Grenze International Journal of Engineering and Technology, January Issue

Technology Enabled Zero Waste Manufacturing to Attain Sustainability

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***Abstract*— We need to implement novel techniques to prevent waste generation. Countries worldwide should plan affordable waste management solutions and ensure the waste is managed safely. Managing a huge quantity of garbage sustainably is a great challenge. The growth of the population and changes in the volumes and types of garbage increases the challenge of waste management. Researchers say that by 2050 global waste generation will take over the global population. Zero waste manufacturing is a technique that can help to reduce the generated waste and at the same time help to develop methods to recycle and reuse it. There are many technologies available for implementing zero-waste manufacturing. An evaluation of the technologies should be done to select an appropriate one. Reduction of waste generation and its proper reuse should be done to tackle the impact of environmental pollution and climate change.**

***Keywords*—Waste management, zero waste, Recycle, Reuse, Reduce.**

I. Introduction

Nations all around are facing many challenges in achieving sustainable development for all their people. One of the challenges is dealing with the environment: different types of pollution and waste management. Have we ever thought, about how much waste is generated globally daily? Very few have time to think about where the waste goes and what happens to the waste once you remove it from our homes.

People need to develop greater insights into how the waste dumped in landfills puts enormous pressure on the environment. Researchers, and environmental activists, are working on how to reduce, reuse, and recycle waste, at the same time a large population worldwide is ignorant of the danger of overconsumption and overproduction [1]. Our planet produces 2.01 million tons of municipal solid waste (MSW) annually. The figure is anticipated to increase by 70% in the next 30 years and the annual MSW generated at the global level may reach 3.40 billion tons. East Asia and the Pacific region generate 23 percent of the world's waste while North Africa and Middle East countries produce 6 percent. It has been predicted that the waste generated by low-income countries will increase three times by 2050. In regions like the Middle East and Sub-Saharan Africa most of the waste is openly dumped and therefore the implications of the waste on the environment in these regions require immediate action [2]. MSW, generally called thrash or garbage consists of household, office, and retail waste. It does not include the hazardous, industrial waste and the waste generated from the construction. The handling and disposal of MSW raises a great concern in countries like the USA due to the rapid increase in the waste generated daily [3]. The amount of MSW generated is influenced by the daily practices of each individual, their purchasing habits, and the methods used by them for waste management.

Grenze ID: 01.GIJET.11.1.502

The waste depends upon how many commodities or things are bought, used, and discarded. Generating more waste means more pollution and more greenhouse gas emissions. A voluminous amount of MSW is generated daily and most of it is never collected [4].

Landfilling is one of the most common waste management techniques used in many countries irrespective of the development status. Landfills are used for MSW, industrial waste, and hazardous waste. Green waste landfills are an emerging concept that is not used widely. Uncontrolled and illegal landfills known as dumpsites are found in many developing countries. The world is facing numerous issues related to environmental pollution and health hazards caused due to the increasing usage of landfills. Underground water pollution, air pollution, odor pollution, and marine pollution are a few types of pollution caused by landfilling. They cause serious health impacts for the people living near the landfill [5]. Apart from the landfills and the dumping sites a large volume of waste is being dumped into oceans and other parts of the environment. A report by a national geographic explorer in 2015 revealed that 8.8 million tons of plastic reach oceans every year. It is equivalent to nearly a truck filled with plastic being dumped into the oceans every minute [6].

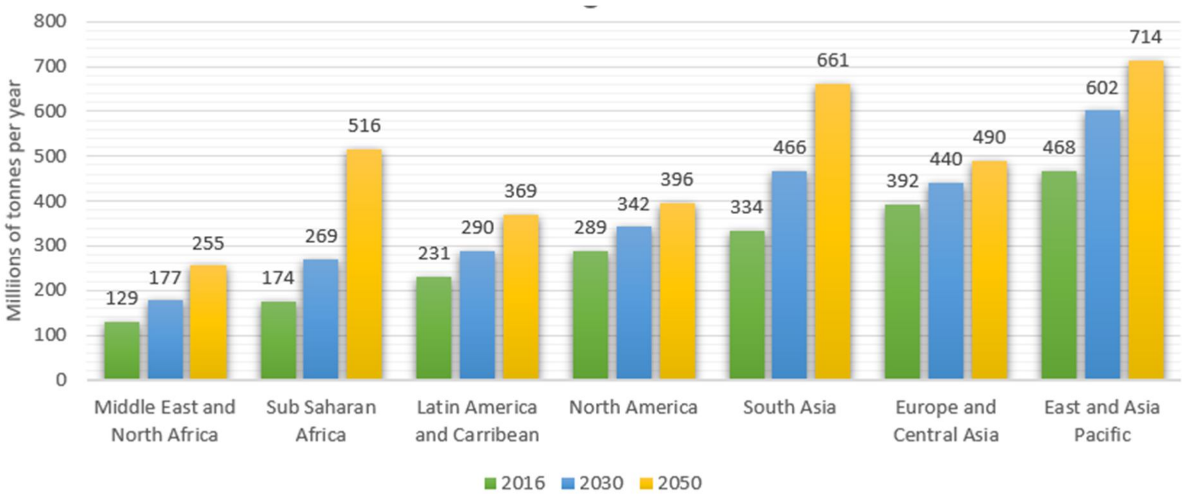

Fig 1. Projected Waste Generation by Region [1]

Pollution, environmental degradation, and climate change are indicators that we are living on an unsustainable planet. It's time to change from a linear economy to a circular economy. According to an environmental educator, Lillygol Sedaghat, the linear economy that supports turning resources into disposable products is not a sustainable solution. We need to promote a circular economy to maximize resources and reduce waste. People should realize that they are a part of the waste system, they can make a difference by adopting a sustainable lifestyle and the waste that we dump does not disappear but goes somewhere and affects someone [7].

Zero Waste Manufacturing (ZWM) is an approach that would help countries transform into circular economies by upgrading manufacturing technologies that will minimize waste and at the same time provide sufficient support for reuse and recycling [8]. A gigantic amount of waste is generated daily, and discarded but its treatment is missing. ZWM is being considered as a guide to future goals of manufacturing processes to tackle the issue of waste. This concept supports the recycling and reusability of wastes in manufacturing processes, using optimization tools, and developing sustainable manufacturing systems and theories [9]. ZWM includes techniques that encourage manufacturing systems that use the least possible materials, generate minimal waste, and promote re-utilization. The conventional manufacturing processes are backed up by challenges related to sustainable material utilization, manufacturing lean materials, and minimizing removing material during manufacturing [15].

Wastes cannot be prevented completely irrespective of the manufacturing facilities in use. ZWM will support the reuse of waste generated from one process to be used as a raw material for the other. This concept will help the manufacturing industries to earn profits and ensure clean and hygienic societies for everyone. There is a need to motivate manufacturing industries to adopt ZWM practices to reap its benefits in the future [10]. It is believed that nearly two-thirds of the global population will be residing in urban areas [11].

But as global manufacturing progresses through the advancements brought by the fourth industrial revolution, the variety and the volume of waste will keep growing. The stakeholders along the waste value chain won't be able to continue with the existing methods [12].

The paper will discuss the challenges faced during the selection and implementation of ZWM in section 2. Section 3 will describe the six steps of a holistic framework for achieving ZWM, best practices and solutions will be discussed in section 4 and section 5 will conclude the chapter.

II. Challenges and Recommendations

An analysis of waste management for 38 countries shows that Turkey produces the largest amount of waste compared to other nations used for the survey. Though Turkey has started with the recycling techniques one of the challenges to waste management is the illegal dumping of the waste. Uncontrolled disposal creates problems for waste management and reduction agencies to predict the amount of waste generated and take steps for recycling. Another challenge is deciding on zero-waste manufacturing is the new kind of waste that may occur due to unpredictable situations.

For example, the ban on plastic in the European Union could not work well due to the Corona pandemic. The pandemic phase saw the generation of new disposable items like medical masks and COVID-19 rapid test kids [13]. Some challenges that make zero-waste manufacturing difficult are the lack of effective waste management policies, lack of funds, selection of suitable technologies, shortage of trained staff, and poor participation of people [14].

There is a lack of effective waste management policies in many countries, especially the low-income and developing economies. There is a need to have clear and consistent regulations and standards for waste management practices. The guidelines should enable progression towards zero waste manufacturing and a circular economy. The existing policies should be revised by identifying the gaps between the current practices and the desired goals. Assessments of the project sites, waste audits, gap analysis, and revising the existing policies can facilitate the implementation of suitable waste management policies. These policies should be made after knowing the actual state of waste generation, its disposal, and the recycling scenario of a place. As the patterns of waste generation and its disposal vary from place to place, framing suitable policies becomes difficult. The data on waste collection and disposal should be regularly updated. It will help the related organizations to frame appropriate policies for all.

The recycling and composting methods involve more investments than traditional landfilling and incineration. However, there is a need to find revenue streams and cost recovery mechanisms to make recycling and composting economically viable. There is a need to create a market for recycled products. Limited demand for recycled products can prevent people from investing in recycling methods.

It will slow down the efforts taken for waste reduction. Change in the mindset of the people and their practices should be encouraged. There should be awareness camps to overcome the stereotypes and prejudices ingrained among the people. This mindset should be promoted among the government and the companies too. Everyone should understand the importance of waste reduction and recycling. Along with this training and refresher courses should be designed especially for the staff of the agencies and organizations involved in waste management. The workforce availability can be enhanced by upskilling the staff to meet the challenges of the evolving and complex markets.

One of the challenges related to zero waste is the rapid changes in the IT industry. Data centers generate a large amount of e-waste and most are difficult to recycle. This will require specialized recycling facilities. The fast upgrading of technologies leads to regular upgrades of the existing equipment and disposal of the old ones. This results in a lot of waste that cannot be used. It is tough to adhere to the zero-waste concepts for safe disposal and recycling of this waste. Recycling of data storage devices involves innate security risks. Similarly, the disposal of data storage devices is also difficult due to security and privacy concerns [16].

The disposal of e-waste has to be done very carefully due to the toxic substances like lead, cadmium, and beryllium that may get released into the atmosphere when exposed to UV radiation. These substances can affect our health if they flow with water or penetrate soil. The electronic devices like the laptops and the smartphones are not designed to be recycled. For example, smartphones are becoming lighter and most do not have removable batteries. It makes recycling difficult and labor-intensive.

The machines needed for recycling need upgradation with the technology change. Another problem with e-waste is that nearly only 10 out of 60 elements can be recycled through mechanical processing. Manual sorting is used most of the time.

Recycling prevents the toxic substances from reaching the environment but the workers involved in this process are continuously exposed to the hazardous substances, hurting their health. Electronics producers and manufacturers should try to design more recyclable friendly devices and conduct further research to facilitate the mechanical processing of more chemical elements and reduce the health risks of the workers in the industry [17].

III. HOLISTIC FRAMEWORK FOR ZWM

The various stakeholders can implement a six-step holistic framework to achieve ZWM. It consists of six technology themes that will diminish waste generation in all the stages of production and consumption systems (P.Kerdlap.,et. al, 2018).

A. Architecture for Zero Waste

This step includes designing products that will need fewer materials to be made and will be easy to disassemble. This method will decrease the generated waste. It will ensure easier collection of the used parts. At the same time, it will be feasible to recover useful parts from a product at the end of its life. Two methods that can help to attain this for the manufacturing industry are design for disassembly (DFD) and additive manufacturing (AM).

DFD is planning and designing to decrease the complexity of the deconstruction process. Deconstruction is demolishing a building but at the same time reusing the demolished materials. Its adoption changes the traditional waste management process [18]. It gives greater attention to management of the End of Life (EOL) products. It facilitates the eventual dismantlement for recovery of the system, its components, and materials. The recovery of materials maximizes the economic value and minimizes the environmental impact through consecutive reuse, repair, remanufacture, and recycling [19].

AM supports making physical components from virtual three-dimensional computer models by constructing the component layer by layer until the part is complete. This model is typically in the form of a fully enclosed volume converted into a file format to be understood by the AM machine [20]. AM helps in reducing scrap waste as compared to conventional systems. It adds materials instead of removing a large piece of materials from the workpiece [21]. AM can minimize plastic waste by using only the material needed to manufacture final components. Power bed/binder jets are the technologies that support waste reduction by recycling or reusing excess powder [22].

B. Planning for Waste Reduction and Conducting a Smart Waste Audit

The hardware and software methods help analyze waste volumes, and automatic waste segregation, and determine convenient options for reducing waste and diversion through reuse and recycling. The software solutions include online tools that use data analytics to study the data of waste generation, current waste collection methods and related expenditures, and actual levels of onsite recycling [23]. These tools can be used to identify convenient techniques to boost recycling. For example, an internet-based tool, Smart Engine recognizes favorable options for cost savings for different workplaces. It uses an extensive database of waste and recycling of nearly 20 years, gathered from industry and national databases. Many industries have used this tool for waste audits [24]. Another example is SMARTwaste which simplifies reporting of environmental compliances in construction projects by handling environmental data and allowing users to upload data from their projects. SMARTwaste helps in a 40% reduction of onsite waste generation [25]. These methods help in building a ZWM ecosystem by conducting audits efficiently. Their performance can be enhanced by using the latest and advanced hardware and software tools.

C. Technology-Enabled Waste Collection

The waste collection process has improved due to technologies like Artificial Intelligence (AI), the Internet of Things (IoT), Geographic Information Systems, and Data Access Networks [26]. The conventional waste management methods have some limitations the garbage bins are full but the municipal staff does not reach to collect them, which creates unhygienic surroundings for all moreover sometimes the staff visits areas with less or no garbage due to which their time gets wasted and increases the expenditure involved in waste collection and its disposal. AI, IoT, and Blockchain can be used to develop smart waste collection and recycling methods and help to find sustainable solutions [27]. An IoT-based remote monitoring system can monitor garbage levels, temperature, smoke detection, and location. This solar-powered system converts the solar energy into electrical and thermal energy and recharges the batteries. It is an eco-friendly system that determines the garbage levels by using sensors and sends notifications to the garbage collectors when the dustbins are full. The garbage collector reaches the dustbins according to the location provided in the notification. Sometimes the dustbins overflow in case the garbage collectors do not visit the place. Such situations can be avoided as the garbage collector will reach the location after receiving the alert. Sometimes the garbage collectors visit the locations where the dustbins are not full. This wastes their time and also the fuel required for the vehicles. Waste collection based on sensors and alerts will ensure cleaner surroundings and save fuel and energy. It allows remote monitoring of the thrash using a smartphone or a web browser [28]. IoT can be used to determine effective routes to collect garbage from the bins. This will help the garbage collectors reach the location using Google Maps on their

mobile. The garbage may sometimes contain combustible substances. The IoT-based bins can use a water pump, which will be activated once the bins catch fire and send notifications of fire eruption to authorized persons [29].
AI can revolutionize waste collection mechanisms using Machine Learning and Image Processing algorithms. These smart bins contain audio-compatible cameras to capture images of the waste. The image is sent to the backend server that uses Convolutional Neural Network (CNN) to identify the item. These smart bins have storage divided into four parts to collect metal, glass, plastic, and undetected waste. The storage compartments are covered with a lid. When the waste is placed on the lid, it gets identified by the imaging technique and CNN and the servo motor rotates the lid, at the required angle. The lid opens and the waste is dropped in the respective container. The bin uses sensors to determine the garbage level by updating the database once the waste is collected. It uses open-source routing hosted by Google Cloud to determine the shortest distance [30]. Robots can help to classify plastic waste into seven different types and thus help in plastic recycling. Deep Learning, CNN, and computer vision techniques are used for object recognition. These robots can be used on land and seas [31]. AI can be used for designing waste prediction models. The amount of waste depends on population, number of households, etc. These bins use weight sensors to know the weight of the garbage and a pre-trained CNN layer is used to improve its performance. The waste prediction models will help estimate the amount of waste and plan for deploying the number of vehicles and staff for waste collection from the given area [32].
Decentralized and immutable ledgers in Blockchain will enable transparency, traceability, and efficiency of the waste management system. This will help toward economic and environmental benefits [35]. Blockchain can be used for rewarding people according to waste collection, help in real-time tracking of collected waste, and enable securing data transactions to reduce the risk of hacking [33]. Blockchain can be a great help for e-waste management. The electronics products are connected to an Ethereum Blockchain by the manufacturer. Each time the product is bought or sold; its information is updated in the Blockchain. This helps in knowing who owns the product. Once the owner wants to dispose of the product, he returns it to the e-waste center. Smart contracts are used to calculate the incentives and transfer them to the participating entities. This method allows safe disposal of the e-waste. Some of the products can be reused or sold to other users while those obsolete products can be discarded. This method will prevent the accumulation of e-waste and create jobs due to the options for resale and incentives [34]. Blockchain combined with IoT can be used for managing medical and water waste. Sensors and actuators are installed on the water monitoring equipment like flowmeters, water meters, storage tanks, and the different kinds of trash bins used in the hospital. These IoT-enabled devices will collect data on stored water, its usage, and the amount of wastewater generated and treated by the plant. The collected data is sent to the peripheral nodes using acceptable communication technologies like 4G, 5G, or wi-fi. The peripheral nodes group the collected data into data blocks. These data blocks are added to the Blockchain after verification. The edge nodes perform real-time analysis of the collected information and decision-making. Each node receives an incentive to verify and extract a new block. These incentives called digital coins can be exchanged for various benefits like discounts on utility bills and taxes. This will motivate the stakeholders to adopt the system. Such systems help to analyze the effectiveness of waste management methods and modify or alter them to achieve the desired quality standards prescribed by the environment and health organizations [36].

D. Mixed Waste Processing

Mixed Waste Processing (MWP) enables the separation of recyclable materials from the MSW. It uses various new and existing technologies to separate the recyclable materials from the mixed thrash. MWP is considered an option to reduce the collection costs and increase recovery costs in the waste stream. The MWP facilities can process and recover food waste and organic waste. Organic materials are recovered at these facilities for composting and feedstock for anaerobic digestion. The technology delivers a higher volume of recycled materials. Some materials may have lower unit values due to contamination [37]. Material Recovery facilities (MRF) and MWPs can increase the revenue from recycling materials. However, their outcomes depend on the availability and application of the technology. They can be evaluated based on the quality of the finished products, the speed of the processing equipment, and the ratio of the volume of captured materials vs lost. The technologies used at the MWP facilities are mentioned in table 1 below [38].
MWP can achieve higher recycling rates for plastic recovery. HDPE (high-density polyethylene) and PET (polyethylene terephthalate) are easily recyclable but their recycling rates are less. Most of these wastes are being landfilled or processed through traditional mass burn. Only 30% of HDPE and PET containers were recycled in 2012 [39]. MWP facilities allow lower collection costs as they accept one unsorted stream of waste and recyclable materials. The requirement of extensive sorting and processing equipment and labor are the factors that increase the capital and operating cost of MWP facilities compared to MRF [40]. The recovery rates of MWP facilities are nearly 45-70% of the incoming waste.

The mixed waste MRFs allow the processing of wastes from under-resourced waste generators thereby reducing the burden on landfills and increasing recyclable materials. The MRFs are co-located at landfills to achieve maximum utilization of the recyclable materials from the waste stream. Automated MRFs reduce the need for manual labor for sorting recyclable materials [41].

TABLE I. TECHNOLOGIES USED AT MWP FACILITIES [38]

Technology	Type of equipment or process
Conveyors	Materials are moved from the processing equipment to the final stage using metal and rubber conveyor belts. The fine and wet materials may remain on the belt. These are removed using the belt cleaning mechanism in modern conveyors.
Bag openers	These machines are designed to remove materials from plastic bags without resizing or reshaping their contents. Most designs allow large or unbreakable objects to pass through by exiting spring loads. Some bag openers may experience jamming problems due to oversized objects while some use logic control to avoid jamming.
Primary shredders	They are used for size reduction of primary materials. Hammer mills are used for softer materials like wood, asphalt, sandstone, etc. while the single-rotor shredders are used for high organic content. The downside of hammer mills create a lot of dust and are not suited for plastic materials.
Secondary shredders	This type of shredders is used with the primary size reduction when additional size reduction is needed for refused-driven fuels, densification, and other processes. High-speed, high inertia hammer mills, medium-speed single-rotor shredders, and low-speed sheer shredders with multiple shafts are different types of secondary shredders.
Screens	The four basic types of screens used in MSW applications include vibratory, trommel, disc, and ballistic. These screens allow mechanical separation of material by size. The screens agitate and spread-out materials to separate smaller items from the larger ones.
Ferrous Magnets	They are generally used for metal recovery. The three types of magnets used in MWP facilities are the belt magnet, the head-pulley, and the drum magnet. A belt magnet has a cleated rubber belt that moves between two magnetic pulleys over a central magnet and the ferrous materials are attracted towards the magnet. Head pulley magnets use a permanent magnet as the head pulley of the conveyor. The ferrous materials are attracted towards the head pulley. Drum magnets have non-magnetic steel covers that move around fixed internal permanent or electromagnets.
Non-Ferrous Magnets	Eddy Current Separator (ECS) units remove non-ferrous materials like aluminum and copper. These ECS units can be targeted to remove a particular size range of non-ferrous materials.
Air Separation Systems	Air Drum Separators remove heavy or light items from the material stream. In the case of higher-volume streams, the air separators split the materials into even fractions by weight.
Optical Sorting System	These systems recognize different types of plastics by using a light source to illuminate a material stream. The sensors collect the reflected or transmitted light to analyze the light properties using spectrometry. As different objects reflect different wavelengths the optical processor looks for a specific wavelength to recognize the desired object.
Densification System	Densification is used at MWP facilities to compact the resulting streams into smaller and transportable forms. It can be used to create a desirable fuel shape and to allow easier and more economical storage and transportation of the materials.

E. Collaboration Platform for Industrial Symbiosis

Industrial symbiosis (IS) is an important step towards realizing the vision of zero waste to landfill. It is enabled by the physical exchange of byproducts within the companies and across different industries. The companies should work collectively and collaboratively to achieve mutual economic and environmental sustainability. One of the barriers faced while achieving industrial symbiosis is a lack of knowledge and information regarding the available byproduct exchanges [42]. IS has emerged as a Cross-Organizational cooperation that counts on transferring knowledge, information, and proficiency to encourage eco-innovation and long-term cultural change [43]. Some barriers to the implementation of IS are a lack of responsibility for sustainability, a lack of cooperation, and barriers related to information, technical, and economic issues. The obstacles like lack of collaboration and technical barriers can be solved by arranging workshops for firms to explore synergetic opportunities, getting assistance to gather relevant data, and providing tools and expert knowledge for implementing IS.

Digital platforms can play a significant role in supporting IS. They act as an online marketplace to foster interaction among resource suppliers and buyers [44]. IoT and data analytics can provide solutions for an efficient circular economy and Industrial symbiosis.

IoT can help the waste producer to connect with the waste collector and waste user. It enables the flow of information and optimizes operations. Real-time monitoring using IoT and sensors combined with data analytics will provide valuable information that can be used to predict and achieve accurate estimations for a longer period. There should be control over the source and type of information to add more value to the information [45]. The complexity and diversity of waste generation sources prevent efficient utilization of the collected data to initiate and operate industrial symbiosis. Data on the exact location, type, and quantity of waste streams across the concerned geographical location is a prerequisite to exploring industrial symbiosis. Big data analytics can be used in a three-step approach: i. Searching the internet, web portal, and webpages for the company data sets. It will provide data related to geographical location, the name of the company, its address, and the type of product or service, ii. A modeling approach to identify the input materials and waste streams. and iii. Estimate the quantity of input materials and waste streams. This approach can help to obtain accurate values for the suitability of individual members and feasible assessment of industrial symbiosis [46].

F. Recycling and Reuse of Waste

Recycling and reusing are two important steps toward minimizing, reducing, and managing waste. These practices reduce the burdens of landfills and incinerators. Recycling and reusing encourage the conservation of natural resources, save energy, and decrease pollution and contamination. Recycling wastes helps to save the money required for buying new raw materials and saves the environment from the negative impacts caused by disposal in landfills. It also saves energy needed by the manufacturing sector. Paper, cardboard, plastics, food, metals, rubber, etc. are common wastes that can be recycled and reused [47]. Waste glass is a non-biodegradable substance. Recycling glass is a cost-effective method to minimize glass waste, reduce the waste in landfills, and decrease the environmental impact. Paper is biodegradable and can be used in many ways. In our regular office uses we can minimize using paper by adopting digital ways of storing and sending information. Some other tips can be making paper bags and envelopes out of used newspapers, using both sides of the paper for taking printouts, donating or giving books to the needy, etc. These practices can reduce waste in the landfill. Plastic is one of the most generated household wastes worldwide. It pollutes land and water and is the greatest source of pollution. Metals can be ferrous or non-ferrous and can be used for various applications. Metal recycling reduces landfill growth but the energy required for the collection, sorting, melting, etc. is more and the workers are exposed to toxic conditions while working in the factories. Fast fashion has led to buying many garments and dumping them off after using them for a short while. This has increased the burden on landfills. Incineration of clothes may release harmful gases. Some fabrics are not easily degradable. It is better to go for biodegradable fabrics and maintain it for longer periods. Wastewater is the used water for domestic, commercial, and industrial purposes. Untreated wastewater disposal can contaminate water and soil. It should be treated before disposal. The number of waste tires has increased considerably due to the large usage of vehicles worldwide. Tires are nonbiodegradable and can cause a nuisance to the environment on disposal. Some of the recycling uses for the commonly generated household wastes are given in table 2.

TABLE II: RECYCLING WASTES INTO USEFUL PRODUCTS [15]

Type of Waste	**Recycling Uses**
Glass	#Substitute for fine aggregates and concrete to reduce the cost and impact of cement products on the environment. This concrete has better durability, strength, and mechanical properties and can be used for roads and buildings. #Converted into low-cost polymetric tiles with better compressive strength and load-carrying capacity. #Converted into a high-capacity Lithium storage battery that is cost-effective and has a longer life
Paper	Converted into bioethanol, butyric acid, cellulose nanofibers, biofuels, building materials, and other chemicals. All these products are cost-effective, improve sanitation, and ensure a greener approach to safeguarding the environment.
Plastic	Converted into petrol, diesel, and hydrogen fuels. These fuels are environment-friendly and discharge lesser harmful emissions when used to power internal combustion engines
Metals	The collected metal is sorted, cleaned, and melted to transform into new products. They are cast into bigots and sold to industries for further use.
Textiles	Buy only when required. Donate to the needy or convert the used clothes into usable household items like bags, doormats, etc.
Water	Purification of wastewater using oxidation-filtration, electrocoagulation/ electro flotation, and natural coagulants. The contaminants are removed and the purified water is safe and hygienic.
Tires	#Conversion techniques like retreading, combustion, grinding, and pyrolysis are used. #Recycled waste tires are used in road construction, vibration reduction in railways, and producing chemicals, biofuels, and bio-based products.

IV. BEST PRACTICES AND SOLUTIONS

The core principles of zero waste, reduce, reuse, and recycle help to achieve zero waste manufacturing. Some additional best practices should be adopted to promote sustainability and zero waste. These practices are (E. Babii, 2024):

- Effective systems should be implemented to separate different trash or garbage at the source, facilitating effortless recycling and diversion from landfills.

- Organic waste like food, fruits, vegetables, and plant waste can be converted into organic manure by composting. This will enrich the soil and save from the harmful chemicals and pesticides used for plants or crops.
- Promote a circular economy by prioritizing recycling and reuse of trash and reducing the need for raw materials.
- Reducing waste generation by promotion of environment-friendly and reusable products.
- Awareness and training programs for the stakeholders to raise awareness about waste management strategies and increase people’s participation.
- These best practices promote inclusive resource efficiency and environmental protection by the stakeholders and the organizations. Along with this, the challenges for ZWM should be addressed using a combination of the latest technologies and viable solutions. Some of these solutions are:
- Local regulations and policies should be enforced to create a sustainable environment. It is the first step towards mass adoption of the ZWM practices.
- Accurate data about waste management should be available for framing policies and planning at the local levels. Once the quantity and types of waste are known it becomes easier for the authorities to choose strategies and prepare for future needs.
- Reporting of the adopted practices and their effectiveness should be encouraged to enhance accountability and provide valuable insights into ZWM practices to the stakeholders.
- Awareness is an essential step towards increasing the adaptability of the ZWM practices among the people. Interactive workshops, engaging videos, posters, articles, and street plays can illustrate the benefits of ZWM to a diverse audience and empower the stakeholders.
- Financial assistance in the form of grants should be given to the businesses that encourage ZWM practices. At the same time, people can be provided with incentives to adopt the recycling and reusing practices.
- Mobile applications should be developed to inform of waste management practices, encourage their adoption, and select appropriate solutions for the waste generated at their homes or organizations.

V. Conclusion

ZWM has become one of the requirements to achieve sustainability worldwide. It can be beneficial to the environment, economy, and the community. Innovative technologies are helpful to achieve ZWM. Most ZWM processes are energy-saving and cost-effective but few can be time-consuming, confusing, and difficult to achieve. Many people and communities are not aware of what happens to the waste disposed of by them and where it goes. There should be strict regulations by all Governments for disposal, recycling, and reuse of the wastes. Awareness regarding waste management practices and their benefits should reach the people through awareness campaigns or social media. As we raise awareness on reducing, recycling, and reusing, we should also educate people on the harmful impacts of waste on the environment and health. People should be mindful of their purchasing habits to lessen the harm caused by waste. ZWM can be achieved by promoting 100 % recycling and reusing of wastes and zero percent of landfills and incineration.

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