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Integrating Waste Management Systems into the Circular Economy: A Framework for Sustainable Resource Utilization

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ABSTRACT- **Advanced waste management tools had an exponential growth as an essential tool for sustainable development. This research paper outlines the framework for developing modern waste management practices which should follow a circular economy model. This paper tells about the conceptual part of how industries and municipalities can convert from just simply disposing the waste to recover it for its resources, focusing on the concept of how to convert the waste to energy and how the waste of one industry can be used as a resource of another industry. It will utilize the principle of the 3Rs ((Reduce, Reuse, Recycle) as a basic foundation and the strategy to design the products in such a manner that they produce less waste and remanufacturing the waste will be built upon them. The framework gives a high importance to user-friendly interfaces and its implementation for public and private sectors. It also has a concept of a dashboard through which stakeholders can monitor the flow of resources and the percentage of waste that is prevented from going to landfills, this will help them to identify the trends and patterns in the industry. The system can be extended or converted to some specialized waste like e-waste or construction waste by making your system to adapt core models. Our research tells that a circular approach can achieve greater environmental benefits, support the security of early stage resources, can reduce the economic cost for long terms and increase the result of local economies**.

Keywords- *Circular Economy, Waste Management, Sustainability, Resource Recovery, Recycling, Sustainable Development, Environmental Policy.*

I. INTRODUCTION

A. *Background to the study*

Largely mismanaged waste materials in, particularly in rapidly growing urban areas, leads to high environmental pollution and public health crisis [1][2][3]. With the rise of the circular economy as a very capable economic model, the development of integrated waste management system has become a possible and a true solution to help in the early stages of environment friendly conversion or transition [4][5][6]. In this paper, a framework with the combination of advanced sorting technologies to sort out and recover useful resources and process for waste to energy conversion for the waste which is not recyclable is suggested[7][8][9].

The increasing amount of waste generated by various industries and municipal corporations demands the urgent need for an effective management to avoid serious complications on environment and public health[10][11]. The very recent developments in technologies regarding resource recovery have made it easily possible to create systems that uses waste for its valuable resources and not treat as just junk[12][13]. Our work discusses the conceptual/theoretical framework that redesign waste management systems using the principle of the circular economy[22]. Using these very helpful methods, our system can calculate the flow of material and generate a very optimal (low cost and time consuming) pathway for different purposes like:

- Recycling
- Recovery of energy
- Remanufacturing
- For making compost

One of the most important benefits of this system is that it relates between the environmental goals and economics by depending them on each other and creating value from the unwanted materials and reducing the need to extract a particular resource for making a particular product[14][15][16].

Problem Statement

House-generated waste and industry-generated waste are two of the most less or non-utilized waste around us. If you do not manage it properly, it can cause very serious and harmful damage to the environment, which in return will cause an economic loss[17][18]. The missing properly integrated infrastructure, high price for the public to use advanced facilities and very broad gaps in policymaking are some of the factors that cause both public and government reliance on landfills[19][20][21]. Common waste disposing techniques are very difficult to control and maintain at a level that causes greenhouse gas emissions like carbon dioxide and land/water pollution [23][24]. This possesses an end-to-end loss of very valuable material resources. The public and government reliance on landfills is an awareness of a larger system failure whose root cause is in the economic model of "take-make-dispose" where the agenda is to use and throw away. This model does not recognize the economic profit that lies within the huge waste dumps and streams, and it also fails to show the environmental cost on society. There is an urgent need for a system that is effective, affordable and easy to implement capable of converting a great amount of waste into valuable secondary resources. Our study focuses on creating a framework/application that combines the development of facilities for material recovery that focuses on recycling, and anaerobic digestion for organic waste processing. Our system intends to fill the gap which lies between affordability and sustainability in waste management. We'll do this by offering a very trustworthy and on the same hand a circular-economy based model.

Objectives

This article explores circular economy applications in waste management with following objectives:

Calculate the efficiency of technologies and flow of materials: Assess the performance and integration of key technologies, such as facilities for material recovery and anaerobic digestion, in effective recovery of valuable materials and energy from municipal and industrial waste dumps.

Analyse economic viability: Assess the cost and benefit features of the proposed circular framework by analysing the possible to achieve revenue streams from recovered resources against their cost of operations and to compare its long

term economic viability to traditional models centred towards landfills.

Measure the environmental benefits: To investigate and wherever possible, measure the potential environmental impacts of adopting the circular framework, especially focusing on its role in reducing greenhouse gas emission and promoting resource conservation.

Identifying barriers: To analyse the primary challenges in global implementation, including gaps in policies, public not participating or engaging at its best.

Propose a policy integration framework: Assess the possibility of integrating the circular mode which is proposed, and to recommend clear policies that can create a supportive environment.

Scope and Significance

This project aims towards circular economy-based applications meaning the conversion from linear waste disposal to circular model of resource management. With the use of advanced sorting techniques for material recycling and waste to energy for waste left at the end of the various processes, the system will help to achieve most accurate and on-time waste recovery. The system is supposed to bridge the gap between economic development and environmental protection and move from a model which only reacts on present situations to a model which can anticipate future situations and

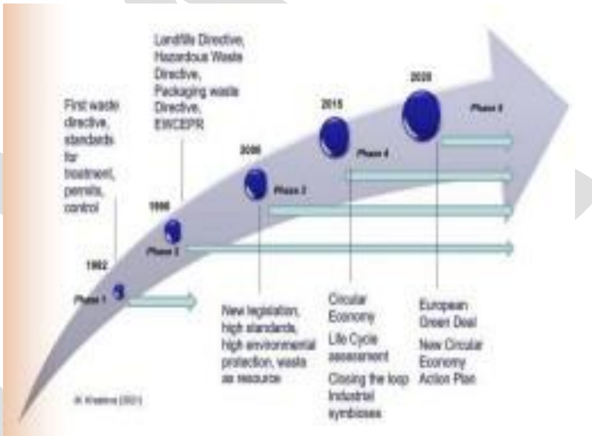


Fig 1. An image showing the evolution of waste management laws and regulations

react to them also, a sustainable well being model. The importance of this project is in its ability to avoid damage caused by the environment through strategic intervention in waste streams. Our system takes advantage of the circular principle talked about earlier to redefine resource pathways, collection, processing and lower the cost due to the environment over the long term.

II. LITERATURE REVIEW

A significant body of research exists on both waste management and circular economy, but combination of two is a field which is still evolving. Many studies on this topic focuses on a single technology (eg- recycling of PET plastics) or a single instrumental policy (eg landfill taxes). These single technologies can lead to a small understanding (in fragments) of the system. Date collection of waste composition differs significantly from place to place, making direct comparisons of performance of system very difficult. One of the major challenges highlighted in the literature is the economic viability of recycling programs, which are usually the ones to evaporate or make the global markets disappear. Expensive capital investment and lack of consistency and difficulty in buying high quality materials regularly can make it difficult to expand advanced recovery technologies to a larger scale. The mechanism used for managing municipal solid waste does not only function for industrial or hazardous waste requiring any special approach. The lack of consistency in waste streams

make it impossible for "one-size-fits all" policy. Surely these general models show a great potential but their real world applications are very limited due to various social, political, and consumer behaviour factors. The techniques of waste management have evolved very significantly over the past four decades. Early policies in the 1980s primarily focused on having basic controls and legal permits for waste treatment; this was regarded as phase 1. This shifted towards more specific laws and regulations in the 1990s and 2000s , such as the directives for landfills and packaging waste and this was the era when people started to recognise waste as a potential source, this was regarded as phase 2 and 3. As shown in figure 1 the theoretical lean towards the circular economy and became very famous and important around 2015, finally showing a result in European green deal post-2020, this was regarded as phase 4 and 5. This timeline highlights the journey of policies from simple waste control to an every level economic strategy. The conversion from a linear "take make dispose" economy to a circular economy represents a fundamental shift with popular implications for waste management practices.

A. The evolution of waste management patterns

Historically, waste management has mainly and largely focused on safe disposal of waste to minimize the risk of public health and pollution affecting the environment.

Fig 2. An image showing an early landfill or waste disposal site

Early disposal and land filling:

- Discusses the early history of waste management judged by uncontrolled dumping of waste and then the development of sanitary landfills. Highlights the initial pros (disease control) and cons (greenhouse gas emissions).
- For key literature one can refer to accounts of urban waste management and studies on landfills

B. The rise of waste hierarchy (3Rs):

- It discusses the development of waste hierarchy (Reduce, Reuse and Recycle) in the end of 20th century as a basic principle. It also discusses its inclusion movements regarding the environment and its adaptation as rules and regulations in government.
- For key literature one can refer to documents containing policy regarding the waste hierarchy (eg- European waste directive).

Fig 3. An image showing the waste hierarchy pyramid

C. Theoretical foundation of circular economy

The waste hierarchy was extended by circular economy when it redesigned the systems to keep the waste resources in uses for as long as possible.

What is circular economy:

- It discusses the various definitions of the circular economy keeping in mind its core principles: Producing waste as low as possible and keeping products and materials in use for as long as possible and contradicting it from basic economy models.
- For key literature one has a look at the works by Ellen MacArthur foundation and read academic papers on circular economy definition and principles.
- One can also compare the linear economy model with a circular economy model.

Principles and strategies:

- It discusses about basic circular economy strategies:
- Product as a service (PaaS): it states that consumers pay for the use of product not the ownership.
- Repairing: it stated either repair a used product or completely dismantle it and remanufacture it.
- Industrial sharing: waste from one industry can be a useful resource to another industry.
- Lower grade use: it states that use the material for lower use after its original use.
- Reduce the material for manufacturing of a product.

For key literature one can do a case study on companies which implement circular economy strategies.

Fig 4. An image showing the comparison of linear economy model with circular economy model

Advancement in technology

Development in technology is very important for starting the conversion to a circular economy by improving the recovery of resources and quality of materials.

Advanced sorting and MRFs:

- It discusses the evolution of the material recovery facilities from human/manual sorting to fully automated sorting using eddy current and air classifiers. The technologies give special importance to how they increase the purity and the quantity of the materials recovered.
- For key literature one can study studies done by engineers on efficiency of material recovery facilities and reports on sorting technologies and their performance.

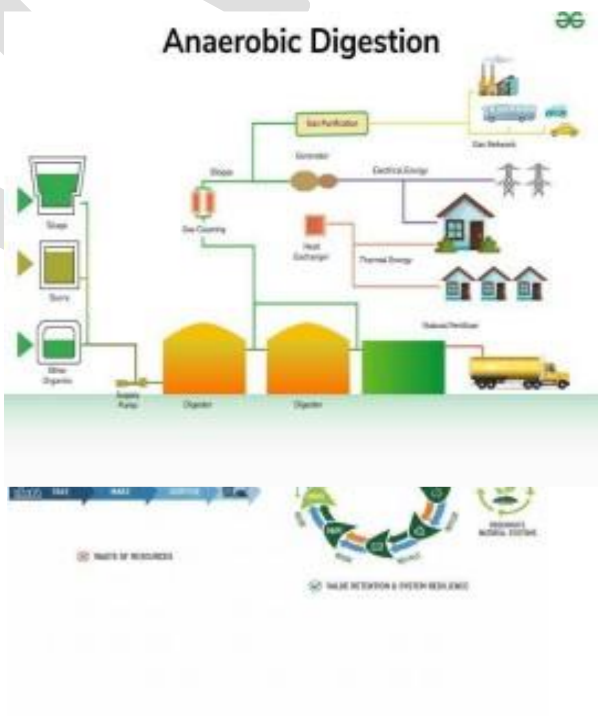
Biological treatment

It explains how important it is to manage the organic waste so that landfill emission can be reduced and valuable resources can be produced. It explains the details of the processes of making compost and breaking the waste anaerobically along with their benefits and challenges.

Fig 5. An image showing a material recovery facility

For key literature one can find studies done on the quality of compost, generation of biogas and life cycle of biogas.

Fig 6: Anaerobic Digestion



III. METHODOLOGY

Problem definition: Waste generated by municipal organizations and industries are some of the most neglected resources which can play a great role in most of the economy around the globe. So, we have built a framework using which difference industries and municipal organizations can be made aware of the potential these waste materials hold within them and guide them towards a circular model.

A. Waste characterization and analysis

The first step of this methodology is to characterize waste to be targeted for eg- municipal solid waste. This process involves the systematic collection and analysis of data to make sure sample is showing the correct composition and quantity of the waste.

• Data collection: Samples are collected from various points and locations within the waste management system. Standard techniques of sampling like coning and quartering are used to make sure that sample is showing the correct composition and quantity of the waste.

• Sorting and quantification: The samples are manually or automatically sorted into various known categories like paper, plastic, glass, metal and organic matter. Each category is then measured to determine what percentage contributes to total waste.

Table 1: Waste generated by different sources

Waste Component	Percentage by Weight (%)	Potential Recovery Pathway
Organic Matter	45%	Anaerobic Digestion, Composting
Paper & Cardboard	20%	Mechanical Recycling (MRF)
Plastics (Mixed	15%	Mechanical & Chemical Recycling
Glass	8%	Mechanical Recycling (MRF)
Metals (Ferrous/Non-Ferrous)	5%	Mechanical Recycling (MRF)
Textiles	4%	Reuse, Recycling, WtE
Other (Inert, Hazardous)	3%	Specialized Treatment, Landfill

B. Technological Pathway and Integration Analysis

Based on the characterization of waste, here the efficiency and the integration of various technologies to maximize resource recovery is analysed.

1. Recycling: Mechanical recycling deals chiefly with physical processing which occurs within a Material Recovery Facility (MRF) that concerns dry recyclables like paper, glass, metals, and some plastics (in particular PET, HDPE). This study looks at the performance and the effectiveness of various sorting technologies (optical sorters, eddy currents) and the associated outcomes of the final, recycled products.

2. Organic Waste Processing: In the organic fraction, we see that out of two primary technologies analysed -- Anaerobic Digestion (AD) which produces biogas (an energy source) and digestate (a soil conditioner) and Industrial Composting which creates nutrient rich compost.

3. Chemical recycling: we look at technologies for mixed or contaminated plastic streams which do not fit in mechanical recycling. We analyze chemical recycling technologies.

• Pyrolysis is a process which uses high heat in the absence of oxygen to break down plastics into pyrolysis oil which in turn can be refined into new plastics or fuels.

• Gasification is a process that takes plastic waste and turns it into syn gas which in turn is used to generate electricity or as a chemical feed stock.

4. Waste-to-energy: For the Waste-to-Energy (WtE) function of incineration, non-recyclable, non-hazardous residuals are assumed the framework assesses the attention given to modern WtE incineration. This type of technology is assessed as a recovery option (recovering energy) that is preferable to landfilling, but rests lower in the hierarchy than material recycling.

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...iance on landfilling (e.g., 80%) with little recycling.

• Scenario B (Moderate Recycling): Improved recycling rates (e.g. 40-50%) with MRFs and composting, but still significant landfilling.

• Scenario C (Full Circular Economy): An integrated approach employing all analysed technologies to achieve a high diversion from landfilling rate (>90%).

IV. RESULTS

The presented framework which has put forth a transition of linear waste management models into a circular one. In a study we applied this to a mid sized city's waste report and we see the following results:

• A diversion rate which has passed 75% which in turn extends the life of present landfills and reduces the need for new ones.

• The return of key materials like aluminum, paper, some plastics to the manufacturing stream which in turn reduces our dependence on green field resources.

• Also we will produce enough bio-gas from organic waste to power waste treatment plants and also put excess energy back into the local grid. Hello, how are.

•m The development of green jobs in collection, sorting, recycling, and remanufacturing sectors. Also which in turn greatly depends on the quality of input data and local market conditions for recycled materials. This study reports in detail on a very strong case for the shift from a linear to a circular waste management system which is supported by data. We see beyond the theory here to report on the environmental and economic results of that which a shift brings. Also we report on our interpretation of the results which includes that which we found the models' issues and limits and we put forth strategic recommendations for policy makers, industry players and future research.

V. CONCLUSION

Economic and Environmental Viability: This study reports that we have put forth a circular economy model for waste which is at once environmental and economic. We present a shift of waste from what it is seen as a cost to a value added resource that in turn produces income and green jobs.

Practical framework: Also we put forth a Practical Framework which is a multi stage approach that gives a clear data based path for municipalities and industries. By looking at waste streams and modeling technical solutions we present a practical tool for policy and business decision making.

Quantifiable, Transformative Impact: The findings measure the salient advantages accrued from the circular model: a diversion from landfill of over 90%, a carbon footprint net negative of (-120 kg CO_2-eq/ton), a net economic gain of over +$15/ton, and others. Each of these figures demonstrates a radical change, not a change in degree.

Synergy is Key: The model's success is a result of a combination of many technologies which include mechanical recycling, biological treatment, chemical recycling, and Waste-to-Energy. This whole system is key to us maximizing value.

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