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Editorial

Artificial intelligence for Circular Economy 2.0: Opportunities, challenges, and outlook

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1. Introduction

The circular economy is an economic framework that aims to eliminate waste and maximize the utility derived from finite resources. Core principles of circular economy include designing products for durability, reuse and recycling, maintaining and repairing products for extended lifespan, and recovering materials at end-of-life through recycling and upcycling [1,2]. The traditional concept of circular economy focuses primarily on closing material loops through recycling [3]. Circular Economy 2.0, also referred to as the Regenerative Circular Economy, expands this vision with a more holistic approach across entire value chains and lifecycles [4]. It emphasizes the use of renewable energy, minimizing toxic materials, prioritizing regenerative resources, and restoring natural systems [5]. The goal of Circular Economy 2.0 is to move society away from the conventional linear take-make-waste model and toward a circular system that decouples economic growth from the consumption of natural resources. This goal is made possible by cutting-edge digital technologies like IoT sensors, blockchain, and artificial intelligence.

Exciting new opportunities for the optimization of circular systems and processes have emerged as a result of the rapid advancements in artificial intelligence and machine learning [6,7]. Large datasets from various supply chains can be analyzed by AI to spot inefficiencies in material flows and product lifecycles. Complex circular business models can be modeled by algorithms, and their techno-economic viability can be assessed. Automated disassembly, component reuse, and material sorting for high-value recycling are made possible by machine vision. In order to increase product lives, AI also supports predictive maintenance and remanufacturing [8,9]. In the sharing economy, recommender systems match underutilized assets to consumer needs [10,11]. Across all stages of the circular economy, AI provides data-driven intelligence to transition to more regenerative systems [12,13]. With the ability to continuously learn, adjust, and improve over time, AI solutions can accelerate the transition to Circular Economy 2.0 in a way that maximizes the environmental and economic benefits.

2. Motivation for this Special Issue

The potential for sustainability is enormous given the convergence of AI and circular economy principles [14]. However, there is still substantial dispersion in the research in this developing subject [15]. This special issue seeks to synthesize the state-of-the-art at the intersection of artificial intelligence and the Circular Economy 2.0, whereas fragmentation is an indication of a field of study's nascence. Researchers in management science, industrial ecology, computer science, engineering, and sustainability will all contribute to it. This special issue aims to strengthen the theoretical underpinnings and present applied case studies of AI speeding a regenerative circular economy by gathering a variety of unique studies in one location. It will inspire new perspectives across disciplines to utilize AI in creative ways that maximize social benefit. The long-term vision is an open AI architecture that can be leveraged globally to transition today's dominant linear systems into resilient, equitable, and circular models of production and consumption.

3. The Circular Economy 2.0 framework

While there is no full agreement in the scholarly circles on what Circular Economy 2.0 actually is, diverse perspectives all agree that it builds upon traditional circular economy principles to create an integrated framework across entire value chains and product/material lifecycles [16]. Some key goals and principles of Circular Economy 2.0 include:

- Decoupling economic growth from natural resource consumption
- Transitioning to renewable energy and materials
- Eliminating waste through superior design and closed loop recycling
- Maintaining and extending product lifetime through repair and remanufacturing
- Enabling shared access to underutilized products and assets
- Regenerating natural systems damaged by economic activity.

To achieve these goals, Circular Economy 2.0 engages stakeholders across all lifecycle stages:

- Design stage—Products designed for durability, standardization, modularity, disassembly, and recycling
- Production stage—Utilize renewable energy, non-toxic materials, and processes that minimize waste
- Distribution stage—Right-sized and optimized packaging and transportation
- Consumption stage—Product-as-service, sharing platforms, and an ownership to usership model
- End-of-life stage—Collection, disassembly, recycling, and waste-to-resource conversion
- The implementation of Circular Economy 2.0 principles across these lifecycle stages aims to create a holistic, regenerative, and waste-free economic system.

4. Situating AI within the circular economy

The potential of AI across circular stages is immense [17–19]. The following is merely a small set of all the possibilities.

- Product design phase
    - Generative design algorithms to design for circularity, modularity, disassembly
    - AI-based lifecycle assessment to model environmental impact
    - Material substitution recommendation systems
- Production and distribution phase
    - Predictive maintenance and defect detection to maximize equipment lifetime.
    - Production optimization to minimize material waste
    - AI-optimized logistics for efficient transportation
- Consumption phase
    - Product recommender systems to match underutilized inventory to consumer needs
    - Demand forecasting to right-size production and inventory
    - Segmentation algorithms for targeted circular marketing
- End-of-life phase
    - Automated disassembly systems using robotics and computer vision.
    - Machine learning for waste stream characterization and sorting
    - Optimization of reverse logistics and product return flows
- Cross-cutting topics
    - Techno-economic evaluation of circular business models
    - Material flow analysis and LCA using big data and AI
    - Blockchain for circular supply chain transparency
    - Policy insights from data modeling and scenario analysis

5. Limiting factors

Although AI has many potential uses for a more sustainable economy and society, these applications are not without constraints [20]. Many of these restrictions are "manmade", in the sense that they might be eliminated as soon as we choose to alter the algorithmic, legal, political, and cultural barriers. Some might be overcome by more deliberate measures, such data gathering. Let me provide below a list of limitations of AI interventions that are widely known currently:

- Data availability and quality
    - Lack of standardized data across circular supply chains
    - Confidentiality issues and reluctance in sharing data
    - Biased or incomplete data failing to represent full system
- Algorithmic bias and ethical risks
    - Reflecting historical biases in data patterns
    - Lack of transparency in AI decision making
    - Potential to exacerbate rebound effects without holistic understanding
- Practical implementation barriers
    - High upfront costs of sensors, IoT infrastructure, robotics
    - Integration difficulties across disparate legacy systems

    - Cultural inertia and change management challenges
- Rebound effects of efficiency gains
    - Jevons paradox where efficiency drives increased consumption
    - Need for complementary policies to avoid unintended consequences
- Limits of AI in modeling complex systems
    - Inability to completely capture emergent system behaviors
    - Black box algorithms fail to provide explanatory understanding
    - Need for hybrid human-AI approaches for system transitions

6. Conclusions

AI has been transforming every aspect of public life and this will only continue to accelerate [21,22]. A lot of these are transactional changes but the real challenge is to leverage AI for transformative effects [23]. The convergence of artificial intelligence and circular economy principles presents an enormous opportunity for sustainability but requires thoughtful implementation to maximize benefit [24]. This introductory chapter discusses the main obstacles and constraints while summarizing the current state of the art in using AI across circular systems. There are still large gaps in the process of turning theoretical potential into practical impact. It will take cross-disciplinary cooperation, incentives that are in line, and participatory governance to fully realize the potential of AI for Circular Economy 2.0.

The articles in this special issue seek to advance understanding of the intersection of circularity and AI. This special issue intends to lay the intellectual groundwork for future development by gathering a wide range of studies in one location. Our collective long-term goal is a world in which artificial intelligence (AI) speeds up and improves circular flows across our economic system, reducing waste, increasing resource productivity, and regenerating natural ecosystems. The contributors to this issue will demonstrate the potential and limitations of artificial intelligence in contributing significantly to this regenerative model of human flourishing.

Conflict of interest

The author declares no conflict of interest.

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