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Waste-to-Energy Technologies: Global Trends, Challenges, and Opportunities for Sustainable Development

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ABSTRACT

The accumulation of municipal solid waste (MSW) has become an escalating environmental and public health concern, particularly in developing countries such as Iraq. Landfills are nearing their full capacity, while formal waste management systems are still in the process of development. At the same time, the growing demand for energy presents an additional challenge to sustainability efforts. This study is based on the hypothesis that Waste-to-Energy (WtE) technologies can offer a Partial solution to both the waste crisis and energy shortages.

The primary objective of this research is to examine global experiences with WtE technologies and assess their potential applicability in Iraq. The study explores various WtE methods, including incineration, gasification, anaerobic digestion, and landfill gas recovery, emphasizing their environmental and economic benefits. Drawing from case studies in China, Germany, Sweden, and Japan, the research highlights key elements of success such as supportive legal frameworks, balanced risk-sharing mechanisms, and active community involvement. In contrast, Iraq faces several obstacles, including inconsistent waste composition, regulatory gaps, and limited financial capacity.

The findings suggest that the successful adoption of WtE technologies in Iraq requires integrated policy reforms, sustainable financing strategies, institutional strengthening, and effective public-private partnerships. These measures are essential to ensure that WtE becomes a practical and sustainable component of Iraq's future waste and energy management strategies.

keywords:

Waste-to-Energy (WtE), Municipal Solid Waste (MSW), Renewable Energy, Waste Management, Sustainable Development, Energy Recovery, Environmental Sustainability

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تقنيات تحويل النفايات إلى طاقة: الاتجاهات العالمية، التحديات، والفرص لتحقيق التنمية المستدامة"

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قسم الهندسة المدنية , كلية الهندسة / جامعة بغداد

المستخلص

أصبح يشكِّل تراكم النفايات الصلبة البلدية(MSW) تحديًا ملحًا على المستويين البيئي والصحي، لا سيما في الدول النامية مثل العراق، حيث تشارف مواقع الطمر الصحي على الامتلاء، وتظل أنظمة إدارة النفايات المؤسسية في طور التطور. في الوقت ذاته، يؤدّي تصاعد الطلب على الطاقة إلى خلق تحدٍ مزدوج أمام تحقيق الاستدامة. تستند هذه الدراسة إلى فرضية مفادها أن تقنيات تحويل النفايات إلى طاقة (WtE)يمكن أن تقدم حلاً جزئياً لكل من أزمة تراكم النفايات ونقص الطاقة.

يتمثَّل الهدف الرئيس لهذه الدراسة في تقييم تقنيات WtE على المستوى العالمي، واستخلاص الدروس المستفادة من التجارب الدولية الناجحة، وتحديد مدى قابليتها للتطبيق في السياق العراقي. وتتناول الدراسة عدة تقنيات مستخدمة في هذا المجال، منها الحرق، والتغوير، والهضم اللاهوائي، والتقاط غازات المكبات، مع التركيز على الفوائد البيئية والاقتصادية التي توفرها.

تُقدّم دراسات الحالة من بلدان مثل الصين وألمانيا والسويد واليابان رؤى قيّمة بشأن الأطر التنظيمية الفعالة، واستراتيجيات تقاسم المخاطر المتوازنة، وآليات إشراك المجتمع المحلي. وفي المقابل، يواجه العراق تحديات كبيرة، منها التباين في تركيب النفايات، والفجوات التشريعية، وضعف الموارد المالية.

وتُبرز نتائج الدراسة الحاجة إلى إصلاحات سياسية شاملة، وآليات تمويل مستدامة، وتعزيز القدرات المؤسسية، وتفعيل الشراكات بين القطاعين العام والخاص، لضمان التنفيذ الناجح لتقنيات WtE في العراق. وتُعدُّ هذه التدابير ضرورية لوضع WtE كمسار عملي نحو الاستدامة البيئية وتعزيز أمن الطاقة على المدى الطويل.

الكلمات المفتاحية:

تحويل النفايات إلى طاقة، النفايات الصلبة البلدية، الطاقة المتجددة، إدارة النفايات، التنمية المستدامة، استعادة الطاقة، الاستدامة البيئية

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1- Introduction to Waste-to-Energy (WtE)

Contemporary society faces a significant demand for energy, as each technological advancement relies on consistent energy supply. For many years, the primary sources of energy have depended largely on limited, non-renewable fossil fuels. The excessive consumption of these fossil fuels in the past has resulted in severe consequences, including the depletion of the ozone layer, environmental degradation, air pollution, global warming, and deforestation. As the global population continues to rise and the demand for energy for everyday activities escalates, the world is suffering from pollution and climate change due to the unfair consumption of fossil fuels. The environment must be protected from pollution and climate change.

Consequently, investigating clean and sustainable energy sources, including solar energy, hydropower, tidal energy, bioenergy, wind energy, and geothermal energy, is crucial for ensuring a sustainable future. A diverse array of stakeholders, encompassing global communities, governmental bodies, and individuals, expressed a keen interest in fostering a sustainable future. This future hinges on leveraging technologies cultivated over recent decades to transition from hydrocarbon-based fuels to renewable energy sources. Among various renewable energy resources, such as solar, wind, tidal energy, and fuel cells, utilising waste for energy production presents a cost-effective strategy and offers a clean solution to the growing waste problem.(Gupta K. Ram & Nguyen .Tuan Anh, 2022)

"This study aims to evaluate global Waste-to-Energy (WtE) technologies, extract lessons from international best practices, and assess the relevance and challenges of implementing WtE in Iraq to support its waste and energy sectors."

1.1Definition and Overview of WtE

Waste-to-Energy (WtE), often known as energy-from-waste, is a sophisticated technology in the realm of renewable energy. The trash that is not utilised nor recycled is converted into energy, appearing as heat, steam, or electricity. The produced power is incorporated into the system and then allocated to residences, industries, and communities, among others. Consequently, trash-to-Energy (WtE) offers a financially sustainable and hygienic solution for the management of residual trash, reducing its volume by 90%. Waste-to-Energy (WtE) is crucial to achieving 100% renewable energy in the future, in conjunction with other renewable sources. **(Namrata Joshi, 2015)**

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The combustion process is widely recognised as the leading and most substantiated waste-to-energy (WTE) technology, boasting more than 2000 operational plants and references worldwide. Globally, waste-to-energy (WTE) facilities handle more than 250 million tonnes annually. According to projections from the International Solid Waste Association and the United Nations Environment Program, this capacity is expected to rise by 500% over the next decade, as many developing nations implement WTE technology to greatly reduce their reliance on landfills and dumpsites. In densely populated metropolitan areas like Paris, Frankfurt, Lisbon, Turin, Vienna, Copenhagen, Seoul, Shanghai, Beijing, and Tokyo, waste-to-energy plants that employ combustion processes are frequently situated close to city centres and comply with strict environmental regulations concerning maximum allowable limits.
These WTE plants offer a comprehensive solution, enhancing cutting-edge sustainable waste management for municipal solid waste (MSW) treatment while concurrently generating electricity and district heating/cooling.**(Efstratios N. Kalogirou, 2018)**

1.2Historical Development of WtE Technology

The history of Waste-to-Energy (WtE) can be traced back to the late 19th century when urbanization and industrialization began creating significant waste management challenges. Here's a summary of its beginnings and evolution:

- **Early Beginnings**

Incineration in the Late 1800s:
The initial waste-to-energy incinerator was constructed in Nottingham, England, in the year 1874. Referred to as a "destructor," this device was engineered to minimise the volume of municipal solid waste (MSW).
This approach became widely adopted in Europe and the United States as urban areas looked for solutions to handle rising waste levels while tackling public health issues associated with open dumping.

- **Energy Recovery in the Early 20th Century:**

In the early 1900s, certain incinerators started to integrate heat recovery systems aimed at producing steam for heating or industrial applications.
Zschornewitz**, Germany, built the first WtE plant to recover energy in 1928, pioneering the integration of waste disposal and energy generation.(Brisson, 1996)**

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- **Post-World War II Expansion**

Environmental Awareness and Technological Improvements:
After World War II, industrial growth led to increased waste production. Incineration technology improved to include better air pollution control systems.
The 1970s energy crisis spurred interest in recovering energy from waste as an alternative energy source.
Regulatory Development:
Governments began implementing regulations to reduce emissions and improve the efficiency of WtE plants. For instance, the Clean Air Act in the U.S. introduced stricter air pollution standards.

- **Modern WtE Industry**

Shift to Advanced Technologies:
Modern WtE plants utilize advanced technologies like mass burn incineration, gasification, and anaerobic digestion.
These technologies aim to maximize energy recovery while minimizing environmental impacts. (Brisson, 1996)

2 Types of Waste-to-Energy Technologies (e.g., incineration, gasification, anaerobic digestion)

There are five waste-to-energy (WtE) processes at the municipal level: incineration, co-processing, anaerobic digestion (AD), landfill gas (LFG), and pyrolysis/gasification (sometimes referred to as alternative technologies). These five technologies possess distinct roles and uses within the municipal waste management system. The sequence of technologies is determined by the anticipated need for guidance on them and does not suggest any hierarchy or relevance. Each method is accompanied by technical background material, a list of appropriate waste kinds, and a description of pertinent operational, environmental, legal, and economical considerations. In the following section, we will acquire a fundamental comprehension of the technology most suitable for each waste stream and its ecological implications.(Dieter Mutz, 2017)

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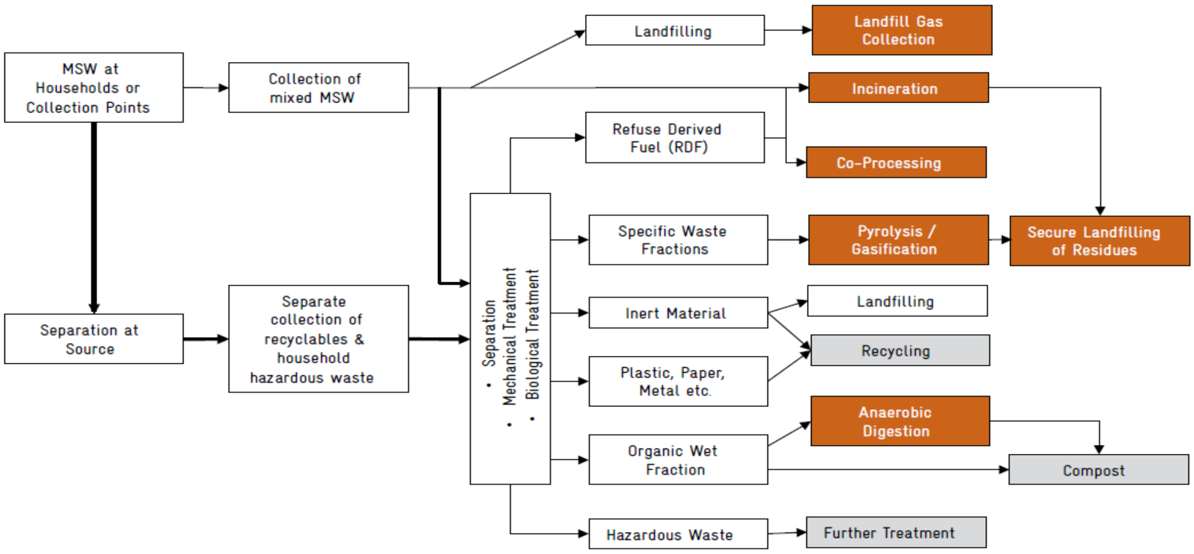

(Figure 1) Overview of MSW material flow and its different utilization and treatment options.(Dieter Mutz, 2017)

2.1Municipal Solid Waste Incineration (MSWI)

Municipal Solid Waste Incineration (MSWI) refers to the controlled combustion of municipal waste in specially designed facilities aimed at reducing waste volume and mass while rendering it chemically inert. MSWI typically achieves autothermic combustion, eliminating the need for additional fuel once ignition is achieved. Besides significantly minimizing waste volume, MSWI facilities enable energy recovery, mineral extraction, and metal recovery from the waste stream. However, incineration results in approximately 25% residual matter, comprising bottom ash and fly ash. Bottom ash consists of heavier particles that settle during combustion, whereas fly ash, composed of finer particulates, is carried with the exhaust gases and requires removal via advanced flue gas treatment systems. These residues, especially fly ash due to its hazardous nature, demand special handling and secure disposal(Joseph et al., 2018) .

2.2Co-Processing

Co-processing involves the substitution of natural raw materials and fossil fuels with waste-derived materials in industrial processes, particularly within the cement and thermal power industries. In co-processing, waste materials contribute both as alternative fuels and raw material inputs, thereby achieving both material recycling and energy recovery. Co-processing is widespread in the European cement industry, where some facilities report thermal substitution rates as high as 80%, with the European Union average around 39%. Although co-processing predominantly utilizes special waste streams such as used tires, industrial hazardous waste, contaminated soils, and sewage sludge, the share of municipal solid waste (MSW) remains comparatively low. Co-processing not only helps manage waste sustainably but also reduces carbon emissions by replacing traditional fossil fuels (Favier et al., 2018).

2.3Anaerobic Digestion for Biogas Production

Anaerobic digestion (AD) is a biological process where microorganisms break down organic matter in an oxygen-free environment, resulting in the production of biogas and a nutrient-rich digestate. Conducted within sealed, gas-tight reactors known as anaerobic digesters, the process converts organic waste into a combustible gas rich in methane (typically 50–75% methane depending on conditions) and a solid-liquid residue suitable for agricultural use as fertilizer if feedstock contamination is avoided. Biogas generated through AD can be used directly for electricity and heat generation or upgraded to biomethane. While AD is successfully deployed at small scales in rural areas, particularly using agricultural waste, its application to heterogeneous municipal solid waste presents operational and economic challenges due to contamination issues. As such, successful deployment requires strict source separation of organic waste fractions(Deublein & Steinhauser, 2009)(Ziad et al., 2014).

2.4Capturing of Landfill Gas

Landfill Gas (LFG) Capture is a crucial mitigation strategy in the management of sanitary landfills, focusing on the recovery of methane generated through the anaerobic decomposition of organic waste within landfill bodies. Methane, a potent greenhouse gas, is typically produced in substantial quantities in landfill environments, effectively transforming landfills into uncontrolled bioreactors. Capturing and utilizing LFG not only reduces greenhouse gas emissions but also enables energy recovery through the combustion of collected methane. Nevertheless, achieving high capture efficiency is challenging, especially during the early phases of landfill operation, and not all emitted gases can be recovered even when gas collection systems are fully operational(Dieter Mutz, 2017) .

2.5Alternative Technologies: Pyrolysis and Gasification

Alternative thermal technologies, notably pyrolysis and gasification, have been developed as advanced methods for the thermal treatment of waste. Pyrolysis involves decomposing waste at high temperatures in the absence of oxygen, resulting in the production of syngas, oil, and char, while gasification involves partial oxidation of waste to produce syngas. Initially developed in the 1970s and 1980s with strong innovation potential, these technologies were later promoted as "non-polluting" alternatives to incineration during the 1990s. However, commercial-scale application remains limited due to the complexities of operation, stringent waste feed requirements, and high capital costs. (Dieter Mutz, 2017) .

3 Drivers for Waste-to-Energy Adoption

The adoption of Waste-to-Energy (WtE) technologies is driven by a confluence of factors, including the escalating challenges of waste management, the increasing global demand for energy, and the environmental advantages offered by this sustainable approach. This section explores it.

3.1Growing Waste Management Challenges

The trend of urbanisation has accelerated the global waste management crisis because rapid population growth and industrialisation lead to unprecedented levels of waste production. The World Bank has predicted that global waste will increase by 70% by 2050; the urban areas will be the major drivers. For example, New York and Beijing are among those urban centers where tens of thousands of tonnes of municipal waste is produced per day. This gives a pressing need for sustainable waste management strategies. Among these solutions are Waste-to-Energy technologies, which can convert waste into energy and thus alleviate the pressure from the conventional forms of waste management.

In many cities, dumps are getting very close to being full which gives a lot of problems for the environment and how to deal with things logistically. For example, Singapore is a small state with not much land, so it puts a lot of focus on building places that can turn waste into energy like the Tuas Nexus Integrated Waste Management Facility. This place would cut down how much it has to use landfills while also making electricity, showing the two good sides of using waste to create energy. Also, dumps are very bad for the environment because the dirty water they create gets out and the methane they make gets into the air, showing why new ways to deal with trash are needed.(Hadi et al., 2024)(Nssaif Jassim Firas Thamer Hammoudi, 2023)

3.2Increasing Energy Demands

The global demand for energy is rising at a fast rate, driven by increased industrial activity and urbanization, along with persistent population growth. In these economies, energy consumption is on the rise very dramatically with betterment in their industrial sectors and also elevation among the middle class. This can be seen in developing countries where increasing numbers of urban residents are putting additional pressure on existing energy systems. The global demand for energy is rising at a fast rate, driven by increased industrial activity and urbanization, along with persistent population growth. In these economies, energy consumption is on the rise very dramatically with betterment in their industrial sectors and also elevation among the middle class. This can be seen in developing countries where increasing numbers of urban residents are putting additional pressure on existing energy systems. (Dieter Mutz, 2017)(Jichi, 2025)

In Nigeria, projections show that electricity demand is expected to increase sharply from 45,490 megawatts in 2020 to about 213,122 megawatts by 2040. This take place of a major increment underlines the requirement urgently for sustainable and diversified sources of energy to help meet the increasing demands on cleaner methods and also promote environmental sustainability: Waste-to-Energy technologies.(Naworio, 2022)(Hadi et al., 2024)

Similarly, very brisk energy use in China's energy transition. It has been propelled by economic growth, technology advancement, and urbanization. This plan for China emphasizes the need for diversified sources and puts forward the integration of renewable and low-carbon energy including waste-to-energy for long-term energy security. (China's government report, 2024)(Williams et al., 2023a)

3.3Environmental Benefits of WtE (Reduced Emissions, Energy Recovery)

- **Reduced Emissions**

Waste-to-Energy technologies operate a key role in the minimization of emissions of greenhouse gases by taking wastes out of landfills. Because disposal wastes on site in controlled conditions much less contributes to methane—one of the most powerful greenhouse gases—than if there was decomposition in landfill beds, these installations indirectly help reduce global warming. For instance, Waste-to-Energy facilities in Denmark have achieved annual reductions of 600,000 tonnes of CO_2. Besides that, WtE plants have state-of-the-art emission control systems which means that the levels of air pollution are very low**.(Dieter Mutz, 2017)**

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- **Energy Recovery**

The ability for energy recovery comes out as one of the main advantages of WtE. Globally, waste-to-energy plants generate sufficient electricity to cater to more than 20 million households every year. An important example is the Shinagawa Incineration Plant in Tokyo, Japan. This plant mixes waste treatment with energy making a big contribution to the city's energy mix.(Asian Development Bank, 2020)

- **Reduction in Land Pollution**

By reducing the amount of waste going to landfill up to 90%, WtE reduces the environmental risks from landfilling soils and ground water contaminations. The Keppel Seghers WtE plant in China has attained an outstanding 95% diminishment of waste volume efectively reducing ecological impacts with disposal of wastes**.(Efstratios N. Kalogirou, 2018)**

4 Global Perspectives on WtE Projects

With the increasing requirement to address the issues of waste management and energy supply, WtE technologies become acknowledged all over the world as a practicable and sustainable alternative. Countries across the globe have already adopted WtE projects, adjusting them to their environmental, economic, and regulatory conditions. The major lessons from global experiences are that there exist successful approaches, appropriate technologies, and typical pitfalls of implementing WtE. This section highlights how top nations have included WtE in their systems for managing wastes as well as their energy policies — lessons that can drive future efforts particularly in developing countries. (Asian Development Bank, 2020)

4.1Leading Countries in WtE Adoption

A few nations have shown global guidance in the embracement and advancement of WtE technologies. These countries have adopted creative ways along with strong rules creating frameworks utilizing their entire societies; this maximizes benefits making them examples for others to follow**.**

4.1.1 China

Having surpassed major benchmarks in both capacity and technical innovation, China has become a worldwide leader in waste-to- energy (WtE) acceptance. The nation's commitment to address its waste management problem and growing urbanisation have helped it to become front and front in WTE application. China has achieved a Guinness World Record for the largest Waste-to-Energy facility, the Shenzhen East Waste-to-Energy facility, underscoring its dedication to sustainable development.

Situated in Guangdong Province, this plant generates around 168 million kWh of electricity annually, enough to run hundreds of thousands of houses from processing over 5,000 tons of municipal solid waste daily.

Modern incineration and emissions control technologies are used at the site to guarantee compliance with worldwide environmental criteria.

Design and Integration: The building not only shows effectiveness but also includes artistic architectural ideas, therefore producing a visually stunning monument.

With about 400 waste-to----energy plants managing more than 100 million tonnes of waste annually, China

Initiatives like the 13th Five-Year Plan, which gives renewable energy generation and environmental preservation top priority, clearly show the government's will to reduce dependency on landfills and solve urban garbage problems.

China's approach on waste-to---energy emphasizes the great influence government support and large expenditures may have in turning trash into a useful resource. The success of the Shenzhen East Plant set a global benchmark that inspires other nations to apply like-minded policies.

China's development in waste-to---energy projects shows a workable strategy for nations to handle urban garbage problems while guaranteeing energy security and advancing sustainability. China has changed the purpose of waste-to-- energy in modern waste management systems by means of the combination of technical developments and favourable policies**.**(China’s government report, 2024)(Asian Development Bank, 2020)

4.1.2 Germany

Driven by its commitment to sustainability and circular economy ideas, Germany is often considered as a leader in waste-to- energy (WtE) application. Processing roughly 26 million tons of municipal solid trash annually, the country runs more than 96 waste-to- electricity plants, These facilities produce in excess of 13 terawatt-hours (TWh) of energy, sufficient to supply power to millions of residences.

Germany's stringent waste management legislation, particularly the Landfill Directive, have markedly decreased landfill reliance to below 1% of total trash.

The use of modern technology guarantees adherence to the European Union's rigorous emission requirements.
Germany’s model has demonstrated how efficient WtE systems can complement recycling efforts, ensuring minimal waste leakage into landfills while contributing to national energy needs. (Laureti et al., 2024)

4.1.3 Sweden

Sweden exemplifies how WtE can transform a country’s energy and waste management landscape. The country processes nearly 50% of its municipal solid waste through WtE facilities and imports about 1.5 million tons of waste annually from neighboring countries, such as Norway and the United Kingdom, to fuel its plants.
Sweden’s comprehensive waste hierarchy encourages waste minimization, recycling, and energy recovery.
Public awareness campaigns have fostered widespread acceptance of WtE as an environmentally friendly solution.
The energy produced from WtE facilities contributes significantly to Sweden's district heating systems, providing heat and electricity to millions of households while reducing greenhouse gas emissions.**(Sundqvist & Miljöinstitutet, 2017)**

4.1.4 Japan

Japan has leveraged WtE technologies to address its unique waste management challenges, including limited land availability and high population density. With over 1,000 WtE plants, Japan processes more than 70% of its municipal waste through incineration, recovering energy in the form of electricity and heat.
Japan’s regulatory framework mandates advanced emissions control technologies, ensuring minimal environmental impact.
Public-private partnerships have enabled consistent investment in innovative WtE solutions.
Facilities such as the Shinagawa Incineration Plant in Tokyo integrate cutting-edge technology, processing over 200,000 tons of waste annually and supplying energy to the city’s grid.
The experiences of Germany, Sweden, and Japan highlight the potential of WtE to address waste management challenges while contributing to national energy security and environmental sustainability. By adopting similar **strategies—such**

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as stringent regulations, public awareness initiatives, and advanced technologies—other countries can replicate their successes to achieve sustainable waste and energy management.(Katsuya Kawamoto, 2022)

4.2 Lessons Learned from Successful International Projects

There are many lessons learned from waste-to-energy (WtE) projects around the world that can help improve the implementation of future projects, especially in Iraq.

Here are some lessons learned from international experiences:

4.2.1 The importance of choosing an appropriate contractual model

Successful countries in waste-to-energy projects utilise public-private partnerships or BOOT contracts to specify risks and obligations. The experience in Singapore demonstrates that the implementation of PPP contracts effectively alleviates the financial strain on the government, while simultaneously leveraging the expertise and capabilities of the private sector.

4.2.2 Providing a clear legal and regulatory environment

The success of WtE projects in Germany is closely associated with the establishment of supportive legislation that fosters investment in this area, including measures to guarantee waste supply and maintain stable energy prices. The lack of robust legal frameworks in certain developing nations has resulted in project failures or delays, often stemming from legal disputes and shifts in government policies.

4.2.3 The need to secure waste flows to the plant

Many projects in China and India have failed due to the lack of sufficient quantities of waste that can be converted into energy, which has affected the financial viability of the project.
The successful solution in Denmark was to impose policies that reduce non-combustible waste and increase waste separation at the source to ensure efficient operation of the plant.

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4.2.4 Distributing risks between parties in a balanced manner

In Britain, contracts were designed so that the government bears part of the risks, such as changes in energy prices or lack of financing, while the investor bears the operational risks.
Some projects in the Maldives failed because the investor bore all the risks, which led to companies withdrawing after implementation began.

4.2.5 The importance of developing a sustainable financing strategy

In Japan, financing WtE projects relied on a combination of government loans and private sector investors, which contributed to the financial sustainability of the projects.
In contrast, projects that relied entirely on government financing were vulnerable to suspension in the event of financial crises.

4.2.6 Integrating modern technology to increase efficiency

Some projects in the United States used technologies such as smart emission control and integration with renewable energy sources to improve environmental and economic performance.
In some developing countries, the technology used has not been updated, which led to operational problems and increased costs.

4.2.7 Involving the local community to increase social acceptance

In Sweden, public awareness campaigns and community outreach have been key factors in the acceptance of WtE projects by the population.
In some countries, lack of community engagement has led to protests and closures of some plants due to environmental concerns. (Dieter Mutz, 2017)**(Rezania et al., 2023)**

4.2.8 Need for long-term post-project waste management plans

Some projects in France and South Korea have failed due to the lack of clear strategies for what will happen after the contract period ends, leading to problems in handing over the project to the government.

- Good legal and financial planning is key to the success of WtE projects.
- Securing waste supply is essential to ensuring the continuity of plant operation.
- A balanced distribution of risks makes projects more attractive to investors.

- Community engagement reduces resistance and increases the chances of success.

4.2.9 Summary of Lessons Learned from International WtE Projects

Table 2 prefer to International Lessons Learned from WtE Projects

No.	Lesson Learned	Successful Example	Failed Example	Key Takeaway
1	Choosing an appropriate contractual model	Singapore – PPP alleviated financial burden	–	PPPs and BOOT models clarify risk-sharing
2	Clear legal and regulatory environment	Germany – supportive laws ensured stability	Developing countries – legal uncertainty led to delays	Legal clarity attracts investors
3	Securing consistent waste supply	Denmark – policies ensured quality feedstock	India, China – projects failed due to insufficient waste	Guaranteed waste flow = financial viability
4	Balanced risk distribution	UK – shared risks increased project stability	Maldives – investors withdrew due to high risk	Balanced risk = investor confidence
5	Sustainable financing strategy	Japan – mix of public/private funds ensured stability	Government-only funding failed in crises	Mixed financing reduces financial vulnerability
6	Modern technology integration	US – smart tech enhanced efficiency	Developing countries – outdated tech raised costs	Advanced tech = lower emissions + better performance
7	Community engagement	Sweden – outreach increased acceptance	Some countries – protests led to shutdowns	Public trust is crucial
8	Post-project waste management plan	–	France, South Korea – unclear plans caused handover issues	Plan ahead for end-of-contract phase

These international insights underline the importance of strategic planning in legal, financial, and social dimensions when designing WtE projects, particularly for Iraq.

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4.3Common Challenges and Risks in WtE Implementation

The implementation of Waste-to-Energy (WtE) projects presents numerous challenges and risks that can significantly impact their success. These challenges can be categorized into technical, financial, environmental, regulatory, and social aspects.

4.3.1 Insufficient or Poor Waste Feedstock

- A major challenge is the **quantity and quality** of waste. Plants often require a guaranteed minimum volume of combustible waste to operate efficiently
- Poor segregation at source, high moisture content, or non-combustible materials can drastically reduce energy output(Williams et al., 2023b) .(Nassar et al., 2023)

4.3.2 High Capital and Operational Costs

- WtE plants require significant upfront investment. Operating costs can also be substantial, especially if high environmental standards are applied
- Financial risk increases if user fees (like tipping fees) or power purchase agreements (PPAs) are not well secured

(ESWET Organization, 2022) (Abdul Nasir et al., 2020). (UNEP REPORT, 2014).

4.3.3 Regulatory and Policy Uncertainty

- Many countries lack clear, stable regulatory frameworks for WtE, making project financing and operation risky
- Changing environmental regulations (e.g., stricter emission limits) can increase retrofit costs(ESWET Organization, 2022)

4.3.4 Public Opposition and Social Acceptance (NIMBY Effect)

- Communities often resist WtE plants due to fear of pollution, Odors, or impacts on property values
- Transparency and early stakeholder engagement are key to mitigating this risk.(Nurany et al., 2020)(Dieter Mutz, 2017)

4.3.5 Environmental Risks and Emissions Compliance

- Achieving low emissions (dioxins, NOx, heavy metals) demands advanced, costly technologies
- Non-compliance can lead to shutdowns, fines, or revocation of operating licenses.(ESWET Organization, 2022)

4.3.6 Technical Risks (Technology Failures)

- Poor technology selection or design mismatches to local waste streams can cause operational inefficiencies or plant failures.
- Risk is heightened if the technology is unproven in similar contexts (Xu et al., 2015) (Wheatcroft et al., 2021) (Wheatcroft et al., 2021)

4.3.7 Financing and Payment Risks

- Weak municipal creditworthiness threatens the timely payment of tipping fees or electricity bills
- Securing long-term reliable cash flows is essential to attract private investment(Loh Ah Tuan, 2016) (Abdul Nasir et al., 2020)

4.3.8 Political and Institutional Risks

- Changes in political leadership may alter priorities, cancel agreements, or delay approvals.
- Institutional fragmentation between waste and energy sectors also complicates coordination.(Williams et al., 2023a)

4.3.9 Waste Collection and Logistics Challenges

- Inefficient collection systems or high transportation costs can disrupt feedstock supply.
- Infrastructure gaps (roads, transfer stations) further complicate waste delivery.(Dieter Mutz, 2017)

4.3.10 Market Risks for Electricity or Byproducts

- If there is no guaranteed buyer for electricity or recyclable by products (e.g., bottom ash, metals), project revenue becomes uncertain.
- Competition from cheaper fossil fuel or renewable energy sources can also undermine WtE marketability.(China's government report, 2024)(Nassar et al., 2023)

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5 Contribution of WtE to Sustainable Development Goals (SDGs)

Waste-to-Energy (WtE) plays a vital role in advancing multiple Sustainable Development Goals (SDGs) by addressing environmental, social, and economic challenges. The primary SDGs impacted by WtE projects include:

5.1SDG 7 – Affordable and Clean Energy

WtE provides an alternative source of renewable energy by converting municipal solid waste (MSW) into electricity and heat.

It reduces dependence on fossil fuels and enhances energy security, especially in developing countries where energy access remains a challenge.

(ESWET Organization, 2022) ((Dieter Mutz, 2017)

5.2SDG 11 – Sustainable Cities and Communities

WtE facilities contribute to improved waste management practices, helping cities deal with rapidly increasing volumes of waste caused by urbanization (Dieter Mutz, 2017)

Proper waste disposal reduces open dumping and burning, improving urban air quality and public health (UNEP REPORT, 2014) **(Nurany et al., 2020)**

5.3**SDG 12 – Responsible Consumption and Production**

WtE technologies are part of an integrated waste management system that promotes waste minimization, resource recovery, and circular economy practices.

They provide a solution for non-recyclable waste fractions that cannot be reused or composted.(Dieter Mutz, 2017) **(Rezania et al., 2023)**

5.4**SDG 13 – Climate Action.**

By reducing the volume of waste sent to landfills, WtE lowers methane emissions, a potent greenhouse gas from organic waste decomposition.

It also helps in offsetting fossil fuel use by generating green energy, thus contributing to carbon footprint reduction (China’s government report, 2024)

5.5SDG 6 – Clean Water and Sanitation

Proper waste management through WtE plants reduces the risk of landfill leachate contamination in water bodies(UNEP REPORT, 2014).

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5.6SDG 8 – Decent Work and Economic Growth

The establishment and operation of WtE plants create job opportunities across sectors such as waste collection, transport, plant construction, operation, and maintenance.

WtE projects can stimulate green investments and promote the development of sustainable industries (ESWET Organization, 2022)

5.7 SDG 15 – Life on Land

Minimising landfilling and illegal dumping contributes to the protection of land ecosystems and biodiversity.
Waste-to-Energy should be approached with meticulous consideration: As highlighted in various case studies (e.g., Surabaya, Indonesia).
The effectiveness of waste-to-energy initiatives in advancing sustainable development goals relies on well-established regulatory frameworks, robust environmental protections, collaborative public-private partnerships, and active community involvement.
Environmental standards hold significant importance: It is essential to uphold stringent emission control standards to guarantee that waste-to-energy facilities do not add to air pollution.**(UNEP REPORT, 2014)**

6 Relevance of WtE to Iraq

Waste-to-Energy (WtE) technologies present a compelling solution to tackle Iraq's waste management issues while also meeting its energy needs. Transforming non-recyclable waste fractions into valuable energy sources can play a crucial role in enhancing environmental protection, improving public health, and fostering economic growth. Nonetheless, the effective implementation of WtE technologies requires a thorough understanding of Iraq's unique local context, encompassing waste characteristics, economic conditions, institutional readiness, and infrastructural constraints. This document delves into the existing waste management challenges in Iraq, examines the potential advantages of waste-to-energy solutions, and identifies the critical obstacles that need to be overcome for effective implementation.

6.1Current Waste Management Issues in Iraq

The rising levels of waste production in Iraq, alongside persistent energy deficits and environmental decline, have highlighted the critical necessity for

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sustainable approaches. As shown in Table (1), Iraq faces significant challenges in managing municipal solid waste. Although 90.9% of the urban population is served with waste collection services, only 64.1% of the total population benefits from such services at the national level. Additionally, the average waste generation per capita rose sharply to 2.5 kg/day in 2022, indicating an increasing burden on waste management infrastructure.

Table (1) Key Environmental Statistics Indicators for Iraq - Municipal Services Sector

Indicator	2018	2019	2020	2021	2022
Total number of municipal institutions	261	265	265	265	267
Percentage of population served with waste collection in urban areas (%)	88.8	88.7	89.9	90.7	90.9
Percentage of population served with waste collection in Iraq (%)	63.5	63.7	64.6	65.7	64.1
Quantity of collected waste (million tons/year)	18.1	17.3	19.7	17.4	11.9
Quantity of household waste collected (million tons/year)	9.6	10.6	10.6	11.8	11.2
Quantity of bulky/construction waste collected (million tons/year)	8.2	5.9	7.3	5.8	6.4
Average generated waste per capita (kg/day)	1.3	1.4	1.5	1.3	2.5
Quantity of hazardous waste collected (tons/year)	926.7	3218.7	1053	2052	2773
Percentage of recyclable waste from total collected (%)	53.1	61.1	60	64.3	63.4
Number of sanitary landfill sites with environmental approval	64	67	74	72	74
Number of non-sanitary landfill sites without environmental approval	149	157	146	149	149
Percentage of household waste disposed in non-approved landfill sites (%)	93.8	93.8	87.5	87.5	93.8

(Central Statistical Organization, 2023).

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Recent statistics indicate that the average waste generation rate in Baghdad has reached 2.5 kilograms per person per day. With a population estimated at nine million, this produces approximately 22,500 tons of municipal solid waste daily, equivalent to more than 8.2 million tons annually. This significant volume highlights the urgent need for a reliable and sustainable waste management system, including the development of waste-to-energy infrastructure. (Central Statistical Organization, 2023).

The most important thing that can be summarized from the above paragraph is:

- **Rapid urbanization** and population growth have significantly increased municipal solid waste (MSW) generation across Iraq's cities.
- **Open dumping** remains the dominant waste disposal method, leading to severe land, air, and water pollution.
- **Lack of modern landfill infrastructure** and inefficient waste collection systems result in waste accumulation in residential areas.
- **High organic content and moisture** in the waste stream (especially food waste) make traditional landfill-based waste disposal environmentally harmful.
- **Institutional and regulatory frameworks** for integrated waste management are fragmented and underdeveloped, with weak enforcement mechanisms
- **Uncontrolled burning of waste** is widespread, causing toxic air pollution and contributing to public health issues such as respiratory diseases.(Dieter Mutz, 2017)

6.2Growing Electricity Demand in Iraq and the Role of WtE

Iraq has witnessed a steady increase in electricity demand over recent years, driven by rapid population growth, urbanization, and the expansion of residential, commercial, and industrial sectors. According to Iraq's Central Statistical Organization (COSIT), national electricity generation rose from approximately 86 billion kWh in 2021 to 115 billion kWh in 2022, while the total electricity available within the grid (including imports and purchases) exceeded 139 billion kWh. The average per capita electricity supply also increased from 1.51 MWh/year in 2021 to 1.55 MWh/year in 2022. Broader energy consumption per capita—combining electricity, transportation, and industrial use—reached approximately 14,392 kWh in 2022, and is projected to exceed 15,300 kWh in 2023. (Central Statistical Organization, 2023).

This rapid increase poses serious pressure on Iraq's aging energy infrastructure and increases the need for diversified, sustainable energy sources. Waste-to-Energy (WtE) technologies can play a significant role in this context by converting non-recyclable waste fractions into electricity and heat, thereby:

- Reducing the burden on fossil-based power plants,
- Enhancing grid stability during peak demand,
- And supporting Iraq's goals for energy diversification and climate resilience.

Integrating WtE into Iraq's national waste and energy strategies not only supports better resource management but also contributes directly to global Sustainable Development Goals—particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action)—by enhancing renewable energy availability and reducing greenhouse gas emissions from both landfills and fossil fuels.

6.3Potential Benefits of Adopting WtE in Iraq

In recent years, Iraq has officially initiated its first large-scale Waste-to-Energy (WtE) project. According to the National Investment Commission, in collaboration with the Baghdad Municipality and the Ministries of Electricity and Environment, an international investment opportunity was announced for establishing a WtE power plant in Al-Nahrawan, Baghdad. The plant is planned to process approximately 3,000 tons of municipal solid waste per day using high-efficiency full incineration technology (fourth generation and above) with electricity generation efficiency above 30% and a landfilling rate below 5%.
The project will be developed under a Design, Build, Own, and Operate (DBOO) model. This marks a significant policy shift in Iraq's waste management strategy, aiming to reduce dependence on landfilling and adopt environmentally sound solutions aligned with sustainable development goal.(National Investment Commission. (2023)).

Projects of this type can contribute to many benefits, including:

Energy Generation: WtE can produce electricity and heat from non-recyclable waste, helping alleviate Iraq's chronic electricity shortages
Environmental Protection: Reducing reliance on open dumping and open burning would decrease greenhouse gas emissions, air pollutants, and contamination of land and water bodies
Public Health Improvement: Proper waste treatment would mitigate health risks associated with current waste practices.

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Economic Development: WtE projects can attract foreign investment, create green jobs, and stimulate local industries related to construction, operation, and maintenance.

Support Circular Economy: WtE fits into sustainable resource management strategies by treating residual waste after recycling and composting, supporting Iraq's environmental sustainability efforts.

Climate Change Mitigation: By recovering energy from waste and displacing fossil fuels, WtE supports Iraq's potential commitments to reducing carbon emissions under global agreements. **(Dieter Mutz, 2017)**(Rezania et al., 2023)

A previous study on waste in an Iraqi city (Ramadi) indicated that 11,304 kilowatt-hours of electricity could be generated, which could be used to serve approximately 5,500 people for a year.(Al-Rawi, 2013) Therefore, the potential benefits should be taken into account.

6.4Challenges Specific to Iraq

6.5

6.5.1 Waste Composition: Iraq's MSW has high moisture and organic content, which reduces its energy value, requiring either pre-treatment or specific technology choices (like anaerobic digestion or advanced thermal processes)

6.5.2 Capital Investment Needs: High initial investment and operational costs for WtE projects might be difficult to finance without international support or private sector involvement.

6.5.3 Lack of Waste Segregation: Absence of source-separated collection systems makes it harder to ensure consistent, energy-rich feedstock for WtE plant

6.5.4 Weak Institutional Framework: Successful WtE implementation requires strong regulatory, policy, and incentive structures, which currently remain underdeveloped in Iraq.

6.5.5 Electricity Market Challenges: Issues like low electricity tariffs, unstable grid infrastructure, and uncertain power purchase agreements may discourage private investment in WtE-based electricity generation.

6.5.6 Security and Stability Issues: Political and security instability can delay or disrupt large-scale infrastructure projects like WtE plants.

The implementation of Waste-to-Energy (WtE) technologies offers a significant opportunity for Iraq to tackle its escalating environmental, energy, and public health issues. Transforming non-recyclable waste into a valuable energy source presents an opportunity for Iraq to significantly decrease its dependence on

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landfills, improve urban environmental conditions, and bolster national energy security. Nonetheless, the effective execution of WtE projects in Iraq necessitates meticulous consideration of local waste characteristics, financial viability, regulatory advancement, and infrastructure enhancement. Moreover, incorporating WtE initiatives into comprehensive sustainable development strategies will be essential for achieving lasting success. To fully harness the potential of WtE in contributing to Iraq's sustainable future, it is crucial to focus on strategic planning, robust institutional support, and fostering international collaboration.

7 Conclusion

The transition toward Waste-to-Energy (WtE) technologies represents a critical step in addressing the intertwined challenges of waste management, energy scarcity, and environmental degradation. The global experiences analyzed demonstrate that WtE is not merely a waste treatment method but a strategic solution contributing to renewable energy production, climate change mitigation, and sustainable urban development.

Iraq, facing acute waste accumulation and chronic energy shortages, stands to benefit significantly from the adoption of WtE systems. By leveraging international best practices while tailoring solutions to its local context, Iraq can transform its waste into a valuable resource, reduce reliance on landfills, and move closer to achieving its sustainable development goals.

Nevertheless, the success of WtE initiatives in Iraq hinges on overcoming significant challenges, including waste stream quality, financing barriers, regulatory gaps, and infrastructural limitations. Strategic planning, strong public-private partnerships, institutional reforms, and community engagement will be essential to ensure the long-term viability and impact of WtE projects.

Overall, integrating WtE into Iraq's broader environmental and energy strategies offers a promising pathway to support sustainable development, economic resilience, and improved quality of life for its population

8 Recommendations

Based on the findings of this study and lessons learned from international case studies, the following recommendations are proposed to guide the successful adoption of waste-to-energy projects in Iraq:

- Develop a comprehensive national policy to regulate and incentivize waste-to-energy investments, while ensuring legal stability and alignment with sustainable development goals.

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- Adopt public-private partnership (PPP) or build-operate-transfer (BOOT) models to distribute financial and operational risks equally between the public sector and investors.
- Ensure reliable and segregated waste streams, with an emphasis on source separation and minimizing non-combustible materials, to improve the efficiency of waste-to-energy plants.
- Invest in modern and proven technologies with environmental control systems that meet international emission standards.
- Securing sustainable financing mechanisms that combine public funds, international aid, and private sector contributions to mitigate project impacts.
- Implement community engagement and awareness campaigns to address the "Not in My Backyard" (NIMBY) phenomenon and build public confidence.
- Develop long-term post-project waste management plans, including facility transfer strategies and post-contract maintenance protocols.
- Strengthening technical and institutional capacities through training programs and international cooperation in waste-to-energy project management and technology transfer.

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