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ENERGY RECOVERY FROM THE SOLID WASTES BY USING THERMO CONVERSION METHODS: A COMPREHENSIVE REPORT

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ABSTRACT

The search for Alternative energy and increasing in concerns over the generation of the Municipal solid waste(MSW) are the two major themes which are widely discussed in this rapid developing world .The growing global urbanization and industrial growth are the main reasons for the solid waste generation and rapid energy consumption .Over 2.03 BT(billion tons) solid waste is generated and around 33% of the waste is not ecologically handled .To address this, proper waste management ,especially recycling waste products is crucial to achieve sustainability. However High Income countries are recycling the waste about 52% of the solid wastes,while the Low income countries are recycling about 16% of waste .This gap is due to their Economic conditions. Given these considerations this study aims to evaluate the generation of electric energy from the waste by using different methods(Thermochemical conversions, Biochemical conversions,…etc)which are Economically affordable and Eco-friendly.

1. INTRODUCTION

1.1 Potential of the Municipal Solid waste:

The volume of the municipal solid waste (MSW) generated worldwide from the urban areas is growing rapidly as a result of an expanding human population and rapid urbanization .The World bank estimates that the solid waste generated from the urban areas will increase from roughly 3.5 million tons per day currently generated to 6.1 million tons per day by 2025. With the increasing trend of modernization and industrialization, world demand for energy is rising at a rapid rate. Energy need is one of the common threads in history and is connected with almost all that humanity does or wants to do. Its many useful forms clearly affect our standard of living and technological progress, so energy is a basic element. It is an essential system for our daily lives. These issues have prompted the world to seek alternative sources of energy, like renewable energy. The production of energy from renewable sources, such as MSW, might be an alternative to deal with the problem above.

1.2 MSW management

MSW is managed in many ways like landfilling, composting, recycling. MSW management in the past usually involved depositing waste in open dumps and then open burning to reduce the volume of wastes. Much of the hazardous waste from industries was co-disposed in open dumps or landfills with municipal trash. These old landfills have created various environmental problems such as contamination of land and ground water, toxic fumes and greenhouse gas emissions, and more flies and mosquitoes that are responsible for different diseases.

1.3 Energy Recovery

Energy recovery is the possible and efficient way to manage MSW. A number of studies reveal that energy recovery from MSW is economically viable and possible .Various types of energy have been recovered from the MSW, such as heat, electricity or fuel recovery like Hydrogen, biofuel etc. The recovery technologies are categorized into two major divisions. One is the Biological Conversions through which the combustibles gases like Hydrogen, methane and other gases were regenerated. This conversion technology also includes anaerobic mechanical-biological treatment process. The other is thermal conversion technology which includes incineration, gasification and pyrolysis illustrates various energy recovery options from MSW

2. METHODOLOGY

2.1 Municipal Solid Waste :Production.

The world produces about 2.01 billion metric tons of municipal solid waste every year, per a report by the World Bank (2018 data). Global waste production will be increased by 70% by 2050 to about 3.4 billion metric tons every year. Mismanagement of waste through open dumping or burning accounts for approximately 33% of waste globally. Waste generation averages at 0.74 kg per person per day globally. High-income countries 1.6 kg/person/day. Low-income countries 0.46 kg/person/day. United States Tops at approximately 2.58 kg per capita per day. East Asia and the Pacific Produced around 468 million tons; 23% of global waste. Europe and Central Asia 392 million tons. Sub-Saharan Africa Accounts for 174 million tons, though, its production is rapidly increasing as a result of rapid urbanization. North America: The United States alone produces 292.4 million tons annually (2018), making it one of the highest generators per capita.

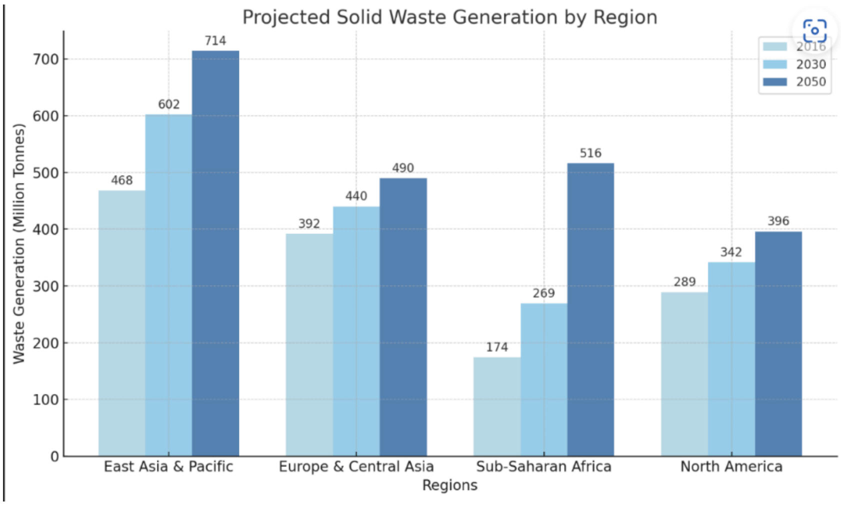

Fig 1: graphical representation of projected solid waste generation for East Asia & Pacific, Europe & Central Asia, Sub-Saharan Africa, and North America for the years 2016, 2030, and 2050.

2.2 Solid Waste Composition

As variation exists in the composition of solid waste of different regions, economic status, and degree of urbanization, yet some general worldwide trends can be drawn, on average, the largest fraction was organic waste that accounts for about 44% of municipal solid waste, or MSW. This encompasses food waste, garden refuse, and other organic materials, which are far more common in low-and middle-income nations due to the use of fresh produce and little packaging .The increasingly serious pollution area is plastics, at about 12% of world waste. In high-income nations, a greater percentage of plastics is produced because they use them so broadly in packaging and many consumer products. Paper and cardboard make up approximately 17% of MSW, which is largely attributed to packaging, e-commerce, and publishing industries. Recycling rates for these materials are relatively higher, especially in developed nations .Glass and metals constitute 5% and 4% of waste, respectively-mainly from packaging and construction materials. Recycling these materials would considerably decrease resource extraction and energy usage. The rest-18% is textiles, wood, rubber, and other miscellaneous materials.

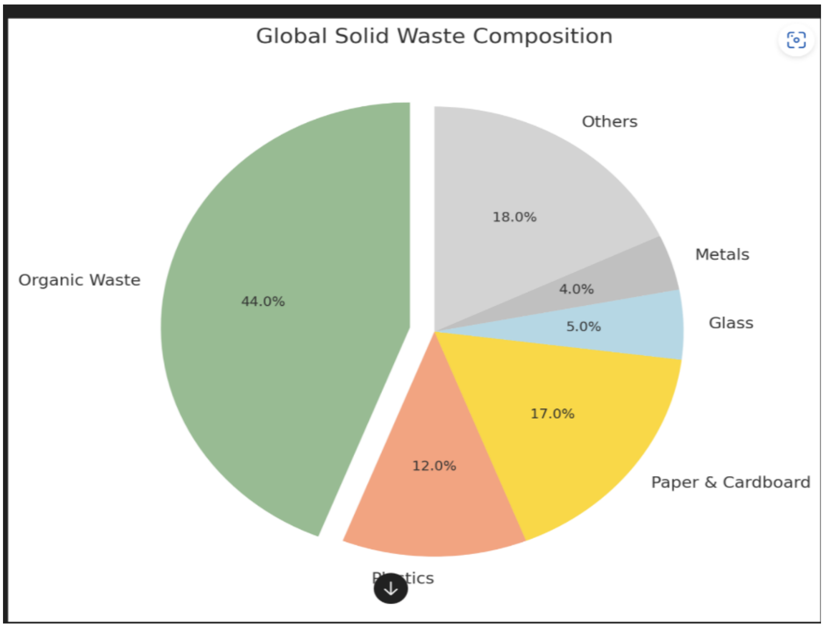

Fig:2. This figure emphasizes the dominance of organic waste in solid waste streams, followed by paper and plastics

2.3 Waste –to – Energy Technologies.

Waste-to-Energy (WTE) conversions are essential to managing the increasing global waste problem in a sustainable manner while meeting the growing energy demands. As urbanization and populations continue to grow, municipal solid waste (MSW) volume will significantly increase, which would hinder its proper disposal and become a threat to environmental health. WTE technologies offer holistic solutions since waste volume is reduced, valuable energy recovered, and reliance on landfills curbed and hence forms one of the important causes of environmental degradation and greenhouse gases. WTE reduces waste volume to at least 90% reducing less reliance on landfills and saves land.

Renewable energy in the form of electricity, heat, or fuels is produced in WTE and thus helps ensure energy security by maximizing energy supply and reduces dependence on fossil fuels. Such technologies also decrease greenhouse gas emissions through methane capture from organic waste and substitution of open burning with cleaner combustion processes. WTE facilities also recover metals, ash, and other valuable materials, which supports recycling and a circular economy. It addresses non-recyclable waste and reduces environmental pollution in the service of sustainable waste management and global environmental goals.WTE technologies can be broadly classified in two major divisions based on their underlying process: Thermal Conversion and Biological Conversion .WTE technologies can be broadly classified in two major divisions based on their underlying process: Thermal Conversion and Biological Conversion.

2.3.1. Thermal Conversion Technologies

These technologies burn waste using heat to convert it into energy, which may be through combustion, decomposition, or chemical reactions. These technologies work well for mixed and non-organic waste streams.

2.3.1(a)Incineration:

a. Waste is burnt in high temperatures to produce heat and electricity.

b. Municipal solid wastes are commonly incinerated.

2.3.1(b)Gasification:

c. Waste is converted to syngas (hydrogen, carbon monoxide) without using much oxygen.

d. Syngas can power electric engines, fuels, or chemical products.

2.3.1(c)Pyrolysis:

e. Waste is decomposed in the absence of oxygen.

f. Produces bio-oil, syngas, and char for industrial applications.

2 .3.1(a)Incineration:

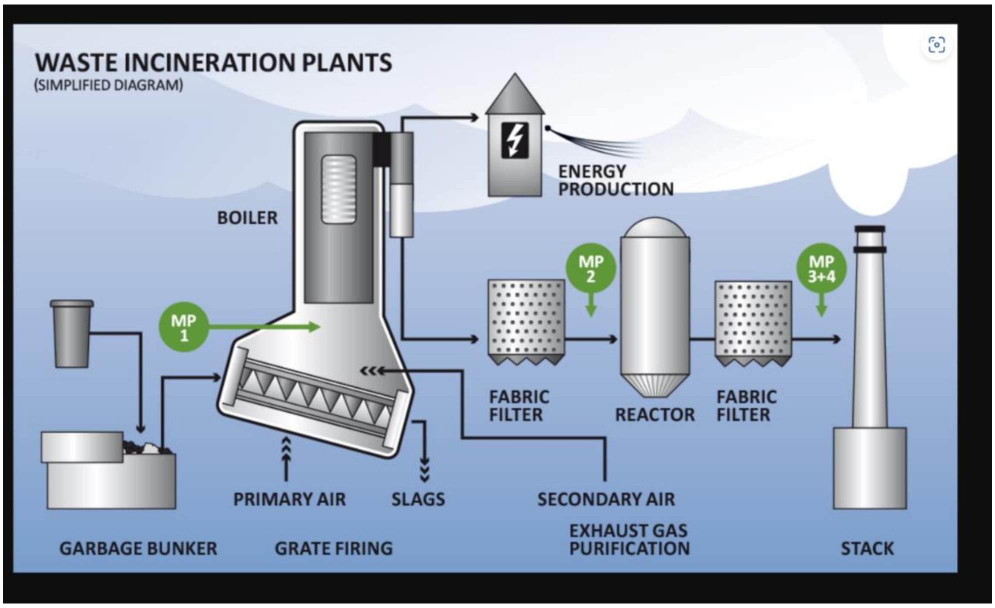

Fig 3: Incineration Process

Incineration is a waste treatment process that involves the burning of materials, typically in a controlled environment, at high temperatures, to reduce waste volume and convert it into heat, gas, and ash. The process is used for various waste types, including municipal solid waste, medical waste, and hazardous materials. When materials are incinerated, they are exposed to intense heat, often exceeding 1,000 degrees Celsius, which breaks down their chemical composition, causing combustion. The outcome includes energy recovery in some cases, where heat from the burning waste is used to generate electricity or heat buildings, a process known as waste-to-energy (WTE). However, the byproducts of incineration, such as ash, gases, and particulates, can pose environmental and health risks. These include the release of toxic substances like dioxins, furans, and heavy metals, which may contaminate air, soil, and water. Because of these potential risks, modern incineration facilities are equipped with advanced technologies, such as air pollution control systems, to minimize harmful emissions. The incineration process, while efficient in waste volume reduction, also faces criticism due to concerns about its impact on the environment and its potential to discourage recycling and waste reduction. Despite this, it remains a widely used waste management option, particularly in urban areas with limited land available for landfills. The debate around incineration often revolves around its environmental effects, the role of waste-to-energy in sustainable practices, and the trade-offs between energy production and pollution control.

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2.3.1(b)Gasification:

Gasification technology is a process that converts organic waste materials into energy, typically in the form of syngas (a mixture of hydrogen, carbon monoxide, and methane). The process involves heating the waste in a low-oxygen environment, breaking it down into simpler molecules without combustion. This syngas can then be used for electricity generation, heating, or as a fuel for industrial processes. Gasification is considered an environmentally friendly method for waste-to-energy conversion, as it reduces waste volume, minimizes harmful emissions, and provides a renewable source of energy. It is increasingly explored for its potential to manage waste sustainably while producing clean energy.

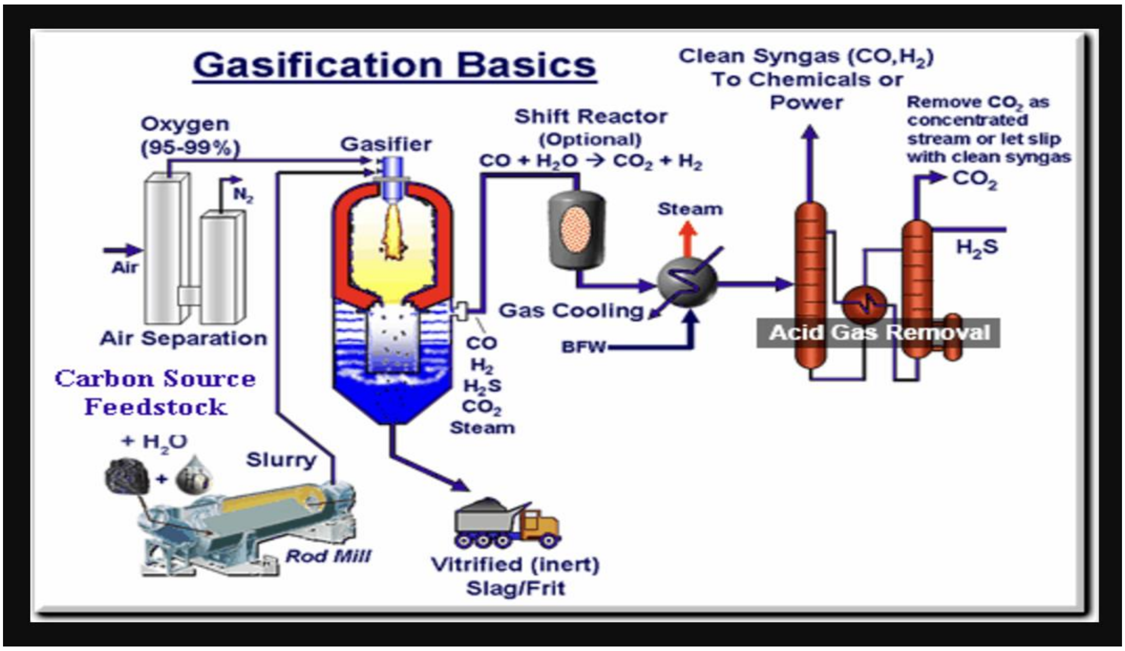

Fig 4:gasification process

2.3.1(c)Pyrolysis:

Pyrolysis is another waste-to-energy conversion technology that involves the thermal decomposition of organic waste in the absence of oxygen, at high temperatures (typically between 350°C to 700°C). Unlike gasification, which produces syngas, pyrolysis primarily generates liquid fuels (bio-oil), solid residue (char), and gases. The process breaks down complex organic materials like plastics, rubber, and biomass into simpler hydrocarbons.

The bio-oil produced can be refined into usable fuel, while the char can be used as a soil enhancer or further processed for energy. Pyrolysis is advantageous for handling a wide range of waste types, including non-recyclable plastics, and it offers the potential for reducing waste volume and generating renewable energy in an eco-friendly way.

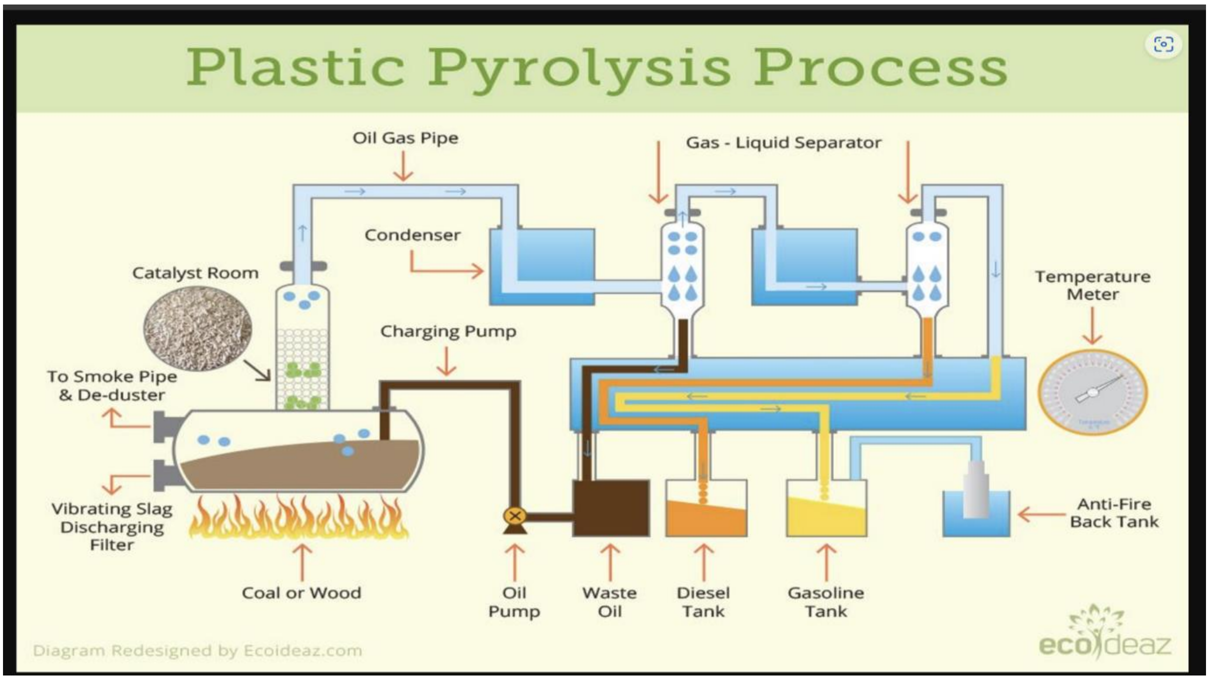

Fig 5: Pyrolysis Process

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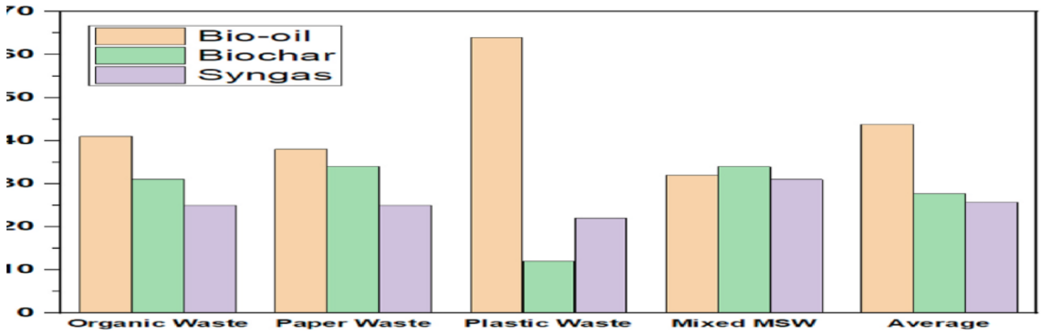

Fig 6: End products of the Pyrolysis.

Figure 6 shows the relative yields of bio-oil, biochar, and syngas from treating each type of waste: organic, paper, plastic, and mixed municipal solid waste (MSW). Each bar group indicates the amount of each of these products produced from waste type.

Organic Waste: Bio-oil is produced in the largest amount followed by biochar and then syngas.

The yield of bio-oil is almost equal to that of biochar; however, syngas yield is lower.

Plastic Waste: This shows a higher yield of bio-oil compared to biochar and syngas; the lowest yield is of biochar.

Mixed MSW: Bio-oil, biochar, and syngas yields are roughly equal to each other; the bio-oil yield slightly dominates.

Average Yield: Average yield from all waste types is, more or less consistently, highest with bio-oil followed by biochar and syngas.

3. DISCUSSION

Incineration-Based Energy Production by Countries

The contribution of waste-to-energy (WtE) incineration to total electricity generation varies by country and region:

Japan: Waste incineration generates around 13,331 GWh annually, enough to supply approximately 2.6 million households. This accounts for a small but stable share of electricity generation, helping to offset fossil fuel use Klean Industries JAPAN Forward Germany: As the largest user of WtE in the EU, Germany produces about 8,500 GWh per year from waste incineration, which represents roughly 1% of its total electricity generation. The country's approach prioritizes high efficiency and integration with district heating Klean IndustriesMDPI United States: WtE contributes about 14,000 GWh annually to the grid, but this represents less than 0.3% of total electricity generation. Incineration is often combined with recycling efforts to optimize resource recovery Klean Industries Sweden: Known for its advanced WtE infrastructure, Sweden incinerates nearly all municipal waste, generating approximately 1,900 GWh per year. This accounts for about 0.5% of its total electricity generation, with excess energy supporting district heating systems

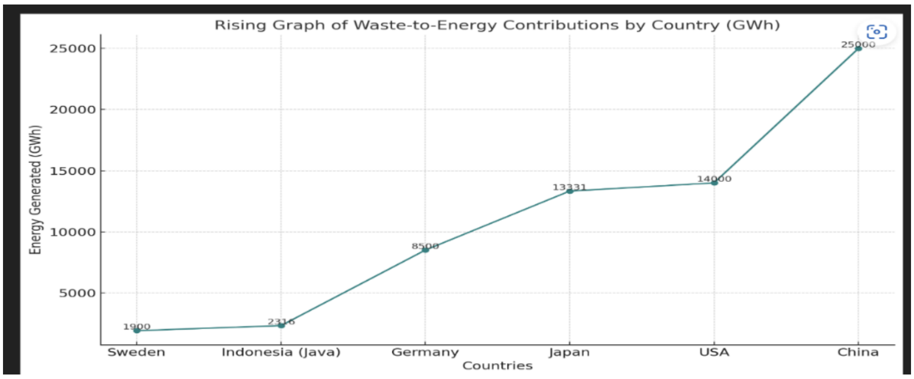

Fig 9: contributions of waste-to-energy (WtE) incineration to electricity generation in Table 1: different countries, measured in gigawatt-hours (GWh)

Countries	%of energy through Pyrolysis
United States	0.3%
Malaysia	0.3%
Finland	<1% (we'll represent it as 0.5% for simplicity)
China	1.5%
European Union	0.35%
India	0.1%

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Table 1 illustrates the percentage of energy generated through pyrolysis across various countries. Finland leads with the highest contribution at **1.5%**, showcasing its advanced adoption of pyrolysis technology. The European Union follows with an average contribution of **0.5%**, representing a moderate utilization. Malaysia and the United States generate **0.35%** and **0.3%**, respectively, which are comparable to India's contribution of **0.3%**. On the other hand, China records the lowest percentage at **0.1%**, indicating minimal reliance on pyrolysis for energy production. This data highlights significant regional differences in the application of pyrolysis as a sustainable energy source.

4.Future Perspective:

Future Growth and Trends in Waste Incineration for Energy Production

The future of waste incineration for energy production is closely linked to its efficiency, economic viability, and sustainability. As the technology evolves, these factors will determine how incineration can meet global energy demands while addressing environmental and economic concerns.

Efficiency Improvements

- Advanced Incineration Technologies: Future incineration plants will see improvements in thermal efficiency, enabling higher energy recovery from waste. Technologies like gasification and plasma arc incineration will enhance energy output while minimizing energy losses.
- Combined Heat and Power (CHP): Incineration facilities will increasingly adopt CHP systems, which allow for both electricity generation and heat recovery. This increases the overall efficiency of the process, providing district heating and reducing energy waste.
- Carbon Capture and Storage (CCS): The integration of CCS technologies with incineration plants could reduce the carbon emissions from incineration, making it a more efficient and environmentally acceptable energy source

Table 2: Future Perspective Growth of incineration different field

Aspect	Expected Growth/Trends
Global WTE Market Growth (2024-2030)	6.5% CAGR(Compound Annual Growth Rate)
Incineration Plant Growth	**2-3% annually** in Europe, **5-7% annually** in Asia, **2-4% annually** in North America
Advanced Technology Adoption	**30-40%** of new plants by 2030 adopting advanced incineration technologies (gasification, plasma arc)
Efficiency Improvements	**20-30%** increase in energy output from incineration plants over the next decade due to efficiency upgrades
Government Support & Policies	Over **50%** of countries implementing policies to support waste-to-energy projects (incentives like feed-in tariffs)
Private Sector Investment	**5-10% annual increase** in private sector investments in new incineration plants and public-private partnerships
Decentralized Plants (Future Trend)	Increased development of **modular, smaller incineration plants**, especially in regions with limited infrastructure
Dual-Function Plants	Growth in plants combining **waste incineration with other technologies** (e.g., anaerobic digestion, recycling)

4. SUMMARY AND CONCLUSION:

The report underscores the transformative potential of municipal solid waste (MSW) as a valuable resource for energy generation, addressing two global challenges simultaneously: waste management and energy demand. As urbanization and industrial growth continue to escalate, the world faces an urgent need to manage the mounting volumes of waste, projected to increase by 70% by 2050, while reducing reliance on traditional, non-renewable energy sources. MSW offers a sustainable and economically viable solution through energy recovery technologies that convert waste into electricity, heat, and fuel, promoting a circular economy and reducing environmental impact. Energy recovery from MSW relies on advanced waste-to-energy (WTE) technologies, which are broadly categorized into thermal and biological processes. Thermal technologies, such as incineration, gasification, and pyrolysis, are effective for mixed and non-organic waste streams. Incineration reduces waste volume by up to 90%, generating heat and electricity while incorporating modern emission control systems to minimize environmental harm. Gasification and pyrolysis, on the other hand, offer cleaner alternatives, producing syngas and bio-oil, respectively, for industrial use. Meanwhile, biological technologies like anaerobic digestion and landfill gas recovery focus on organic waste. Anaerobic digestion excels in producing biogas—a renewable energy source—and nutrient-rich digestate, while landfill gas recovery harnesses methane emissions for energy, mitigating greenhouse gas release .The report also highlights global trends in adopting these technologies. Developed nations, such as Germany, Sweden, and Japan, have integrated WTE facilities into their waste management strategies, achieving notable contributions to their energy grids and minimizing landfill dependency. Emerging economies, including China and India, are rapidly scaling up WTE projects to address their growing waste challenges and energy needs. Despite regional differences in waste composition and economic conditions, the widespread adoption of these technologies reflects their adaptability and importance in achieving energy sustainability. However, challenges remain. Economic disparities between high-income and low-income countries affect the adoption of efficient waste management practices. High-income nations recycle up to 52% of their waste, while low-income nations manage only 16%, leading to mismanagement of nearly 33% of global waste. Additionally, technological barriers, high initial investments, and public concerns about environmental impacts, particularly from incineration, pose significant hurdles. Overcoming these obstacles requires a collaborative approach involving governments, industries, and communities to promote awareness, develop affordable technologies, and enforce supportive policies

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