Zero-Waste Manufacturing

Subjects: Engineering, Mechanical

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At first glance, zero waste (ZW) means complete and total elimination or absence of waste. However, much more than that, ZW entails waste prevention and where all materials are reused. It is a philosophy that forbids sending any unused material to landfills, dumpsites, or incinerators.

zero waste waste minimization manufacturing waste recycling

1. Zero Waste Manufacturing

At first glance, zero waste (ZW) means complete and total elimination or absence of waste. However, much more than that, ZW entails waste prevention and where all materials are reused. It is a philosophy that forbids sending any unused material to landfills, dumpsites, or incinerators. Under ZW, the keyword is conservation of resources. It involves responsible utilization, re-utilization, and recycling of resources to safeguard human health and preserve the environment [1]. The Zero Waste International Alliance (ZWIA), an organization working towards a world without waste, seeks to eliminate wastes by resisting incineration, landfilling, and dumping but by developing innovative ways of promoting resource conservation and waste conversion to use raw materials for the production process and for the sustainability of the environment [2][3].

Improved waste management, inappropriate waste disposal, open dumping of waste, and landfilling pollutes natural habitats (air, land, and water) and exacerbates health-related problems. Greenhouse gases such as carbon monoxide and methane generated from the refuse heaps at dumpsites promote air pollution, whereas the leachate formed in the landfills contaminates ground and surface water sources. Proper waste management strategies including waste prevention, minimization, remediation, and re-utilization can help solve many avoidable problems and safeguard the ecosystem.

Zero waste manufacturing (ZWM) entails the various techniques that promote a manufacturing system that utilizes minimum materials, generates minimum wastes, and encourages waste re-utilization. Though wastes cannot be completely prevented in manufacturing processes, strategies that allow waste prevention, minimization, recycling, redesigning, and re-use contribute towards ZWM processes. Waste generated from manufacturing can be substantially reduced by the adoption of methodologies that allow a product to be used for other applications after becoming obsolete or undesirable for its primary application. This means creating a product with multi-utility capability and a dependable service life across multiple utilization cycles is a way to achieve ZW in the manufacturing sector. Additionally, conventional manufacturing processing poses a great challenge to the concept of sustainable material utilization, lean material production, and minimum material removal during production. To achieve ZWM, innovative manufacturing techniques and pathways must be adopted and utilized.

2. Major Avenues for Achieving ZWM

2.1. Application of Innovative Technologies

The advent of new technologies has led to improvement in every facet of the economy and lives. The performance of the manufacturing sector has been enhanced by the introduction of various innovative, fast and cost-saving technologies. The fourth industrial revolution (4IR) combines physical, digital, and biological technologies that improve the flexibility, agility, and pace of production systems to meet the rising demand for goods and services. The 4IR involves the application of notable technologies such as the IoT, big data, analytics, robotics, additive manufacturing, machine learning, lean manufacturing, AI, high-performance computing, among others, to produce high-quality products in a cost-effective, labor friendly and environmentally friendly manner [4]. The deployment of 4IR technologies in the manufacturing sector has enhanced productivity, improved product usefulness, reduced energy consumption, ameliorated emission of toxic gases, and led to waste reduction [5][6].

Various researchers have utilized technologies to improve manufacturing processes and outcomes to raise productivity while minimizing waste. In extant research, Lu [7] and Wang et al. [8] chronicled the application of 4IR technologies such as the Industrial Internet of Things (IIoT), cloud computing, big data analytics, robotics, etc. in the manufacturing sector towards improved efficiency, environmental sustainability, energy management, cost reduction, and waste minimization. There are many advantages derivable from the application of innovative technologies to ensure effective manufacturing systems though with obvious challenges (**Table 1**). The application of AI ensures automation and precision manufacturing thereby reducing waste when compared with human or traditional manufacturing processes [9][10].

Table 1. Benefits and limitations of 4IR technologies in manufacturing.

Technologies	Benefits	Limitation	Ref.
AI	Precision manufacturing Automation	High initial cost. Requires maintenance and complex programming	[9][10]
Robotic	Higher output efficiency Precision manufacturing Additive manufacturing Elimination of errors Repetitive operation efficiency Enhance productivity and reliability	Lack of imagination, ingenuity, and personality High initial financial investment Industrial robots require sophisticated operation, maintenance, and programming	[11][12]
Robotic machining	Waste reduction Better quality products	Scarce expertise High initial investment	[13][14]

Technologies	Benefits	Limitation	Ref.
	Consistency in operation	High running cost	
Big data analytics	Ensure mass product customization Attainment of zero-defect product. Intelligent process monitoring Online and offline breakdown prediction Intelligent predictive and preventive maintenance Reduction in downtime due to machine or human failure	High energy utilization Concerns about cybersecurity Likelihood of identity breaches, identity theft, and data loss Connectivity and communication	[15][16]
Cloud computing	Zero defect Zero waste User friendly and convenient Real time machine monitoring Data security in the cloud Opportunities for upskilling Scalability and flexibility Cost minimization Maximum efficiency Compatibility with older systems	Technology vulnerabilities Data leakage, loss, or theft Unreliable internet communication Uncontrollable resources	[17][18][19]
	Waste prevention and reduction Innovativeness Flexibility Improved performance	Relatively new and immature No standard of implementation	[20]
	Waste reduction, reuse, and recovery Flexibility and scalability Increased process resilience	Cyber security issues Difficulties in technology integration	[21]

Additionally, robotic technology helps in automation, performs hazardous jobs, and does repetitive jobs for a long duration with minimum errors due to fatigue thereby ensuring waste prevention and minimization [11][12].

The continuous application of novel technologies and manufacturing techniques holds the key to less waste generation, fewer product errors, and smarter products in the foreseeable future. Though the use of these technologies comes with increased cost, the benefit of their adaptation will be visible in reducing waste and waste management costs, lower cost of materials, and near abrogation of defective products. Effective man-computer symbiotic association, also called Augmented Intelligence can address some of the emerging challenges and increase production output at reduced cost and man-hour.

2.2. Total Waste Recycling and Reuse in Manufacuring

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Waste recycling and reuse is a viable way of waste minimization, waste reduction, and waste management. Most of the items that are discarded by mankind and end up in dumpsters can be recycled and reused. Waste recycling and reuse reduces the number of wastes sent to landfills and incinerators, ensures conservation of natural resources, saves energy, reduce pollution and contamination, and supports the manufacturing sector. Recycling of wastes from the manufacturing sector reduces the use of new raw materials, minimizes environmental impacts of waste treatment and disposal, saves money, and ensures that minimum energy is consumed during product manufacturing. For sustainable wastes recycling systems, the waste generated must be collected, sorted, processed, converted to other usable items, and the consumers are encouraged to patronize items produced from recycled materials. Paper and cardboard, plastic, food, metals, rubber and leather, textiles, wood, stones and brick, glass, and ceramics are the common wastes that can be recycled and reused [22]. Although metal scraps can be converted into aluminum cans, nails, and other steel products, waste papers are transformed into egg cartons, cereal boxes, paper towels, newspapers, glass containers, laundry detergent bottles, etc. are made from waste glass.

2.2.1. Waste Glass

One of the most reported uses of waste glass is as a substitute for fine aggregates and concrete to reduce the cost and environmental impact of Portland cement production [23][24][25]. To further demonstrate this position, Tamanna et al. [26] and Lu et al. [27] investigated the deployment of crushed waste glass as partial replacement for fine aggregates in concrete. The generated concrete exhibited better strength, durability, and improvements in other mechanical properties when used for building and road construction. Waste glass has also been recycled and converted to an architectural mortar with improved durability, compressive strength, and workability [28]. In extant research, Keawthun et al. [29] demonstrated the application of recycled waste glass when they recovered sodium silicate from recycled waste glass. The water glass finds applications as sealants, binders, emulsifiers, and buffers in pulp and paper as well as detergent industries. The waste glass was also converted to a high-capacity Lithium storage battery to store energy. The Li battery was found to be effective, last long, and is cost-effective [30]. When the waste glass was converted to low-cost polymetric tiles for use in the construction industry, it was reported the produced tiles possess improved compressive strength and better load carry capacity [31]. Since glass is not biodegradable, recycling is a practical and cost-effective strategy of minimizing glass wastes, reducing pollution and eliminating waste glass from landfills, and avoiding the harmful environmental impacts of waste glass.

2.2.2. Waste Plastic

One of the avenues for waste plastic recycling is the conversion of waste plastic to fuel. Various techniques have been adopted to convert waste plastic to petrol, diesel, jet fuel, and hydrogen fuels. The generated fuels are environmentally friendly, effective, and generate less harmful emissions when used to power internal combustion engines [32][33][34]. In other research, waste plastic has been converted to catalysts for biomass valorization [35], nanofoam for environmental remediation [36], and oil for engine lubrication applications [37].

2.2.3. Waste Tire

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Recycled waste tires can be used for road construction, noise and vibration reduction in railways, production of chemicals, fuels, and other bio-based products [38]. These products are achieved through various conversion techniques and technologies including retreading, reclaiming, combustion, grinding, and pyrolysis [39][40]. Avenues for the utilization of waste tires for various applications have been well exploited and reported by researchers. Some of these applications offer low-cost, environmentally friendly, and waste conversion advantages in road and building construction, energy conversion, wastewater treatment, soil decontamination, and raw materials for the tire industry [41][42][43][44][45][46][47].

2.2.4. Wastepaper

Activity in the paper recycling sector has been propelled by numerous environmental, sanitation, and cost benefits derivable from the process. Besides, with the increase in the global literacy index, industrialization, and replacement of most plastic with paper products, the use of books and other paper products will continue to increase. Papers are used in the production of books, magazines, cardboards, stationaries, copying, commercial printing, and packaging. Application of waste papers includes production of bioethanol, butyric acid, cellulose nanofibers, fluorescent Carbon Dots, ceiling boards, and other chemicals and bioproducts [48][49][50][51][52][53][54]. The conversion of wastepaper into biofuels, building materials, chemicals, and other products are cost-effective, enhance sanitation, ensure appropriate disposal of waste paper, a green approach to waste management, and safeguards the environment.

2.2.5. Waste Metals

There are huge prospects for metal recycling in meeting the demand for adequate materials for the global industrialization drive. The major process for metal recycling includes collection, separation/sorting, cleaning, fragmentizing, weighing, and selling. The ferrous metals are separated from non-ferrous metals before selling. The collected metals are usually remelted and cast into bigots and sold to industries for further use. Sustainable end-of-life products of metal conversion include construction parts [55], automobile parts [56], fasteners such as machine screws, socket screws, bolt screws and rivets, bed frames, cooking pots and cutleries, tools, toys, bicycles, sinks and bathtubs, farm equipment, eyeglass frames, beverage containers, roofing and window frames, to mention but a few [57]. The numerous environmental, sanitary, and economic advantages of metal recycling make the process continue to receive attention. Recycling waste metals also ensures energy savings and slows landfill growth. However, a lot of time, resources, and energy are expended during the collection, sorting, and conversion of waste metals. Additionally, workers at the various recycling facilities are often exposed to unhealthy environments and toxins. The quality of some of the products of recycled metals is substandard and low in quality leading to failure during usage [58][59][60].

2.2.6. Waste Textiles

It has been estimated that the conversion and utilization of waste textiles can reduce the production of new textiles from new materials, improve sanitation, slow down the rate of filling of landfill spaces, and lessen the use of water, energy, and chemicals in the production chain. Compared with incineration and landfilling, textile recycling is more

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beneficial from the economic, health, social, and environmental standpoints [61]. However, limitations and underdevelopment of the appropriate practical technologies for recycling various types of waste textiles, economic considerations, technical challenges relating to the complexities of clothes, and undeveloped markets have continued to hamper the recycling of waste textiles. Nonetheless, recent studies have enumerated the various avenues and products of textile recycling. According to Xia et al. [62], Zach et al. [63], Yousef et al. [64], and Sadiq et al. [65], waste textiles are converted into polyethylene terephthalate, thermal and acoustic insulation materials, polyester and carbon electrocatalyst, respectively, for various applications. Recycling waste textiles offers opportunities in material recovery, social, economic, and environmental sustainability.

2.2.7. Wastewater

Various adsorbents have been deployed for the purification of wastewater. Enaime et al. [66] developed biochar, whereas Jaspal and Malviya [67] developed biomass-based composites as low-cost adsorbents for decontamination of wastewater. Several other effective techniques have been developed and applied for the purification of contaminated water. Dimoglo et al. [68], Li et al. [69], and Ang and Mohammad [70] employed electrocoagulation/electroflotation, oxidation-filtration, and natural coagulants, respectively, for the purification of wastewater. The various techniques were found to be cost-effective, efficient, and sustainable for the removal of coloured contaminants, organic and inorganic pollutants from contaminated water. The purified water was found safe, hygienic, and meets international water standards. Decontamination and recycling wastewater contributes to zero wastewater and increases the accessibility of safe water for social, economic, agricultural, commercial, and industrial applications

3. Implications

ZWM is achievable. However, necessary legislations, policies, and programs must be enacted and dutifully implemented. There is need for comprehensive and all-encompassing strategies with specific timelines respected by all stakeholders. The first step towards this is to intensify citizenship education geared towards behavioural change. The people must buy into and wholeheartedly support sustainable consumption. The adverse effects of unmanaged wastes on global climate change and human health are unambiguous and evident. Many people and communities are unwilling to imbibe sustainable behaviour and lifestyles that will mitigate the raging effects of environmental degradation. Governments at various levels must be willing to invest in sensitization, education, training, and research on innovative ways to achieve ZWM [71][72].

Producers of some non-biodegradable and hazardous products must be made to take some responsibility for the impact of their products on the environment. Producers must develop efficient strategies for product take-back to encourage consumers to return the product to them at its end-of-life. Manufacturers must develop innovative technologies that allow the returned products to be refurbished, remodeled, resuscitated, reprocessed, and made anew. Such encouragements must include monetary rewards and other incentives such as discounts on the purchase of new products. This will promote producers' and consumers' responsibility, reduce indiscriminate dumping of used products by consumers, and ensure manufacturers produce products they can recycle [72][73].

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Most countries have weak policies towards waste recycling and material recovery from waste. Enforcement of some of the waste management policies has been prioritized in some countries. In the interest of sustenance of the environment, policies and legislations that promote 100% recycling of wastes, 100% recovery of resources from wastes, and zero landfills and incineration should be prioritized [72][74].

With the advantages of ZW including its cost-saving and economic capabilities, sanitary and environmental sustainability, waste management, material recycling, and resource recovery, it is best to adopt innovative technologies and approaches towards its realization. The use of eco-friendly and innovative technologies will ensure value for money, reduce the risk of infections and contaminations, and allow for metering and adequate record keeping. Some of the techniques and technologies for achieving ZW can be time-consuming, misleading, and difficult to achieve. In some cases, the cost of collection, sorting, and conversion of waste can be greater than the cost of developing new products [75]. Additionally, conversion and re-utilization of wastes can offend some social, religious, and cultural beliefs and practices [76].

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