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Industry 5.0 and Sustainable Biocomposite Materials: A Brief Review of Human-Centric Technologies for Sustainable Manufacturing

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Abstract
Industry 5.0 represents a paradigm shift in manufacturing that extends the digital and automation capabilities of Industry 4.0 by placing human-centricity, sustainability, and resilience at the core of industrial development. This review examines the emerging integration of Industry 5.0 technologies with sustainable biocomposite materials as a pathway towards environmentally responsible and resilient manufacturing. Particular attention is given to bio-based polymer matrices and natural-fibre reinforcements, including flax, hemp, jute, bamboo, wood-derived materials, and Sida acuta*, which offer opportunities for renewable resource utilization, waste valorization, lightweight structures, and reduced life-cycle environmental impacts. The review further explores the roles of artificial intelligence and machine learning, Industrial Internet of Things, digital twins, collaborative robotics, and additive manufacturing in enabling intelligent, adaptive, and human-in-the-loop biocomposite production systems. Life-cycle assessment, circular economy principles, recyclability, biodegradability, and closed-loop material flows are discussed as essential sustainability considerations. Applications in automotive, construction, packaging, and other emerging sectors demonstrate the technical and environmental potential of these materials. However, challenges remain in mechanical and thermal performance, moisture sensitivity, fibre variability, processing, recycling, standardization, cost, and large-scale commercialization. Future research should focus on AI-driven material design, intelligent biocomposites, scalable additive manufacturing, advanced recycling, and supportive regulatory frameworks. The review highlights that integrating sustainable materials with human-centred digital manufacturing can contribute significantly to the transition towards resilient, circular, and low-carbon industrial systems under Industry 5.0.*
Keywords: *Industry 5.0; sustainable biocomposites; natural fibres; circular economy; artificial intelligence; digital twins; additive manufacturing; sustainable manufacturing.*

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I.Introduction

Industry 5.0 builds on but diverges from Industry 4.0. Where Industry 4.0 (circa 2010s) focused on full automation and connectivity using cyber-physical systems (CPS), IoT, cloud computing, and big data [1], Industry 5.0 (initiated ~2020) explicitly adds human-centricity, sustainability, and resilience. According to the European Commission, I5.0 "complements Industry 4.0 by highlighting sustainable, human-centric and resilient industry" [2]. It reframes technology as enabling human and societal goals, not ends in themselves. In practice, this means intelligent automation is designed with humans (e.g. cobots, VR/AR interfaces) and with environmental boundaries (net-zero emissions, circular loops). Industry histories are often summarized in 5 stages (see timeline above), each adding new capabilities (Figure 1):

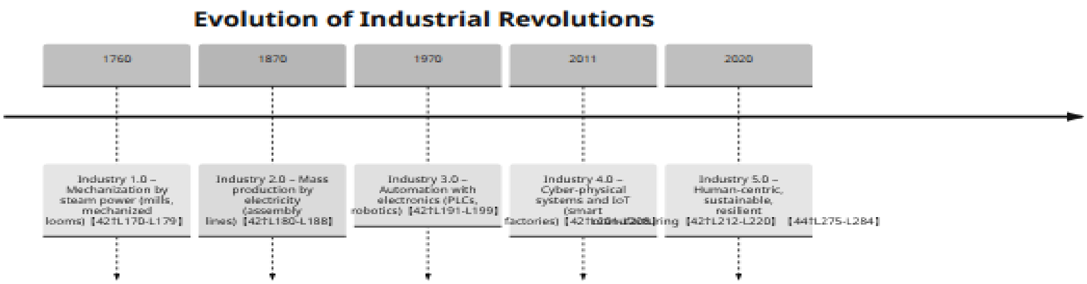

Figure 1: Evolution of Industrial Revolutions [1]

i. **Industry 1.0 (c.1760–1870):** Mechanization via steam and water power [3]
ii. **Industry 2.0 (c.1870–1970):** Mass production via electricity and assembly lines [3].
iii. **Industry 3.0 (c.1970–2010):** Automation via electronics and IT (PLCs, robots) [4].
iv. **Industry 4.0 (c.2010–2020):** Digitization via CPS, IoT, AI, cloud; smart, self-optimizing factories [4].
v. **Industry 5.0 (2020+): Human–Machine Collaboration** with sustainability: integrates AI and data-driven systems *with* human judgement, circular economy, and adaptive resilience [5].

Unlike the purely tech-centric I4.0, I5.0's "human-in-the-loop" designs ensure workers control and benefit from automation . The I5.0 agenda has been codified in policy (e.g. EU Roadmap) and in industry awards, reflecting its goal of "achiev[ing] societal goals beyond jobs and growth" [6].

Core Principles of Industry 5.0

Industry 5.0 is often described by its three pillars: Human-Centricity, Sustainability, and Resilience [7–9]. These guide all I5.0 initiatives:

i. Human-Centric Manufacturing

Workers are treated as valuable assets not dispensable resources. I5.0 stresses co-design and skill development [10]. Trust, inclusiveness, and wellbeing are built into systems. Examples include collaborative robots (cobots) that handle hazardous tasks while humans make complex decisions, and augmented reality (AR) tools that assist workers in assembly [11].

ii. Sustainability (Circular Economy)

I5.0 aligns with UN SDGs (notably SDG12, SDG9)[11]. Circular economy practices are integral: designing products for reuse, using bio-based and recyclable materials, and minimizing waste. For instance, I5.0 factories increasingly incorporate life-cycle thinking, tracking carbon footprints (ISO 14064/14067) and material flows in real time through IoT. Energy and resource efficiency are maximized: smart sensors and AI reduce energy use by 20–30% in trials[12]. Waste streams are closed loop, with by-products recycled back into production [13].

iii. Resilience

Reflecting lessons from COVID-19, I5.0 builds systems that adapt and strengthen through disruption. Companies adopt adaptive feedback loops and robust control so that breakdowns or shocks (e.g. supply shortages) are quickly absorbed [14]. Digital twins and real-time analytics help factories self-heal: a digital twin can predict machine failures before they occur, enabling proactive maintenance [15]. Resilient supply chains (diverse local sourcing) and workforce reskilling are also emphasized. Together, these pillars reorient production from efficiency alone to value – to both society and the planet.

Technology Enablers in Industry 5.0

Advanced digital and automation technologies remain central, but under the I5.0 paradigm they are explicitly harnessed for human and environmental benefit . Key enablers include:

I Artificial Intelligence (AI) and Machine Learning (ML)

AI algorithms optimize production schedules, quality control, and predictive maintenance. They also enable augmented decision-making, supporting workers in situations like AI assistance for defect detection) [10].

Ii Industrial Internet of Things (IIoT)

Ubiquitous sensors and connectivity allow real-time monitoring of machines, products, and environments. IIoT creates transparent supply chains and immediate feedback on energy/carbon usage. In biocomposite plants, for example, IoT sensors can monitor cure temperature and humidity to ensure material quality [15].

Iii Digital Twins (DT)

DTs are virtual replicas of equipment, processes or even entire factories that sync continuously with their physical counterparts [16]. They enable engineers to simulate and optimize production before implementation. In I5.0, digital twins serve human operators with predictive insights such as showing a worker the effect of adjusting machine speed on output quality). DT-enabled simulations can reduce waste by 10–30% [17].

Iv Robotics and Cobots

Collaborative robots (cobots) are specifically built for safe interaction with humans. In I5.0 factories, cobots perform heavy or precise tasks under human supervision. This allows workers to focus on complex or creative tasks. Robots equipped with AI can adapt in real-time to human actions (via sensors), enhancing safety and efficiency [14].

V Additive Manufacturing (3D Printing)

Offers customization and efficient material use. Biocomposites are increasingly 3D-printed for on-demand parts (e.g. medical casts from PLA/cellulose) . I5.0 promotes decentralized, small-batch production (enabled by printers) which shortens supply chains and reduces inventory waste [18].

These technologies are often deployed together in human-in-the-loop systems . For example, an AI-aided cobot may handle repetitive assembly under the guidance of a worker, with a digital twin monitoring metrics in real time. The net effect is higher quality, personalized production with shared human–machine intelligence.

Sustainable Biocomposite Materials

Biocomposites are composite materials where at least one component (matrix or reinforcement) is of biological origin. They can be categorized by the origin of their matrix and fibers [19]:

I Bio-based matrices

Polymers derived from renewable sources, often biodegradable: e.g. polylactic acid (PLA), polyhydroxyalkanoates (PHAs), polybutylene succinate (PBS), starch/polyester blends [20]. These replace petro-polymers (PE, PP, PET). Advances like genetically engineered microbial PHAs and 4D printing (smart bioplastics) are emerging.

Ii Natural fiber reinforcements

Plant fibers (flax, hemp, jute, sisal, kenaf, bamboo, wood flour, etc.) and animal fibers (wool, silk)[21]. Natural fibers are lightweight, have decent specific strength, and are renewable [22]. Wood flour (sawdust) is also used, often as waste valorization.

Iii Biocomposites

Combining the above, for example, PLA/flax, PHA/hemp, starch/jute. Fully biodegradable biocomposites use both bio-matrix and bio-fiber (like PLA/flax). Partially biodegradable ones mix bio-fiber with non-biodeg matix (e.g. PP/flax).

Advantages of Biocomposites

i. Biocomposites typically have much lower life-cycle carbon footprints than glass- or carbon-fiber composites [23]. For example, Duigou *et al.* (2011)*:* compared flax/PLLA biocomposites vs glass/unsaturated polyester; reports much less non-renewable energy (−97%) and lower climate change impact (−38%) [24]. Their biodegradability allows composting or recycling at end-of-life, unlike thermoset composites. Biocomposites are also non-toxic and often cheaper (fiber wastes are low cost) [25].

ii. Natural fibers have moisture sensitivity and variable quality [22]. They tend to have lower tensile strength and stiffness than fiberglass. Processing can be tricky: fibers can scorch in hot molds or float in resin. Researchers use fiber treatments (alkaline, silanes) and compatibilizers to improve fiber–matrix adhesion [26]. Moisture barriers (coatings, hydrophobic matrices) are also studied.

Applications

Biocomposites are used in packaging, consumer goods, and construction (e.g., plant-fiber/PLA sheets for packaging; wood-plastic composites for decking, sida acuta for ceiling panles). In automotive, seats, door panels, and insulation are being made from hemp or kenaf fibers in bio-based resin (reducing vehicle weight and plastic use) [27]. Textiles: PLA/cotton blends [28], biomedical: PCL/collagen scaffolds [29].

Mechanical/Thermal Properties

Generally, natural-fiber biocomposites have lower strength than glass-fiber ones, but specific stiffness can be comparable . Tensile strengths of PLA/hemp composites range ~50–100 MPa, with moduli 2–5 GPa (dependent on fiber content) [30]. They typically have lower density (1.2–1.4 g/cm³) than glass composites (~1.8–2.0 g/cm³).

Thermal stability is an issue: natural fibers char at ~200–300°C [22], so typical processing is done below this (hot-melt processing of PLA or low-temperature curing epoxies).

Processing methods

Conventional methods (injection/compression molding) are used when fibers are short and matrix thermoplastic[22]. For continuous-fiber laminates, wet lay-up, vacuum infusion (VARTM), and even out-of-autoclave (OOA) methods are employed [31]. Additive manufacturing is an active area: e.g., PLA or PHA filaments reinforced with wood flour or short hemp for 3D printing [32]. Studies show adding nanocellulose to PLA decreases oxygen permeability by ~75%, ideal for packaging [33]. Examples of Biocomposite Categories is presented in Table 1.

Table 1. Representative biocomposite categories, matrices, reinforcements, and biodegradability.

Biocomposite Category	Matrix	Reinforcement	Biodegradability	Key Applications	Ref.
Natural fiber + bio-polymer	PLA, PHA, PBS (bio-poly)	Flax, hemp, jute, wood	Often fully biodegradable (plant-based) 【53†L152-L160】	Packaging, automotive panels, consumer goods	34
Natural fiber + synthetic polymer	PP, PET, unsaturated polyester (petro-poly)	Flax, hemp, sisal	Non-biodegradable matrix; partially recyclable	Automotive interiors, building components	35
Wood–plastic composite (WPC)	Recycled HDPE/PP	Wood flour (sawmill waste)	Non-biodegradable	Decking, outdoor furniture, cladding	32
Bio-based thermoset + fiber	Epoxy/resins from plant oils (e.g. soy epoxy)	Cellulose, flax	Potentially biodegradable	Marine, sports equipment, wind blades	26
Fossil fiber + bio-polymer	PLA, PHB	Glass/carbon fiber (mineral)	Partial (matrix biodegradable)	Hybrid composites (limited current use)	36

The choice of matrix/reinforcement depends on the application requirements. For example, fully biodegradable PLA/flax composites are ideal for disposable packaging, whereas PP/flax is used when higher durability is needed (e.g. automotive trims). Cutting-edge research is exploring *"intelligent biocomposites"*: embedding sensors or self-healing agents into biopolymer matrices, or using AI to tailor fiber orientation for optimal strength.

Circular Economy and Sustainability Metrics

Industry 5.0's sustainability pillar demands that materials be assessed over their full life cycle. Key metrics and concepts include:

Life Cycle Assessment (LCA)

LCA (ISO 14040/44) quantifies environmental impacts (GWP, ODP, toxicity, etc.) from raw material to disposal. Biocomposites often outperform conventional composites [37]. For instance, LCA of a flax/PLA panel shows 20–40% lower CO_2 eq. emissions than a comparable glass/epoxy panel [38]. Soto-Barrera *et al.* found coconut-fiber/polyester biocomposites (20–30% fiber) reduce CO_2 by ~7% vs pure polyester, primarily by avoiding polymer production and end-of-life waste [39].

Recyclability & End-of-Life

Biocomposites are designed for multiple pathways: mechanical recycling, composting, or energy recovery. For example, a PLA/flax board could be industrially composted (meeting ISO 17088 compostability standards [40]. Even non-biodegradable composites (PP/flax) can be mechanically recycled if fibers are separated.

Overall, I5.0 encourages quantitative sustainability metrics at every design stage. Digital manufacturing systems can automatically gather data for LCA models, enabling *real-time environmental accounting*. For instance, one automotive plant logged energy and waste data live on a dashboard, achieving 25% energy reduction within one year.

Industrial Case Studies and Pilot Projects

Several industries have piloted I5.0-aligned biocomposite projects:

i. **Automotive (Light Mobility)**

Walczyk *et al.* (2021) studied biocomposite seating for an electric bus [41]. They tested laminate panels (4mm) made with flax/hemp/cellulose reinforcements and high-bio-epoxy matrices, using processes like vacuum infusion and compression molding. Mechanical tests (ASTM tensile/flexure) showed that some combinations (e.g. flax/prepreg) met strength targets, demonstrating feasibility. The project underscored both the potential and limitations of current materials (e.g. need for better fiber consistency).

ii. **Construction and Architecture**

Roy (2026) reviewed the hierarchical and chemical characteristics of bamboo fibres that underpin their mechanical efficiency and discussed how treatments such as alkali, silane, and enzymatic modification improve fibre–matrix adhesion and composite performance. Advances in fabrication, including resin-transfer, compression moulding, and additive manufacturing, have expanded applications to structural, architectural, and prefabricated components [42].

Pilot Manufacturing Cells

Several European factories (e.g. by Siemens and Airbus) have set up Industry 5.0 demonstration cells where human operators work alongside cobots assembling composite parts. These cells emphasize continuous LCA and ergonomics: one such pilot achieved a 17% productivity boost and higher worker satisfaction [43].

These case studies illustrate real supply-chain integration: biocomposite fibers are procured from agriculture waste streams, processed in modern factories with IoT/AI oversight, and final products are designed for reuse. They also show *barriers*: higher unit costs (often 10–30% above conventional plastics), and the need for new skills (operators who can both program robots and handle natural materials).

Supply Chain, Economic and Social Impacts

Implementing I5.0-biocomposite strategies ripples through the supply chain:

a) **Supply Chains**

Biocomposite value chains link agriculture, bio-refineries, and manufacturing. For example, flax farmers supply fiber; resin comes from corn or sugarcane refineries; final parts go to auto plants. This *vertical integration* can shorten and localize supply chains, reducing transport emissions. It also opens rural economies: Europe's "RENEWETECH" report notes ~150,000 jobs in bio-based materials (some studies project I5.0 could add tens of thousands more through new factories) [44].

b) **Economic Impact**

Biocomposites command higher prices (3–5× more than PP) due to feedstock costs and low volumes [45]. However, total cost of ownership can be competitive once environmental taxes and disposal costs are included. Policy incentives (tax credits for bio-based products, carbon pricing) are often needed to make them viable. The EU, for instance, is considering preferential procurement for biocomposite components in public projects [46].

c) **Social Impact**

By emphasizing human value, I5.0 aims to improve job quality. Operators in I5.0 cells reported higher engagement, since mundane tasks are shifted to machines [47]. There's also a focus on upskilling: workers learn data analytics and robotics alongside material handling. Socially, using renewable materials aligns companies with consumer demand for "green" products, potentially expanding market share.

d) **Resilience**

As an example of supply robustness, industries using local biowastes (e.g. rice husks for polymer filler) became less affected by global resin shortages during COVID-19. However, dependence on seasonal crops can be a vulnerability (climate events affecting flax harvests).

e) **Industrial Multipliers**

A study of Ukrainian manufacturers found that introducing I5.0 practices (including biocomposites) in metal, food, and machinery sectors raised labour productivity by ~17–20% and created secondary (multiplier) jobs [48,49]. This "trickle-up" effect, where advanced materials drive growth, is a key economic argument for I5.0.

In summary, I5.0 and biocomposites offer the promise of sustainable growth. The technology integration not only reduces environmental costs but can also enhance economic resilience by diversifying inputs and markets.

Barriers, Research Gaps, and Future Directions

Despite their potential, several challenges hinder the widespread adoption of sustainable biocomposites in Industry 5.0. Material performance remains a concern, as many biocomposites exhibit lower mechanical strength and thermal stability than synthetic composites, necessitating the development of advanced biopolymers and nanomodified reinforcements. Moisture absorption by natural fibers also reduces durability, highlighting the need for improved fiber treatments and protective matrices. Additionally, the lack of standardized life cycle assessment (LCA) frameworks and sustainability indicators limits consistent evaluation and comparison of biocomposite products. Recycling technologies require further advancement, as current mechanical recycling degrades fiber quality and chemical recycling processes remain at the pilot stage. Finally, improving the economic viability of bio-based feedstocks, particularly through the utilization of algae and agricultural waste, will be essential for achieving large-scale, sustainable commercialization.

Future research directions and Conclusion

Future research should prioritize AI-driven material design, where machine learning models are employed to predict optimal fiber–matrix combinations, processing conditions, and material performance, thereby accelerating the development of high-performance and sustainable biocomposites. At the same time, advances in additive manufacturing should focus on scalable, high-throughput 3D printing technologies, such as robotic extrusion systems, to enable the efficient production of large and complex biocomposite structures for construction, automotive, and aerospace applications. Another promising direction is the development of hybrid intelligent biocomposites, which integrate embedded smart or biodegradable sensors for real-time structural health monitoring, predictive maintenance, and enhanced product lifecycle management. Equally important is the establishment of robust policy and regulatory frameworks that promote circular economy principles through mandatory recycled or bio-based content requirements, eco-design standards, and incentives for green innovation clusters. Overall, the successful realization of Industry 5.0 depends on the seamless integration of human-centric values, digital intelligence, and sustainable design principles. Sustainable biocomposite materials are central to this transition, offering renewable, low-carbon alternatives to conventional synthetic composites while supporting resource efficiency and environmental stewardship. Recent studies (2020–2026) have demonstrated their technical viability and environmental advantages; however, significant challenges remain in material optimization, large-scale manufacturing, standardization, digital integration, and commercialization. Addressing these challenges will require interdisciplinary collaboration among materials scientists, manufacturing engineers, data scientists, policymakers, and industry stakeholders to advance smart manufacturing technologies, develop next-generation bio-based materials, and implement enabling policies that collectively drive the transition toward a resilient, circular, and zero-waste industrial ecosystem under the Industry 5.0 paradigm.

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