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Editorial

Circular Economy and Waste Management towards Sustainable Development

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Abstract: The vital principles of the circular economy are the utilization of waste as a valuable resource to create a value-added product, known as the "cradle-to-cradle" design approach (Fig. 1). The key approaches of circular economy apply lifecycle thinking, inspire the design of products, materials, and systems that minimize waste production, encompass product durability, and exploit resource efficiency in every stage of the value chain. Unlike conventional linear "cradle -to-grave" model, a circular economy prioritizes closed-loop systems in which materials are incessantly recuperated, recycled, and renewed. In this respect, special consideration is required to innovate in sustainable manufacturing, eco-design, remanufacturing, and resource recovery processes lowering the reliance on virgin raw materials and decreasing environmental impacts. The successful implementation of the circular economy needs progressive policy frameworks, effective legislation, economic incentives, new business models, investor collaboration, and community-driven creativity to inspire sustainable deployment and conscientious waste utilization practices that leads significant environmental, economic, and social benefits. Environmentally, the goals of circular economy are to minimize greenhouse gas emissions, protection of natural resources, and reduced landfill dependence. The role of government agencies, industrial houses, and local policy makers is crucial in making rewarding institutional and social conditions that are obligatory for long-term circularity.

Figure 1. *Cradle-to-cradle design of circular economy*

Keywords: *Circular economy, waste management, eco-design, waste efficiency, sustainability*

Polymers and polymeric materials are highly demanding for present society due to their versatile applications as plastic, rubbers, and composites in fabrication of different articles and components. The main advantages of this class of materials are due to their light weight while maintain desirable durability, flexibility, and relatively low production costs compared to metals and ceramics. Polymer-based materials are extensively used in packaging, construction, electronics, healthcare, agriculture, and transportation. Nevertheless, the high rate of production and consumption of synthetic polymers derived from crude oils has posed severe ecological threats owing to poor waste management and recycling that accumulates plastic waste in landfills, rivers, and oceans, mostly because of their non-biodegradable nature. Improper utilization of the synthetic polymers as single-use plastic products are major contributors to environmental pollution and climate change. Circular economy (CE) offers an environmental solution to plastic waste problems, advocating the reuse, reprocessing, reclamation, and redesign of plastic materials. The goal of the circular waste management schemes is to keep plastics within the production cycle for a long time by reducing ecological impacts and preserving natural resources.[1]

Fast growth of human civilization has tremendously increased the indoctrination and use of fossil-based biomasses for creation and utilization plastic-based products significantly increase the global waste generation. This is leading to serious environmental threat, social challenges and affecting the traditional eco-systems. The linear ecosystems based on the "take–make–dispose" model created shortage of resource, environmental pollution, increased greenhouse gas emissions, and an imbalance between production and consumption. To address tall these multifarious challenges, the perception of the circular economy (CE) has evolved as a disruptive

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Professor Susanta Banerjee has been associated with the Indian Institute of Technology (IIT) Kharagpur for more than two decades. During his tenure, he served as the Head of the Materials Science Centre from May 2014 to May 2017 and later as the Chairperson of the Central Research Facility from July 2022 to December 2025, where he played a pivotal role in strengthening interdisciplinary research infrastructure and fostering collaborative scientific endeavors. Prior to joining IIT Kharagpur, Professor Banerjee accumulated 14 years of research and development experience as a Scientist with the Defence Research and Development Organisation (DRDO) and the GE India Technology Centre (GEITC), Bengaluru. His work during this period contributed to the advancement of materials technologies for both strategic and industrial applications. Professor Banerjee is the recipient of the prestigious Alexander von Humboldt (AvH) Fellowship from Germany. He is also a Fellow of WAST and has been honored as an Institute Chair Professor by IIT Kharagpur in recognition of his distinguished contributions to research and education. An accomplished mentor and educator, Professor Banerjee has supervised more than 30 doctoral dissertations and 52 master's theses in the fields of polymer science, materials science, and materials engineering. Throughout his career at DRDO, GEITC, and IIT Kharagpur, he has led numerous pioneering research and development projects, advancing innovations in materials and polymer technologies. His work is guided by a strong commitment to scientific excellence, technological innovation, and the promotion of sustainable solutions for future generations. He is the founding Editor-in-Chief of the journal Innovation of Chemistry & Materials for Sustainability.

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approach. The concept towards sustainable development concurs through ideas of proficient resource consumption, reducing waste, recycling, and reuse and recovery of materials.[2]

The circular economy focuses preserving products, materials, and resources to maintain a long economic cycle without any environmental concerns. Compared to linear model, the CE advocates the technologies those are regenerative in which waste is used as a valuable resource. The waste can be reintroduced into production processes in a cost-effective manner for a greater number of times. The circular economy, believes the core principle of minimizing resource exploitation, increasing product life cycles, repair and refurbishing, and upgrading the recycling techniques. These contribute to resource effectiveness, energy management, and abridged necessity on petroleum-based raw materials.

The United Nations Sustainable Development Goals (SDGs) advocate waste management as the prime key parameters towards CE. Effective waste management systems include creation waste as minimal as possible, segregation of different types of waste and collection and treatment and then recycling for many times and finally to establish environmentally sound disposal methods. Integrating CE principles into waste management creates economic opportunities, new innovation, resource recovery industries and creation of green jobs.[3]

The CE have been are increasingly worldwide adopted to tackle rising concerns of waste accumulations, different types municipal solid and plastic wastes including electronic wastes and hosts of industrial offshoots. Recent technological advancements in artificial intelligence, blockchain, and smart recycling systems helped tremendously in improving waste categorization, material retrieval, and supply chain transparency. These are accelerating fast transitions in CE. Though, numerous blockades still delay implementation, mostly due to inadequate infrastructure and public awareness, poor policy enforcement and execution, lack of vision, fiscal restraints and poor stakeholder engagement.

In analogy with sustainable development, the CE contributes to environmental protection, prosperity, and social connectedness. The accountable consumption and production (SDG 12), climate action (SDG 13), sustainable cities and communities (SDG 11), and clean water and sanitation (SDG 6) supports the CE. The adoption of integrated CE and sustainable west utilization are the key options towards long term environmental sustainability with an understanding the global waste generation continues to rise to improve the quality of life of the present and future generations.

Path forward towards Circular Economy

Government and industries worldwide have adopted policies for recycling of plastic materials and reuse them multiple applications with particular focuses on minimizing the production and consumption of unnecessary plastic materials, especially single-use plastics such as plastic bags, bottles, straws, and food packaging. Rwanda enforced world's strictest bans on single-use plastic bags in 2008. The policy considerably reduced plastic litter, improved urban cleanliness, and enhanced environmental sustainability. Rwanda is now considered one of the cleanest countries in Africa. Coca-Cola use reusable PET bottles and refill systems in numerous countries, predominantly in Latin America and Africa.[4]

Plastic recycling is one of the most important principles of the circular economy that translates plastic waste into secondary raw materials to creat new products. Different types of recycling technologies are used, predominantly mechanical and chemical recycling are the most favored methods for processing plastic waste. Though, recycling effectiveness varies on judicious waste collection and segregation, and recycling infrastructures. Globally Germany has most advanced plastic waste collection, segregation and recycling systems thereof through their "Green Dot" program.[5]

There is also technologies available where plastic waste cannot be reused or recycled are converted into energy through waste-to-energy by incineration and pyrolysis while reducing landfill dependency. Japan uses innovative thermal treatment technologies to convert non-recyclable plastic waste into fuel and used for generation of electricity way to manage urban plastic waste efficiently.[6]

Eco-design approach targets on developing recyclable and reuse products those are biodegradable, or easier to break down into pieces. Innovative product redesign allows material recovery and reduces environmental burden throughout the product life cycle. Many of the industries are gradually replacing multilayer plastics with recyclable single-layer mono-material packaging. In this direction, Unilever are making all plastic packaging those are reusable, recyclable, or compostable to reduce virgin plastic use.

Extended Producer Responsibility (EPR) created policies that manufacturers are accountable for collecting, recycling, and managing plastic waste produced from their products. These policies inspire industries to innovate environment friendly design towards sustainable plastic products. Government of India has introduced EPR regulations that brand owners to ensure plastic waste collection and recycling.[7]

The use plastic waste from one industry as raw material for another industry an efficient industrial symbiosis is to be created. This will allow to reduce industrial waste and advances in material efficiency. Within this eco-industrial network, industry should exchange by-products and all types of waste materials, thus reducing waste disposal and encouraging resource efficiency.[8]

Community consciousness and accountable consumers behavior are vital for successful plastic waste management. Consumers plays very important role in waste management. The segregation of the different types of wastes, recycling participation, and reducing single-use plastic as much as possible. The European Union launched campaigns to decrease single-use plastics, creating consumer consciousness to plastic pollution and recycling practices.[9]

Concluding remarks

Though CE provides a sustainable framework for handling plastic-based materials and reducing environmental pollution. The major principles such as reduction, reuse, recycling, recovery, eco-design, and consumer responsibility are essential for sustainable plastic waste management. By accepting CE principles, societies can reduce plastic-based pollution, preserve natural resources, improve public health, and support long-term sustainable development goals. Despite the severe benefits of CE, numerous challenges remain, such asthe availability of the recycling infrastructure, recycling technologies costs, different types of plastic materials and their composition, segregation of different types of waste, low community awareness and participation, limited market for the recycled products, cost to performance, and informal waste management systems in developing countries. To alleviate all these challenges, strong environmental policies, technological innovation, investment in recycling infrastructure, and international cooperation are required.

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