Industry 5.0 Innovations for Waste Management and Circular Economy in Sustainable Food systems: A systematic review

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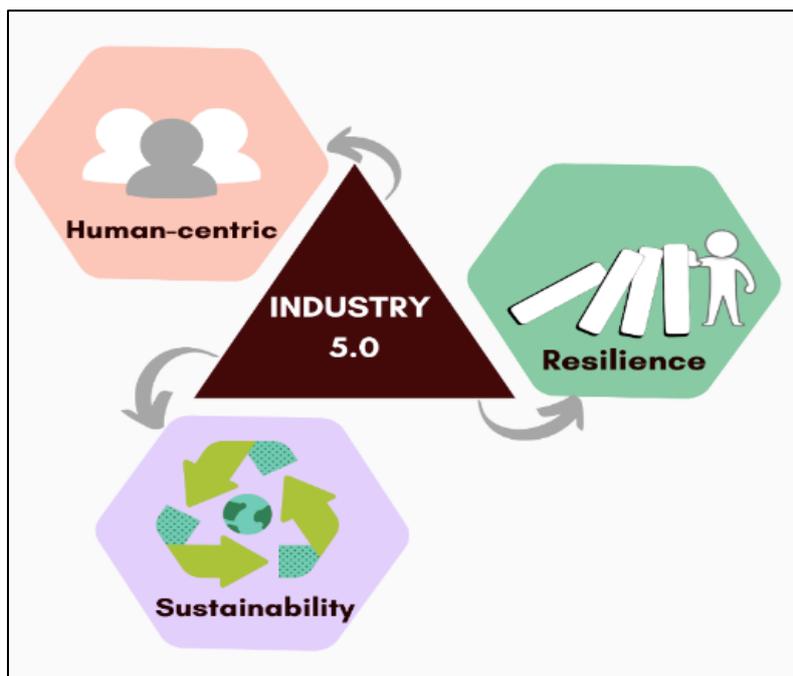*Correspondence author email: gaikwadsneh074@gmail.com

Abstract. The transformation of sustainable food systems demands innovative waste management approaches and circular economy practices. The adoption of Industry 5.0 technologies contributes towards aligning with the recent advancements for sustainable food systems. Industry 5.0, characterized by human-centric automation, artificial intelligence (AI), Internet of Things (IoT), and advanced robotics, extends impactful solutions to enhance efficiency, reduce waste, and promote sustainability in food supply chains. This systematic review delves the role of Industry 5.0 technologies in optimizing waste management and fostering circular economy principles within the food sector. The study synthesizes cutting-edge technologies, focusing on smart waste monitoring, precision resource recovery, AI-driven food waste reduction, and blockchain-enabled traceability, cloud computing and 3D-printing of food waste recovery to valuable edible products. Findings indicate that collaboration of Industry 5.0 innovations can significantly minimize food loss, enhance upcycling and valorization of by-products, and support sustainable production-consumption loops. However, challenges to tackle include high implementation costs, regulatory barriers, and technological adoption gaps persist. Future research should manage the policy frameworks, scalable solutions, and cross-sectoral collaboration to maximize the potential of Industry 5.0 in achieving sustainable food systems.

KEYWORDS: Circular economy, Industry 5.0, sustainable, valorization, waste management

1. INTRODUCTION

Industry 5.0, also called the Fifth Industrial Revolution, is the latest term describing industrial metamorphosis, defined as humans and machines (robots, smart machines) working jointly, centering societal well-being over economic welfare. The goal is to harness human proficiency to utilize machine intelligence to maximize outcomes through proper resource management and user-oriented solutions. The revolution from Industry 1.0 to Industry 5.0 brought up several transformations from mechanization, electrification, automation and digitalization to personalization. Industry 5.0 has advancements with greater degree of perfection, whereas the machine helps in the reduction of time and work of the people [1]. The concerning global challenges for a stronger industrial framework emerged to Industry 5.0 model, the model focusing on three pillars- sustainability, resilience, and human-centric approach. The challenges posed by COVID-19 turned out as catalyst for transition to Industry 5.0 enhancing collaboration with human and machine. The cobotics i.e., human-robot collaboration places human at the centre of innovation, aligning with the sustainability goals and circular models to address environmental issues and focus on advance technologies to foster the innovations evolving customer experiences. The Industry 5.0 model is transfiguring its applications in various domains integrating the human-centric approach and advanced technologies in smart agriculture and food processing, healthcare and biotechnology, industrial manufacturing and automobile industries, energy and utilities, supply chain management and logistics, smart education, disaster management, etc. [2]. Industry 5.0 evolved more towards personalization, customization and innovation as compared to Industry 4.0 emphasizing on technology, data analytics and automation. The innovative technologies from Industry 5.0 can boost the food systems from post-harvest management, supply chain and logistics, processing, packaging and commercialization or retailing. This adaptability of Food Industry 5.0 aligns with food security, market/consumer demand, efficient management of resources and assists cognitive process [3].

Fig 1: Three core pillars of Industry 5.0: Human-centricity, Sustainability, Resiliency

Food loss and food waste, as major concerning issue globally demands attention and action. The United Nations SDGs 12.3 focuses on reduction in food waste and loss at several stages of supply chain and logistics, including the post-harvest losses; during transportation, retail, and consumer stage. Circular economy and Industry 5.0 co-exist as generic concept promoting sustainability and hence targets management of waste generated from the food streams. The major priority of present industrial era lies in managing the waste generated by implementation of effective strategies as well as minimize the environmental detrimental effects caused by exploitation of resources [4]. The present review focusses on the challenges and impacts of food waste, management strategies, implementation of circular economy in food systems to manage the waste generated and the Industry 5.0 enabled technologies, its application to tackle the food loss.

2. FOOD WASTE CHALLENGES IN MODERN PROCESSING SYSTEMS

The United Nation SDGs accounting 'Farm to fork strategy', focuses on building of sustainable food system by primarily tackling the food wastage and losses throughout the supply chain (post-harvest, production, processing, storage) and simultaneously riveting towards bioeconomy [5]. The food processing upstream such as post-harvest operation, production generates about 54 % of waste as food loss, while the downstream such as manufacturing,

distribution and consumption/ household activities generates about 46% waste [6]. Food waste is any food, edible or inedible food. Food waste has a major impact on global and local status in terms of environmental, economic, and social factors. Food wastage negatively impacts the environment, leading to depletion of resources, deforestation, greenhouse gases due to its decomposition in landfills, and biodiversity loss. The economic impact of food wastage causes financial loss for households, cost of purchasing, and storage to retailers and creates inefficiencies in the supply chain during transport, handling, etc. Greater quantities of waste generated demands for the rise in the prices of the food stocks, limiting access to the common man [7]. Moreover, food waste reflects even on societal attitudes, the consequences being hunger and malnutrition, food insecurity, health issues, and environmental risks such as pollution, global warming, etc.

The challenges and opportunities in food waste (FW) valorization are critical in food waste management and leading to environmental and economic impacts. As per FAO estimates, annually, 1.3 billion tonnes of food are wasted, leading to 3.3 billion tonnes of CO_2 emissions and economic losses exceeding \$1 trillion. Various valorization methods, including biochemical (fermentation, anaerobic digestion, composting) and thermochemical (pyrolysis, incineration, hydrothermal liquefaction) processes, can convert FW into biofuels, fertilizers, animal feed, and other value-added products. Integrated approaches that combine these methods

offer the most efficient resource for the recovery. However, FW valorization faces challenges such as high moisture content, variable composition, and technological limitations. To overcome this there is need for a circular economy model, where effective policies, infrastructure, and stakeholder collaboration that can optimize sustainability. However FW management can be both economically beneficial and environmentally responsible, any reduction or valorization efforts must be financially viable and scalable for long-term success.

A lot of food is wasted due to poor distribution and lack of awareness. To fix this, a step-by-step approach needed to change people's habits and improve waste management. The biggest challenges are money, infrastructure, and public participation. ADKAR change management model is used to encourage waste reduction through awareness, behavioral shifts, and better management strategies. Adoption of successful global strategies like South Korea's waste pricing system and the EU's Circular Economy Plan, alongside smart technologies like IoT for efficient waste tracking is need of the hour. The reasons for food wastage making more food than needed, poor storage and transport, and strict quality standards that reject imperfect-looking food. Food also gets wasted due to spoilage, damage during handling, and consumer preferences for "perfect" products. Interviews with food manufacturers revealed other issues like power outages, broken equipment, and human mistakes. To cut down on waste there is need for better logistics, smarter packaging, and finding new ways to use imperfect or leftover food.

3. CIRCULAR ECONOMY IN FOOD PROCESSING SYSTEMS

Circular economic practices for valuing food waste majorly focus on minimizing waste and simultaneously maximising the recovery of valuable items from food byproducts. The circular economy engages the creation of closed loop systems that manages reduction in resources input, prolong product life cycle, and facilitate the recovery and regeneration of materials once they reach the end of their usability [8]. The key strategies to manage the food wastes into value-added products includes biofuel production, production of biopolymers and biodegradable plastics, recovery of bioactive compounds by extraction methods, functional food development, animal feed production, composting food wastes, soil enrichment, production of bio-based renewable catalyst, natural colorants (pigments) and flavors. This aligns with the SDG 7, indicating the sustainable exploitation of bio-

resources to improve the contribution of renewable energy in global energy mix while assuring the equal sustainable energy solutions to all the countries.

3.1. Food waste prevention and reduction

Food wastage is a global concern with severe environmental, economic, and social implications. Food wastage majorly undermines food security issues, even contributing to greenhouse gas emissions, natural resource depletion, and substantial financial losses. Circular economy is widely regarded as a practical approach to address the issue of food wastage. In contrast to the conventional linear economy, treating the used food materials as food waste, a circular economy emphasizes the recycling and continual use of resources within the economy. The major aspects of circular economy engage conserving raw materials, energy, and water, as well as reducing waste generation, carbon emissions, and overall environmental consequence. The strategic approach to reduce food waste inculcates technological innovation to preserve food (cold chain management, smart packaging, sustainable processing), efficient supply chain models and logistics, inventory management, valorisation of food eliminated from supply chain [9].

3.2. Food Redistribution and Recovery

Food redistribution and recovery is a sustainable approach to minimizing food waste and maximizing the value of surplus food by redirecting it for human consumption or other productive uses. The food redistribution strategies involve rescuing of surplus food from farmers, producers, retailers to donate to food banks, meal programs, and community centres. Several researchers studied the food recovery as utilization of food waste to generate valuable compounds such as recovery of essential oils from citrus peels, oil from olive kernels, etc. The integration of food supply along with advanced technologies such as artificial intelligence, blockchain technology helps improve surplus tracking, logistics and traceability. The surplus bread redistribution strategies have been studied to utilize it as breadcrumbs, flour, other baked items such as cakes and cookies, cereal products such as puffed snacks, breakfast cereals, biotechnology application such as conversion to sugar syrups and fermented beverages, sourdough, etc. [10].

3.3. Upcycling Food Byproducts

The transformation of the surplus, byproducts, and food waste from food processing into value-added products enhances the upcycling strategy to a circular economy-based approach, adding economic, nutritional, and functional value to the food that otherwise would have discarded. The by-product and waste discarded from the supply chain or industry are found rich in bioactive compounds such as fibers, polyphenols, lipids, carbohydrates, proteins, minerals, which can be valorized to create a circular economy to the society as well as industry. The food industry by-products can be valorized into potent applications such as food additives, bio-surfactants, organic fertilizers, nutraceuticals, etc. which enable create an economic viable food system. Upcycling of waste and by-products, primarily though extraction has been studied widely and several innovations for sustainable extraction methods- thermal and non-thermal are utilized for higher yield and positive environment impact [11].

3.4. Recovery of bioactive compounds

Food processing industry generally discards the inedible portion (peels, seeds, skin, pomace, pulp residues) irrespective of its economic and sustainable approach. The recovery of food eliminated from processing aligns with the health and circularity goals. Agri-food waste contains wide range of bioactive compounds such as carotenoids, flavonoids, polyphenols, peptides, dietary fibres, tannins, alkaloids, anthocyanins, amino acids, vitamins, minerals, etc. and other phytoconstituents. Several green extraction methods such as supercritical fluid extraction, microwave-assisted extraction, ultrasonic-assisted extraction, pulsed-electric field technology, etc to recover the valueable compounds from waste matrices. Phenolic compounds were extracted from pineapple waste, banana peels, citrus peels using microwave-assisted extraction, deep eutectic solvent, pressurized liquid extraction respectively.

3.5. Functional food development

Development of functional food products from food waste and by-products offers valuable insights in creating a circular economy-based approach. The by-products obtained from food sources are generally rich in coloring compounds, proteins, fibres, minerals, anti-oxidants, anti-microbial compounds that finds application in functional food products sich as snacks, beverages, bakery goods, dairy products, fermented foods, food additives, etc. The waste from grapes processing i.e. grapes pomace has been utilized into baked goods such as bread, cake, cookies, muffins with good levels of fibres, and bioactive compounds adding to anti-oxidant content [12].

3.6. Animal Food Production

Valorizing food waste and by-products provides a sustainable approach in effectively transforming them into valuable feed ingredients, particularly addressing issues of food security, waste management, and environmental loss. Livestock, often referred to as upcyclers, plays a vital role in transforming the inedible food material into nutrient-rich products such as protein rich meat, eggs, milk, supporting the efficient utilization of resources. Before feeding to animals, the food waste is treated by particular treatment; three treatment methods have been studied: dry-based, wet-based and fermentation enhancing the sterilization effect for safe food for animals. By-products of fruits, vegetables, cereals, crop hulls (oats, sunflower, soybeans) especially rich in fibres are utilized in livestock feed, with ensiling treatment to avoid spoilage. The major challenges in animal food production yet lies in safety of the feed free from contaminants, logistics and supply, development of balanced nutrient feed as per livestock requirements and lifecycle assessment determining environmental impact.

3.7. Sustainable Packaging Innovations

Sustainable packaging involves applying materials and design strategies that minimize the environmental impact across a product's lifecycle from manufacturing to disposal [28]. Agricultural, food-waste, and by-products serve as an appealing alternative, providing a base of raw material to produce biodegradable packaging enhancing its performance. Utilization of food waste to create innovative packaging solutions requires pre-treatments to convert the complex matrix producing fibers and polymers for packaging applications with the utilization of crop residues (stem, pod, leaves, stalks), process waste (hull, bran, husk, bagasse, straws), animal waste (egg shells, feathers, non-meat items) in development of packaging films.

3.8. Production of biopolymers and biodegradable plastics

Biopolymers and biodegradable plastic or bioplastics are types of material derived from renewable biological sources compared to conventional petroleum-based plastics. Agri-food waste rich in proteins, fibres, and polysaccharides serves as a material for producing the biopolymers through biotechnological methods such as

conversion/fermentation. Lignin, pectin, chitosan, starch, cellulose, polylactic acid (PLA), polyhydroxyalkanoates (PHAs), as a source of agricultural waste can be utilized for biodegradable packaging such as mulching films, food coating, hydrogels, etc.. The development of such bio-based materials aims to close the loop in plastic production and disposal by enabling composting, recycling, or safe degradation, thereby aligning with the principles of sustainability, waste minimization, and a low-carbon economy.

3.9. Biochemical and biotechnological valorisation

Biochemical and biotechnological valorisation transforms the organic waste, residues, and by-products into high-valued products such as biofuels, bioplastics, organic compounds, by use of enzymes, microbes or other processes such as fermentation. Utilization of agricultural food wastes to produce bioethanol by fermentation technique, biodiesel by enzymatic and microbial processes serves as a sustainable approach.
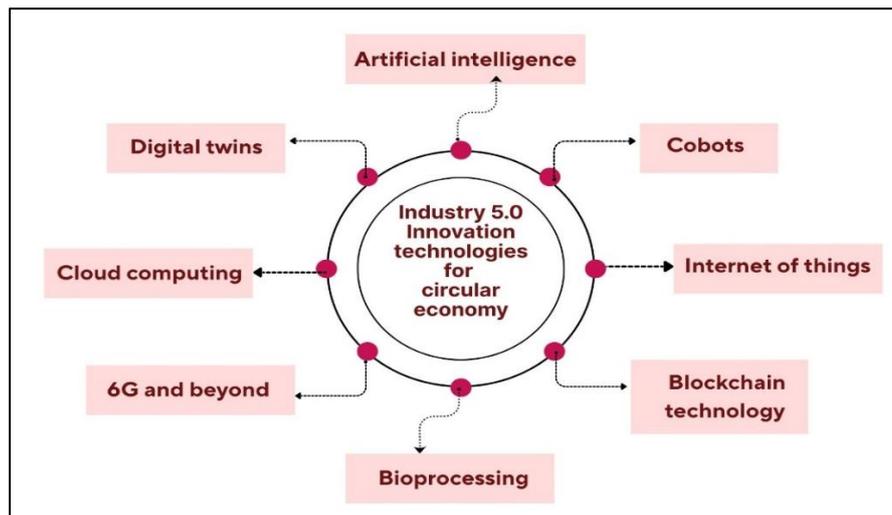
3.10. Composting and soil regeneration

Composting, a natural process of decomposition of organic residues generated from food waste serves as a natural fertilizer and soil conditioner, improving the physical, chemical and biological properties of soil. Food or household waste as fruits and vegetable scraps, eggshells, tea leaves, coffee waste can be utilized in composting as a compost agent. Recycling of organic waste into compost acts as a rich source of carbon, the treatment used for composting includes windrow composting, vermi-composting, aerated static pile composting and in-vessel composting. The transformation of food waste into soil amendments—such as compost, vermicompost, anaerobic digestate, biofertilizer, and various forms of biochar—is considered a highly effective method for nutrient recovery and reuse. When applied to soil, these food waste-derived products can enhance fertility, boost crop yields, and reduce contamination by improving the soil's functionality.

4. INDUSTRY 5.0 TECHNOLOGIES IN WASTE MANAGEMENT

Industry 5.0 characterizes the transition from an automation-driven Industry 4.0 era, Industry 5.0 emphasizing on establishing a circular economy by implementing processes that facilitate the reuse, repurposing, and recycling of products to enhance sustainability. Additionally, it seeks to improve the resilience of industrial operations, enabling them to respond more effectively to crises. Industry 5.0 technologies plays critical role in advancing sustainable manufacturing through intelligent products and dynamic Life Cycle Assessment (LCA). Industry 4.0, which prioritizes automation however, Industry 5.0 integrates human-centric manufacturing with advanced AI, IoT, and real-time data analytics to enhance resource efficiency and circular economy practices. The proposed dynamic LCA model enables smart products to continuously monitor and report their carbon footprint, energy consumption, and material composition thereby facilitating optimized production, maintenance, and end-of-life management. The role of human-robot collaboration (Cobots) is crucial in improving disassembly and recycling efficiency. Intelligent products can assist in diagnostics, repair recommendations, and sustainable disposal strategies by leveraging embedded intelligence, predictive maintenance, and automated decision-making. Integrating real-time environmental impact assessments into manufacturing systems can drive industries toward net-zero emissions and a fully circular economy. Industry 5.0 harnesses cutting-edge technologies to improve efficiency, minimize waste, and increase transparency, fostering a more sustainable and resilient food system. Industry 5.0 focuses on the synergistic approach between the human-machine collaboration and advanced technologies, to achieve the sustainable food production.

Industry 5.0 extends beyond the technological advancements of Industry 4.0 by incorporating a human-centric approach, emphasizing worker well-being, social responsibility, and environmental sustainability. While Industry 4.0 technologies facilitate digital transformation through real-time data analytics, automation, and smart manufacturing systems. Industry 5.0 integrates these innovations with sustainable practices, fostering resource efficiency and waste minimization under the Circular Economy (CE) paradigm. Ultimately, Industry 5.0 provides a more holistic industrial framework that balances economic growth with environmental stewardship and social equity, ensuring a sustainable transition for future manufacturing systems.

Fig 2: Industry 5.0 innovation technologies

4.1. AI and machine learning in predictive waste analysis

The integration of Artificial intelligence and machine learning in predictive waste analysis has significantly improved the status of food waste management by optimizing to greater efficiencies, sustainability, and affordability. Artificial intelligence supported by an advanced computational network is a powerful tool for enhancing food safety, optimizing delivery processes, and streamlining logistics. Machine learning can substantially aid in predictive waste analysis by assisting advanced algorithm patterns to optimize waste management strategies; major strategies including data collection, waste generation forecasting, AI-driven analytics and food redistribution, predict consumer behaviour patterns, food purchases, etc. Artificial intelligence-based image recognition helps in waste reduction by detection of low standard food products at various stages of supply chain during manufacturing, processing. AI techniques have found the integrated approach to manage the municipal waste generated by predicting the characteristics of waste, bin-level monitoring at various location/area, classification, planning of routes for waste collection (GIS route optimization tool), treatment of waste and its recycling, disposal [13].

4.2. IoT-enabled smart sensors for real-time waste monitoring

IoT-based smart sensors can be utilized in food processing systems to continuously monitor and control the real-time waste tracking, data collection and transmission via sensors to predict the future waste generation, ensuring food safety and inventory management. This approach integrated with AI and machine learning based predictive analysis can hence foster sustainability to reduce food loss and wastage in supply chains. IoT systems enable continuous monitoring of food conditions, ensuring compliance with quality standards and reducing spoilage risks. Smart waste management systems in restaurants utilize sensors to classify and measure food waste, providing actionable insights to minimize over-ordering. Machine learning algorithms integrated with IoT sensors allow for early spoilage detection, significantly decreasing waste through proactive interventions [14].

IoT-based Smart Waste Management System designed to enhance waste collection efficiency through real-time monitoring of truck movements and bin fill levels. The developed system integrates a web-based administration dashboard, a mobile application for truck drivers, and a smart dustbin prototype equipped with ultrasonic and weight sensors. Empirical testing demonstrated that real-time GPS tracking of trucks significantly improves route planning and resource utilization, minimizing unnecessary waste collection trips. The smart bins provide accurate fill level data, enabling dynamic scheduling of waste collection based on actual bin occupancy rather than predefined routes. The findings indicate that IoT integration enhances operational efficiency, reduces fuel consumption, and optimizes resource allocation, thereby contributing to sustainable urban waste management.

4.3. Blockchain for traceability and transparency in waste reduction efforts

Blockchain technology has the potential to significantly track and reduce food waste in supply chains by enhancing transparency, traceability, and operational efficiency. By integrating blockchain with other technologies like IoT and AI, stakeholders can optimize inventory management and ensure that surplus food is redirected effectively, thus minimizing waste. Blockchain provides an immutable ledger that records every transaction in the food supply chain, allowing for real-time tracking of food products from farm to table. The technology facilitates better inventory control by providing accurate stock level data, which can reduce overproduction and spoilage. Smart contracts can automate processes, ensuring food is distributed efficiently and reaching those in need, thereby reducing waste. The blockchain technologies can efficiently manage the waste collection, processing and transportation, majorly in smart cities generating larger quantities of wastes as electronic waste (e-waste), liquid and solid domestic waste, medical waste, agricultural waste, etc. enabling the real-time tracking of the waste throughout the system from collection to disposal or recycling].

4.4. Biotechnology and Waste Valorization

Food waste valorization represents a critical avenue for sustainable resource recovery, aligning with global sustainability goals such as zero hunger, clean energy, and responsible consumption. Despite its vast potential, food waste remains underutilized due to the inadequate waste segregation, limited technological interventions, and insufficient policy support, particularly in developing countries. Emerging biorefinery approaches, including enzymatic hydrolysis, microbial fermentation, and anaerobic digestion, offer promising pathways for converting food waste into biofuels, bioactive compounds, and biodegradable materials. Moreover, advancements in immobilized enzyme technology, green extraction methodologies, and integrated waste management strategies enhance the efficiency of waste-to-value conversion processes. However, the implementation of such technologies necessitates a structured framework involving regulatory support, industrial collaboration, and extensive research into scalable valorization models. To optimize the circular bioeconomy, future efforts should emphasize the development of innovative valorization techniques, sustainable biorefinery models, and public awareness initiatives to facilitate the efficient conversion of food waste into high-value products.

Biosynthesized metallic and bimetallic nanoparticles (NPs) have huge potential as sustainable alternatives to conventional pesticides. These NPs, are synthesized using biological sources such as plants, fungi, bacteria, and algae, exhibit antimicrobial properties through mechanisms like cellular structure disruption, oxidative stress induction, enzyme inhibition, and modulation of plant defense responses. Despite of their efficacy, challenges such as potential toxicity to non-target organisms, environmental persistence, and the lack of standardized synthesis and characterization protocols remain significant concerns for their effective utilization. Strategies to mitigate these issues include the use of biocompatible stabilizers, controlled release formulations, and targeted delivery systems.

The valorization of waste biomass and CO_2 as feedstocks is identified as a critical strategy for defossilization, reducing greenhouse gas emissions, and promoting circular bioeconomy principles. Advances in metagenomics, protein engineering, and electro(photo)biocatalysis have facilitated the efficient conversion of lignocellulosic biomass into bio-based solvents, polymers, and platform chemicals, marking a paradigm shift from fossil-derived resources. However, widespread implementation faces challenges related to scalability, economic feasibility, and regulatory frameworks. Future directions should emphasize on the need for interdisciplinary innovations, improved catalytic efficiencies, and sustainable industrial practices to achieve a net-zero emission economy [15].

Fungal bioprocessing for lignocellulosic waste valorization plays critical role in enabling a circular bioeconomy by efficiently degrading recalcitrant lignocellulosic biomass into high-value bioproducts. Fungi, particularly white-rot, brown-rot, and soft-rot species, employ a complex enzymatic system consisting of cellulases, hemicellulases, and ligninolytic enzymes to hydrolyze cellulose and hemicellulose while modifying or breaking down lignin. Despite their enzymatic potential, challenges such as substrate heterogeneity, enzyme production efficiency, and process scalability remain key bottlenecks. Advances in fungal strain engineering, metabolic pathway optimization, and bioprocess integration are essential to enhance efficiency and commercial viability. Fungal-mediated valorization can significantly contribute to sustainable resource management, mitigating environmental impacts while fostering the transition to a bio-based economy

through the production of biofuels, biopolymers, and other value-added chemicals.

Biorefinery alternatives for biowaste valorization represents a techno-economic assessment of enzymatic hydrolysis integrated with anaerobic digestion or solid-state fermentation (SSF) for high-value bioproducts. Hydrolysis of the organic fraction of municipal solid waste (OFMSW) significantly enhances bioproduct recovery, but its economic feasibility depends on enzyme sourcing and the valorization pathway of the solid hydrolyzate. Among the evaluated biorefinery configurations, the scenario utilizing on-site enzyme production combined with SSF for biopesticide synthesis exhibited the highest profitability, yielding a 74% gross profit margin and a reduced payback time of six years. Conversely, reliance on commercial enzymes without high-value bioproduct generation resulted in unviable scenarios due to excessive operating costs. Therefore it is necessary to optimize enzyme production, enhancing anaerobic digestion efficiency, and integrating multiple valorization pathways to improve economic sustainability.

Layered double hydroxide (LDH) catalysts serves as a promising tools for converting biomass into valuable chemicals and fuels. With their tunable acidity, flexibility, and high efficiency, LDHs improve key reactions like hydrogenation and oxidation, boosting product yield and selectivity. However, challenges includes stability, recyclability, and large-scale application. Future research should be focus on optimizing LDH structures and integrating them with emerging technologies like photocatalysis and biocatalysis to drive sustainable biomass valorization and move closer to a carbon-neutral or zero carbon bioeconomy.

4.5. Cloud Computing and Big Data Analytics

The cloud computing platforms deals with industrial big data processing, emphasizing their impact on data processing efficiency, cost optimization, and analytical accuracy. Empirical analyses demonstrated that cloud computing significantly enhances data processing speeds, leading to reduced operational expenditures and improved decision-making capabilities. Statistical assessments, including regression analysis, variance analysis, and time-series modeling, corroborated these findings, revealing a negative correlation between processing speed and cost, as well as an increase in data processing efficiency after the cloud implementation. Key challenges are data security

vulnerabilities, integration complexities, and the necessity for technical workforce upskilling. Despite these obstacles, cloud computing remains a transformative force in industrial data analytics, offering scalable computational resources and facilitating real-time data-driven decision-making.

Big Data analytics plays critical role in optimizing Industry 5.0 operations, where human-technology collaboration drives industrial progress. The comparative analysis demonstrates that processing efficiency is directly influenced by dataset size, with optimized data processing algorithms proving essential for handling large data volumes. Resource utilization assessments reveal the computational intensity of Big Data analytics, underscoring the necessity for strategic resource allocation and optimization to maximize efficiency. The evaluation of error rates and data quality further confirms that well-optimized analytics frameworks, such as those observed in Operation C, enhance data accuracy and processing reliability. Scalability analysis indicates that adaptive analytics frameworks are crucial for managing increasing data volumes, reinforcing the importance of scalable solutions in Industry 5.0.

Artificial intelligence (AI) and big data analytics plays a transformative role in advancing sustainability within Industry 5.0. Empirical findings demonstrate that AI-driven insights contributed to a 10% increase in solar energy utilization, a 6.7% rise in wind energy consumption, and a corresponding 6.7% reduction in grid electricity reliance, highlighting improvements in energy efficiency. Waste reduction measures facilitated a 24% decline in plastic waste and a 14% decrease in paper waste, underscoring AI's capacity for optimizing resource utilization. Furthermore, AI-enhanced quality control, maintained product quality within a 89–94% range, ensuring precision in manufacturing. Moreover, carbon emissions were reduced by 6% in manufacturing, 3.1% in transportation, and 4.6% in energy generation, demonstrating AI's effectiveness in mitigating industrial environmental impact. AI and big data analytics are essential for sustainable industrial practices, aligning with Industry 5.0's objective of integrating advanced technologies for ecological and operational efficiency.

4.6. 3D Printing for Food Waste Reduction

3D printing technology has transformative potential in valorizing agri-food processing waste streams, aligning with sustainable food processing and circular economy principles. 3D printing

minimizes resource wastage and enhances value addition by converting food-processing waste into novel edible and biodegradable products. The integration of nutrient-rich waste fractions into printable food formulations highlights the potential for personalized nutrition and functional food applications. Furthermore, the development of bio-based packaging materials from food waste demonstrates the capability of additive manufacturing in reducing reliance on conventional plastics, thereby mitigating environmental impact. Future advancements should be focused on integrating artificial intelligence and machine learning for process automation, as well as exploring regulatory frameworks to facilitate commercial adoption.

The transition from Food Industry 4.0 to Food Industry 5.0, emphasized technological advancements and their potential applications in the food sector. Industry 5.0 represents an evolution from the automation-driven principles of Industry 4.0 by integrating human-centricity, sustainability, and resilience into food manufacturing and supply chain management. Key enabling technologies, includes artificial intelligence, the Internet of Everything, blockchain, digital twins, 4D and 5D printing, advanced sensors, and collaborative robotics. These innovations facilitate resource efficiency, waste reduction, and precision food production, aligning with circular economy principles and sustainability goals. While Industry 5.0 offers transformative potential, challenges such as regulatory frameworks, workforce adaptation, and infrastructure readiness must be addressed for successful implementation. Future research should focus on empirical validation of these technologies, policy development, and cross-disciplinary collaborations to enhance the adoption and scalability of Industry 5.0 in the agri-food sector.

Utilization of food waste-derived materials for 3D printing applications, offers a carbon-neutral solution to mitigate global food loss. By integrating food waste components into 3D printable formulations enables the development of biodegradable, bio-based polymers with enhanced sustainability. The potential of commercial and industrial (C&I) food waste, such as spent coffee grounds and fruit and vegetable residues can be utilized as valuable feedstock for additive manufacturing. However, a key limitation is incorporation of food waste-derived materials (10–30%) in composite formulations, which affects their mechanical properties and printability. Addressing knowledge gaps in interfacial chemical interactions and rheological behavior is crucial to advancing

material engineering is crucial in this domain. Future research should focus on optimizing material properties through advanced processing techniques and exploring innovative applications in sustainable packaging and functional food products, thereby promoting a circular bioeconomy.

4.7. Digital twins

Digital twins refer to the virtual representation of physical objects, system or processes that are used to stimulate, monitor or optimize the real word counterparts in the real word. In simple terms, digital twins are the real-time digital replica. Digital twins serve as a promising approach aligning food supply chain characterizing the generation of dynamic, virtual models that mirror physical processes, allowing for real-time supervision, enhanced simulation capabilities, and operations optimization. Several studies indicate the application of digital twins in supporting farming operations, environmental uncertainty responses, detection of plant and animal diseases, real-time monitoring in food logistics, etc. Digital twins in agri-food systems can bring up the transparency and visibility through virtual support.

5. CONCLUSION

Adopting a circular economy approach through several strategies such as food recovery, livestock feed, and packaging material provides sustainability by reducing environmental impact, improved resource efficiency and economic benefits. Integrating advanced technologies like artificial intelligence, collaborative robotics (cobots), Internet of Things (IoT), and blockchain technology, Industry 5.0 enables precise tracking, real-time monitoring, and predictive analytics across the food supply chain. These innovation helps prevent overproduction, inventory optimization, repurpose and utilization of food waste into value-added products such as animal feed, functional foods, biofertilizers, sustainable packaging, etc. The industry 5.0 hence fosters the resilient, circular economic approach towards food waste management.

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