metrics that traditional environmental LCA might overlook. This makes circular strategies more socially robust and helps avoid unintended negative social consequences while enhancing local development.[75] For industrial symbiosis, S-LCA can reveal how resource exchanges affect employment patterns, working conditions, and community stakeholders across supply chains, enabling planners to optimize exchanges not just for material efficiency but for positive societal outcomes too. By systematically tracking social indicators (*e.g.*, fair wages, labor rights, and community health), S-LCA supports decision-making that aligns collaborative industrial networks with broader sustainability goals.[76] In biorefinery contexts, integrating S-LCA ensures that scaling bio-based processing considers local socio-economic impacts, stakeholder perceptions, and equity in benefit sharing across upstream (feedstock producers) and downstream (workers and consumers) stages. This is especially important in rural or developing regions where biorefinery projects can significantly alter employment landscapes and community dynamics. S-LCA thus helps stakeholders, investors, and policymakers understand which biorefinery configurations deliver the most socially beneficial outcomes in addition to environmental and economic zones.[77]

6.1.2. Life cycle costing. Life Cycle Costing (LCC) evaluates the total financial expenditure related to a product or system from design and production through to the end of its operational life. Over time, various LCC methodologies have been proposed; however, only two approaches environmental LCC and social LCC have gained significant recognition and adoption within the scientific community. LCC complements LCA and S-LCA by providing critical economic insights that support decision-making and resource optimization.[78] LCC assesses economic performance over the system lifecycle, but assumptions on costs and discount rates can change results by 20–40%. This makes LCC indicative rather than a reliable investment guide for biorefineries and industrial symbiosis. Sasongko & Pertiwi[79] applied LCC across the full palm-oil biodiesel chain incorporating capital, operation, maintenance, disposal, and externality costs. Their results show that Indonesia's B30 biorefinery program reduced diesel imports by 45%, avoided 14.34 Mt CO_2e, saved IDR 63.4 trillion, and supported 1.2 million jobs, demonstrating how integrated biorefineries enable industrial symbiosis *via* waste valorization and co-product utilization. Liu *et al.*[80] integrated LCC with LCA for Jatropha biodiesel in China, estimating a production cost of USD 796.32 per t, with feedstock oil contributing 44.37%, while shell combustion and glycerol recovered 16.76% of total costs. These quantified savings from by-products directly illustrate symbiotic resource loops within biorefineries. Such integrated LCC–LCA studies help identify economic and energy hot-spots while quantifying the value of co-products and waste streams, enabling optimized resource sharing across biorefineries. By revealing cost savings from by-product utilization and infrastructure integration, they strengthen the business case for industrial symbiosis. These system-level insights guide planners and policymakers in designing financially resilient circular networks, accelerating deployment of sustainable biorefinery clusters and translating circular economy concepts into measurable, scalable industrial practice.

6.2 Techno-economic analysis

Recent studies underscore the significance of integrating TEA with sustainability assessments to evaluate innovative technologies across various sectors. For instance, Zahedi *et al.*[78] conducted a comprehensive assessment of carbon capture from thermal power plants, highlighting the potential of converting captured CO_2 into value-added concrete materials. Their analysis encompassed technical, economic, and environmental dimensions, emphasizing the viability of utilizing flue gas in concrete production through chemical reactions that enhance CO_2 absorption while minimizing energy consumption. In the context of renewable energy, Jan *et al.*[81] performed a TEA of renewable energy sources in the rural northern region of Kalam, Pakistan. Their study evaluated the potential of hybrid energy systems, considering diesel, wind, solar, and hydro sources, to meet local energy demands. The analysis provided insights into the economic feasibility and operational efficiency of integrating these renewable sources in remote areas.

Cormos *et al.*[82] focused on green hydrogen production *via* biogas reforming, coupled with membrane-based CO_2 capture. Their TEA and environmental assessment explored innovative concepts in integrating biogas reforming with pre- and post-combustion CO_2 capture using membranes. The study assessed the technical and economic performances of green hydrogen production, providing valuable insights into the feasibility of such integrated systems.

Zhou *et al.*[83] employed machine learning-aided LCA and TEA to evaluate the hydrothermal liquefaction of sewage sludge for bio-oil production. Their study integrated machine learning models with LCA and TEA to predict product distribution and properties, enhancing the assessment of energy, climate change, and economic performance of the process. Collectively, these studies demonstrate the critical role of TEA in assessing the feasibility and sustainability of emerging technologies. By integrating technical, economic, and environmental evaluations, TEA provides a comprehensive framework for decision-making in the development and implementation of sustainable solutions across various sectors. TEA indicates that biorefinery and resource recovery systems can achieve 10–25% cost savings under optimized conditions, but results are highly sensitive to feedstock prices, scale, and technology efficiency. Most studies rely on model projections, with real world validation limited, making TEA indicative rather than fully reliable for investment decisions.[84,85] Building on these findings, TEA serves as a critical bridge between technological innovation and practical deployment in industrial symbiosis and biorefinery systems by quantifying the economic value of resource integration, co-product valorization, and infrastructure sharing. TEA enables comparison of alternative processing pathways and symbiotic configurations, identifying conditions under which waste-derived feedstocks, energy cascading, and CO_2 utilization become economically attractive. When combined with sustainability assessments, TEA supports circular economy implementation by highlighting scale-dependent benefits, cost sensitivities, and system-level trade-offs, guiding stakeholders toward resilient biorefinery networks that maximize resource efficiency while minimizing financial and environmental risks.

7. Emerging trends and future directions

7.1 Digital enablers for circular and symbiotic systems

Digitalization is playing an increasingly transformative role in advancing both the circular economy and industrial symbiosis, offering tools for optimization, real time monitoring, and transparency. Technologies such as the IoT, AI, blockchain, big data, and digital twins are now used to track resource flows, predict material demands, and enhance coordination across industrial networks.[84] In circular economy contexts, these tools support the regeneration, slowing, narrowing, and closing of resource loops by enabling predictive maintenance, LCA, and smart product service systems.[85]

Blockchain technologies further support traceability and accountability in industrial ecosystems by recording transactions of waste, energy, and secondary materials with immutable records, which is particularly beneficial in multi-stakeholder industrial symbiosis networks.[86] Digital twins and building information modeling are also increasingly being used to simulate industrial infrastructure and its environmental performance, supporting design for reuse and real time system optimization.[87] Despite these advancements, several barriers remain, including data projections, high implementation costs, and underdeveloped standards for inter-operability. Moreover, concerns about rebound effects where digital tools inadvertently increase resource consumption highlight the need for holistic evaluation frameworks.[86] While digital tools show potential to enhance efficiency and coordination by 15–30%, practical adoption is constrained by high investment costs, fragmented data systems, and low

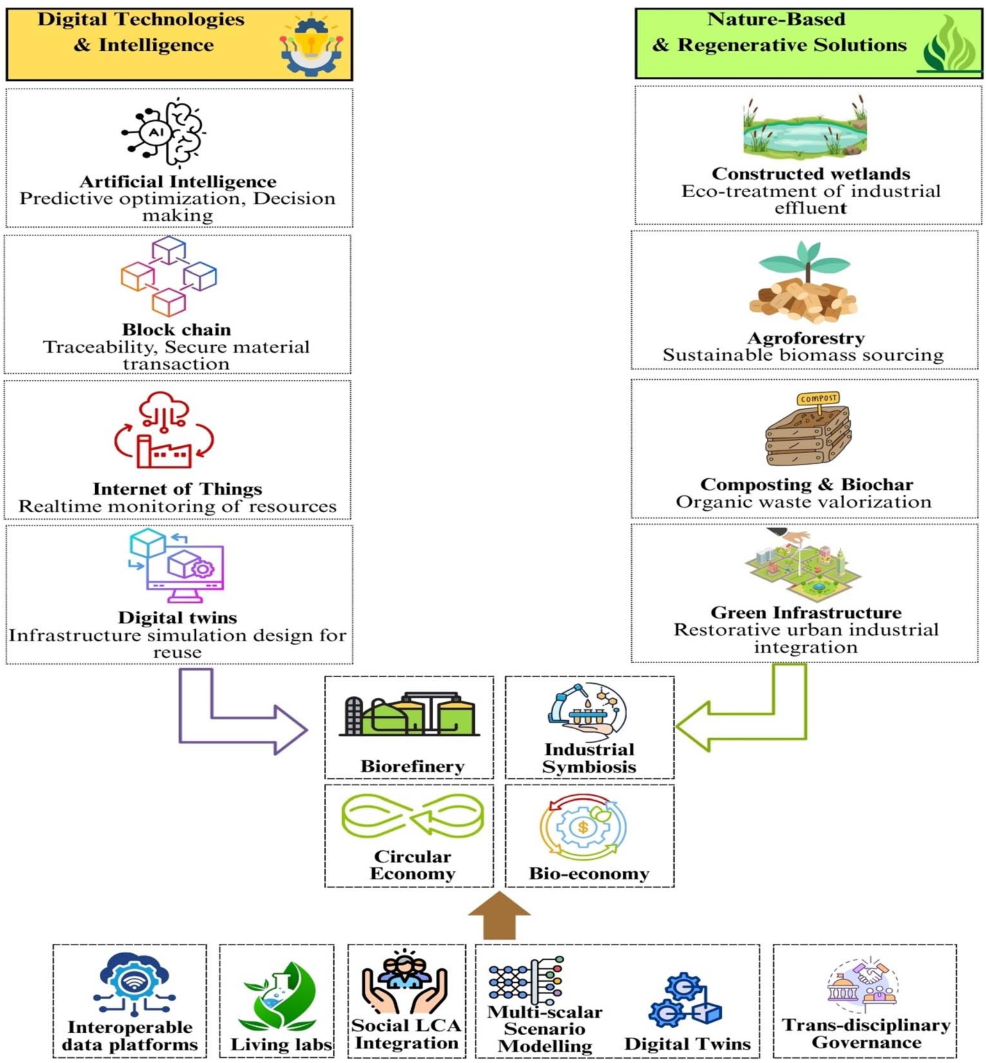

Fig. 6 Conceptual visualization of emerging digital and nature-based enablers in advancing the circular economy, industrial symbiosis, biorefineries, and bioeconomy.

integration across stakeholders, limiting their real-world impact in circular and symbiotic systems.

7.2 Nature based solutions and the regenerative economy

Alongside digital innovation, the emergence of NbSs and the regenerative economy are reframing industrial sustainability by moving beyond efficiency toward ecological restoration. NbSs such as constructed wetlands, agro-forestry, urban green infrastructure, and ecological wastewater treatment restore ecosystem services while supporting circularity in material and nutrient flows.[88] These solutions offer co-benefits including climate resilience, biodiversity restoration, and improved human well-being, especially when embedded into biorefinery and circular economy infrastructures.

Regenerative economy principles go further by emphasizing net positive environmental impact, circular nutrient loops, and long-term ecosystem health. For example, the integration of biochar from biorefineries into agriculture improves soil fertility and sequesters carbon, thus aligning the circular economy with SDG 13 (Climate Action) and SDG 15 (Life on Land).[2] When applied in tandem with industrial symbiosis, regenerative solutions can convert organic waste into compost or biofertilizers, further closing local bioresource cycles. However, to realize these potentials at scale, enabling policies, cross disciplinary collaboration, and ecological accounting systems are needed. Nature based solutions are promoted to restore ecosystems and support circular economies, yet less than 20–25% of projects report measurable ecological or economic benefits at scale. Implementation is often constrained by fragmented governance, short term funding, and lack of monitoring, making many initiatives conceptually appealing but practically underperforming.[87]

7.3 Research gaps and the proposed roadmap

Despite increasing momentum, important research and implementation gaps persist in industrial symbiosis, circular economy, and biorefinery integration. First, most case studies remain fragmented across sectors and geographic scales, with limited multi-scalar system modeling to assess cumulative sustainability outcomes.[85] Furthermore, the social dimension in particular issues of inclusivity, labor quality, and community resilience remains underexplored, especially in the context of emerging economies.[68]

Current LCA tools largely emphasize environmental indicators, but S-LCA and equity metrics are needed to evaluate distributional impacts. Additionally, empirical insights on how informal sectors contribute to circularity, especially in waste management, are insufficiently documented.[89]

A forward-looking research roadmap should include (i) the development of inter-operable data platforms for industrial symbiosis and circular economy collaboration; (ii) the integration of S-LCA and digital twins for dynamic scenario planning; (iii) the establishment of living labs for regenerative circular economy innovations; and (iv) the expansion of trans-disciplinary research that includes design, ecology, behavioral sciences, and systems governance. Such steps will be essential for designing scalable, inclusive, and regenerative industrial models that align with long term climate and sustainability goals. These interrelated enablers and innovation pathways are conceptually illustrated in Fig. 6, highlighting the convergence of digital and nature-based tools in shaping future ready circular and symbiotic industrial systems.

Regardless of advances in industrial symbiosis, biorefineries, and circular economy integration, empirical validation remains limited, with most studies relying on models or pilot cases. Key gaps include standardized metrics, long-term socio-economic impact assessments, and scalable governance frameworks, indicating that future research must focus on measurable outcomes, cross sector integration, and actionable roadmaps to translate theory into practice.

8. Conclusion

This review has mapped the critical interlinkages among industrial symbiosis, biorefineries, the circular economy, and sustainability frameworks, illustrating their collective potential to transform linear, resource intensive industries into closed loop, regenerative systems. Industrial symbiosis enhances resource and energy efficiency through inter firm collaboration. Biorefineries enable biomass valorization and organic waste recovery, while circular economy principles restructure material flows to promote longevity, reuse, and systemic efficiency. When integrated, these approaches reinforce the environmental, economic, and social pillars of sustainability and align industrial development with global goals such as climate resilience and resource decoupling.

Key insights include the emergence of digital tools such as AI, IoT, and blockchain as catalysts for operational transparency and system optimization. Simultaneously, NbS and regenerative models shift the paradigm from sustainability to net positive industrial performance. However, significant gaps remain, including fragmented case studies, weak integration of social metrics, and underrepresentation of informal and rural economies in implementation strategies.

Moving forward, policy must incentivize interoperable platforms for data sharing, cross sector collaboration, and circular infrastructure investment. Research should expand to include dynamic, location-based, and inclusive models especially in the Global South. For industry, the adoption of living labs, circular procurement standards, and value chain redesign will be critical to scale impact.

An integrated nexus approach grounded in systems thinking and regenerative design holds transformative promise. It not only enables sustainability compliance but also unlocks long term economic resilience and societal well-being.

Author contributions

Arun Barathi, Debajyoti Kundu: conceptualization, methodology, writing – original draft, writing – review & editing, supervision; Kumari Pooja, Madhava Surya, Samuel Jacob, Vineet Kumar, Arindam Kuila: writing – original draft, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

All relevant data supporting this study are provided within the manuscript. This review does not include primary research results, software, or code, and no new data were generated or analyzed as part of this work.

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