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Policy Framework for Supporting Methanol Production from Municipal Solid Waste: A Global Perspective

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Abstract:- The increasing challenges posed by municipal solid waste (MSW) management and rising energy demands have prompted the need for innovative solutions that integrate waste-to-energy technologies. Methanol production from MSW presents a promising pathway for sustainable energy generation, combining environmental benefits with economic potential. This paper examines global policy frameworks and their effectiveness in supporting methanol production from MSW, focusing on key enablers such as financial incentives, regulatory mechanisms and technological advancements. Comparative analysis of policies across regions highlights the best practices and identifies barriers to widespread implementation. While developed nations benefit from robust waste management systems and advanced technologies, developing countries face challenges due to limited infrastructure and policy gaps. The study underscores the necessity of cohesive international collaborations, public-private partnerships and targeted policy interventions to promote methanol production as a viable energy solution. Recommendations include fostering innovation through research grants, implementing carbon credits and streamlining regulations to create conducive environments for waste-to-methanol conversion. This framework can significantly contribute to global sustainability goals by reducing greenhouse gas emissions, addressing waste management challenges and diversifying energy sources.

***Keywords**:- Methanol Production, Municipal Solid Waste, Policy Framework, Waste-to-Energy, Sustainable Energy.*

I. INTRODUCTION

Municipal solid waste (MSW) management has emerged as a critical global challenge due to the increasing volume of waste generated by urbanization, industrialization, and population growth. According to the World Bank, global MSW generation is expected to reach 3.4 billion tons annually by 2050, posing significant environmental and social risks if left unmanaged [1]. Amidst this crisis, the conversion of MSW into methanol offers a sustainable solution by integrating waste management with clean energy production. Methanol, a versatile and eco-friendly fuel, has applications in transportation, energy storage and chemical synthesis, making it an attractive alternative for addressing energy and environmental challenges [2,3].

Globally, waste-to-methanol technologies have gained attention for their dual benefits, mitigating waste-related environmental hazards and contributing to renewable energy goals. The process of methanol production from MSW involves thermal gasification or pyrolysis, followed by catalytic conversion of syngas (a mixture of CO and H_2) into methanol [4,5]. Countries such as Japan, the Netherlands, and Germany have pioneered initiatives in this field, supported by robust policy frameworks that integrate financial incentives, technological advancements, and waste management regulations [6,7]. However, in many regions, the lack of supportive policies, insufficient infrastructure and economic barriers hinder the widespread adoption of these technologies [8,9].

Policy frameworks play a pivotal role in promoting waste-to-methanol initiatives. Effective policies can facilitate research and development, reduce investment risks, and create market demand for methanol. For instance, subsidies, carbon credits, and tax exemptions have been instrumental in driving renewable energy projects in Europe and North America [10,11]. In contrast, developing nations face challenges such as poor waste segregation practices, limited funding, and policy gaps, which impede the implementation of waste-to-methanol technologies [12,13].

Recent studies have highlighted the importance of a coordinated global approach to waste-to-energy projects. Public-private partnerships, international collaborations, and policy harmonization are essential for overcoming technological and economic barriers [14,15]. Countries like China and India, with their vast MSW resources, have the potential to become leaders in methanol production if appropriate policies and infrastructure are developed [16,17]. Moreover, the integration of waste-to-methanol projects with carbon-neutral goals aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7

(Affordable and Clean Energy) and SDG 13 (Climate Action) [18,19].

This study explores the global policy landscape for methanol production from MSW, analyzing the best practices, challenges and opportunities for scaling up this technology. Through a comparative analysis of policy frameworks across different regions, we aim to identify key enablers and barriers to implementation. The paper also provides recommendations for developing comprehensive policies to support waste-to-methanol conversion, emphasizing the need for innovation, collaboration and sustainability.

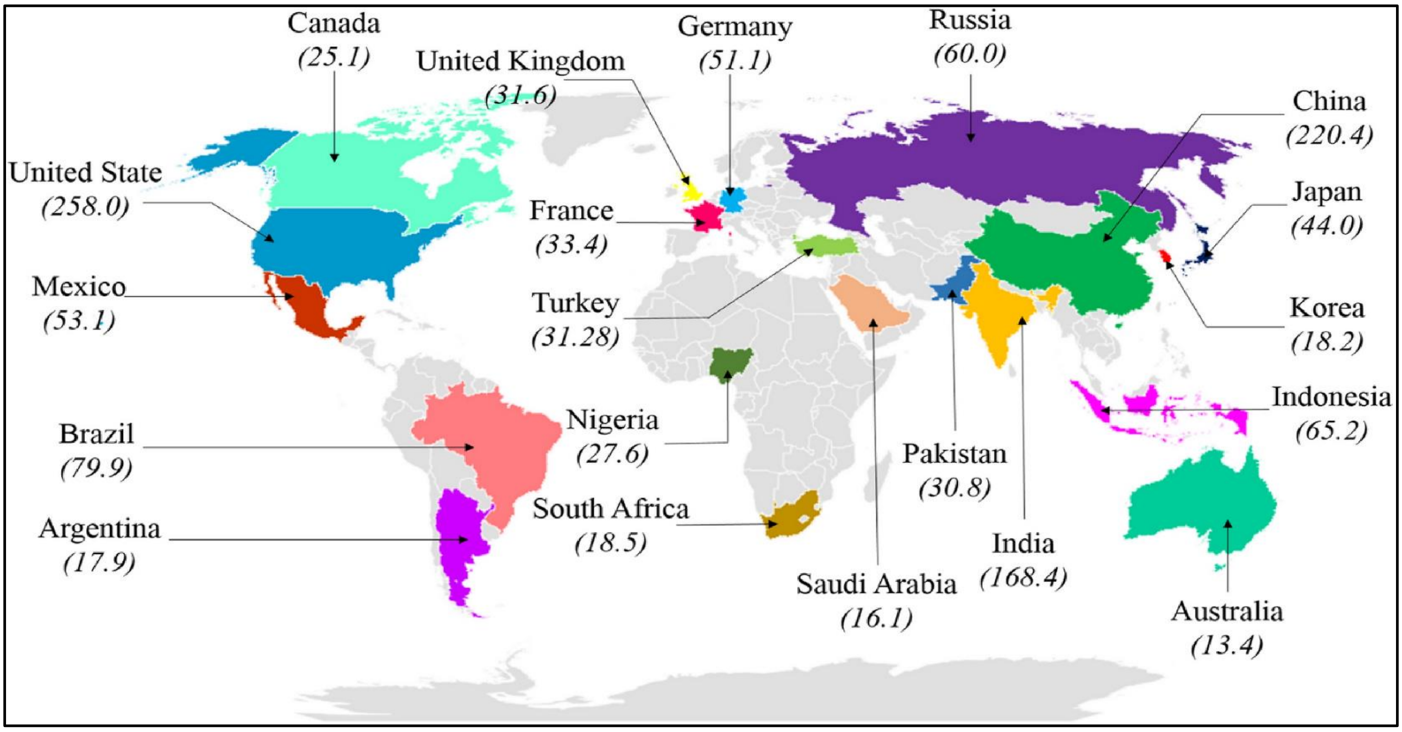


Fig 1 Major Waste-Producing Countries in the World (Data from World Bank [20])

II. LITERATURE REVIEW

The increasing volume of municipal solid waste (MSW) worldwide, coupled with the rising demand for clean energy alternatives, has positioned methanol production from MSW as a promising pathway for addressing both environmental and energy challenges. Methanol, known for its versatility as a fuel and chemical feedstock, can be synthesized from syngas (CO and H_2) produced via the gasification or pyrolysis of MSW. However, its successful adoption requires supportive policy frameworks to overcome economic, technological and infrastructural barriers.

➢ *Global MSW Management and Methanol Potential*

Municipal solid waste has become a critical environmental concern globally, with generation rates expected to rise to 3.4 billion tons annually by 2050 [1]. Developed countries such as the United States and members of the European Union have robust MSW management systems, which include recycling, composting, and waste-to-energy initiatives. For instance, the U.S. Environmental Protection Agency (EPA) emphasizes waste hierarchy strategies, incorporating energy recovery through gasification for advanced fuels like methanol [21,8]. Similarly, Europe's circular economy action plan highlights waste valorization, supporting methanol production as part of its decarbonization goals [22]. Table 1 illustrates composition of MSW in different countries along with its segregation among organic, plastics, paper, glass, metals and others to evaluate energy utilized from the waste.

Table 1 Composition of MSW in Various Regions/Countries

Region/Country	**Organic Waste (%)**	**Plastics (%)**	**Paper (%)**	**Glass (%)**	**Metal (%)**	**Others (%)**	**Reference**
United States	30-35	12-14	20-22	5-7	3-4	25-28	[21]
European Union	40-45	10-12	18-20	6-8	3-5	20-23	[23]
India	50-55	5-7	6-8	1-2	1-2	30-35	[24]
China	50-55	8-10	10-12	2-4	2-3	20-28	[25]
Middle East (UAE, KSA)	45-50	12-15	5-7	2-4	3-5	20-30	[26]
Sub-Saharan Africa	55-60	3-5	2-4	1-2	1-2	30-35	[27]
Japan	40-45	8-10	20-22	6-8	4-5	15-18	[28]

In contrast, developing nations face challenges such as limited waste segregation, inadequate infrastructure, and policy gaps, which hinder the efficient utilization of MSW for methanol production. India and China, despite their high waste generation rates, are beginning to explore waste-to-energy technologies through government incentives and public-private partnerships [24,25].

➢ *Key Policy Instruments Supporting Methanol Production*

- *Financial Incentives:*

Subsidies, grants, and tax exemptions are widely regarded as crucial enablers for methanol production from MSW. Countries like Germany and Japan offer financial support for waste-to-energy facilities, reducing the upfront costs associated with infrastructure development [4,29]. In China, subsidies for renewable energy projects have driven investments in gasification technologies [16].

- *Carbon Credits and Trading Mechanism :*

Methanol production from MSW contributes to greenhouse gas (GHG) mitigation by diverting waste from landfills and reducing CO_2 emissions. Policies that provide carbon credit for waste-to-energy projects incentivize industries to adopt these technologies. The European Union Emissions Trading System (EU ETS) is an example of such a mechanism [30,31].

- *Regulatory Standards:*

Effective policy frameworks must address technical and environmental standards for waste processing and methanol production. The U.S. Renewable Fuel Standard (RFS) includes methanol derived from renewable sources as an advanced biofuel, encouraging its adoption in the energy sector [13]. Similarly, Japan's Waste Management Law enforces stringent regulations to ensure environmental compliance [15].

- *Public-Private Partnerships (PPPs):*

Collaborations between governments and private entities have proven effective in scaling up waste-to-energy projects. The Indian government's Swachh Bharat Mission has supported PPPs for integrating MSW management with energy recovery [32,33].

- *Research and Development:*

Investments in R&D are essential for advancing gasification technologies and reducing the operational costs of methanol production. Policies offering research grants and collaboration opportunities between academic institutions and industries foster innovation in this area. The Netherlands, for instance, promotes research through its Top Sectors policy, focusing on sustainable energy and chemical innovations [7,35].

III. GASIFICATION AS AN ENERGY EFFICIENT STRATEGY

Gasification of municipal solid waste (MSW) offers a comprehensive solution that combines effective waste management with energy recovery. Extensive research has been conducted on the gasification of MSW and its blends to develop sustainable approaches. Numerous gasifier designs have been proposed to enhance the efficiency and effectiveness of the gasification process. Figure 2 illustrates the general gasification process for WTM along with the orientation of fluidised bed gasifier.

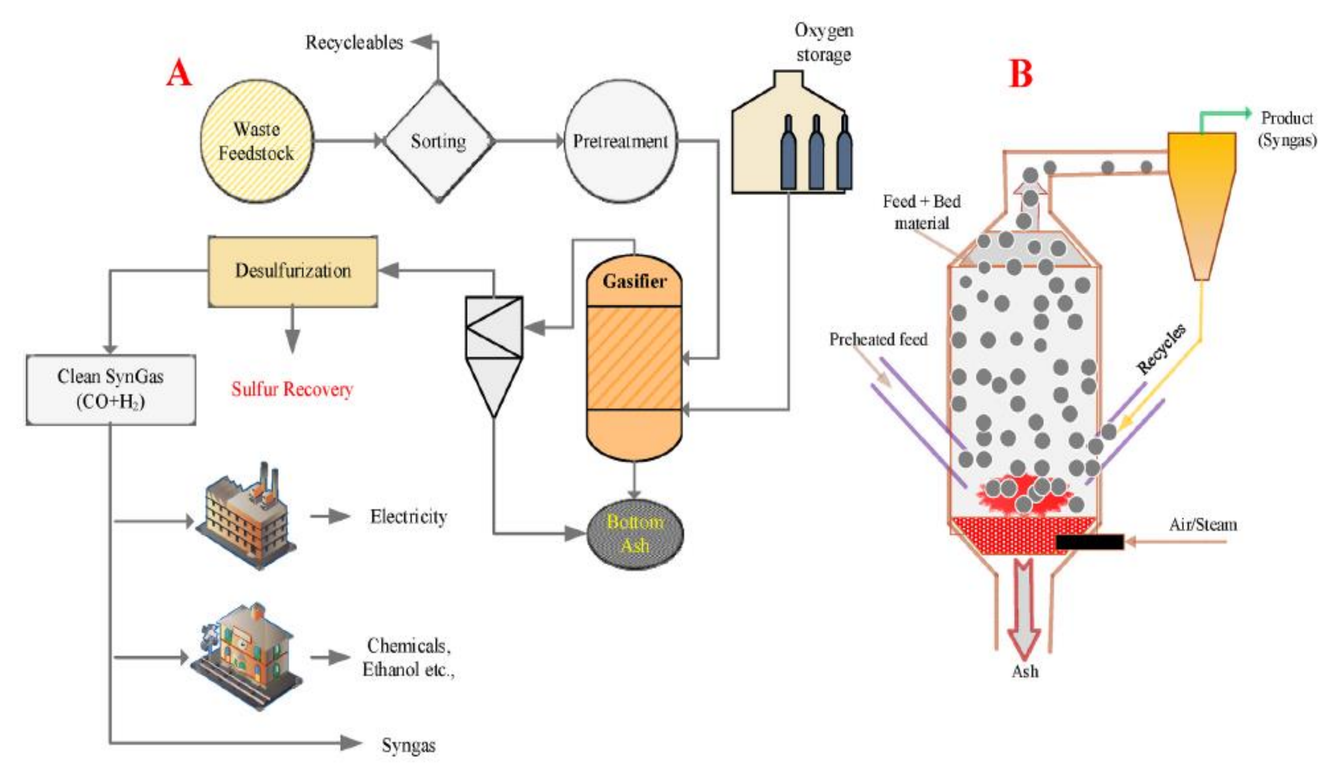


Fig 2 A. General Illustration of Gasifier Process B. Fluidised Bed Gasifier [38]

➢ *Co-Gasification of MSW: A Sustainable Approach to Methanol Production*

Co-gasification, a process that involves the simultaneous gasification of municipal solid waste (MSW) and another feedstock, has emerged as a promising technology for improving the efficiency of waste-to-energy systems. By combining MSW with materials such as biomass, coal, or industrial residues, co-gasification offers enhanced syngas quality, better feedstock utilization, and reduced environmental impact. This process leverages the complementary characteristics of the feedstocks, addressing the heterogeneity and variability of MSW while improving overall process efficiency.

The incorporation of biomass in co-gasification is particularly advantageous due to its renewable nature and higher volatile matter content. This combination enhances syngas production and its composition, yielding a mixture rich in hydrogen (H_2) and carbon monoxide (CO), which are essential precursors for methanol synthesis. Additionally, co-gasification with coal stabilizes the process by compensating for the inconsistent calorific value of MSW. Studies have shown that co-gasification can reduce tar formation and ash-related issues, leading to improved operational performance and lower maintenance costs.

Policy frameworks supporting co-gasification focus on integrating renewable and non-renewable feedstocks to achieve sustainability goals. Regions such as Europe and Japan have demonstrated the feasibility of co-gasification through initiatives emphasizing waste-to-energy technologies. These efforts align with broader environmental goals, including reducing landfill dependency and lowering greenhouse gas emissions [25,27].

In the context of methanol production, co-gasification presents a pathway for utilizing the diverse components of MSW efficiently. By optimizing feedstock combinations and leveraging advanced gasification technologies, this process can significantly contribute to sustainable energy systems. Establishing robust policies, such as financial incentives and technology transfer initiatives, is essential for scaling co-gasification as a viable solution for methanol production from MSW. Figure 3 shows how gasification is classified based on gasifying agent, medium , design and operating conditions different medium.

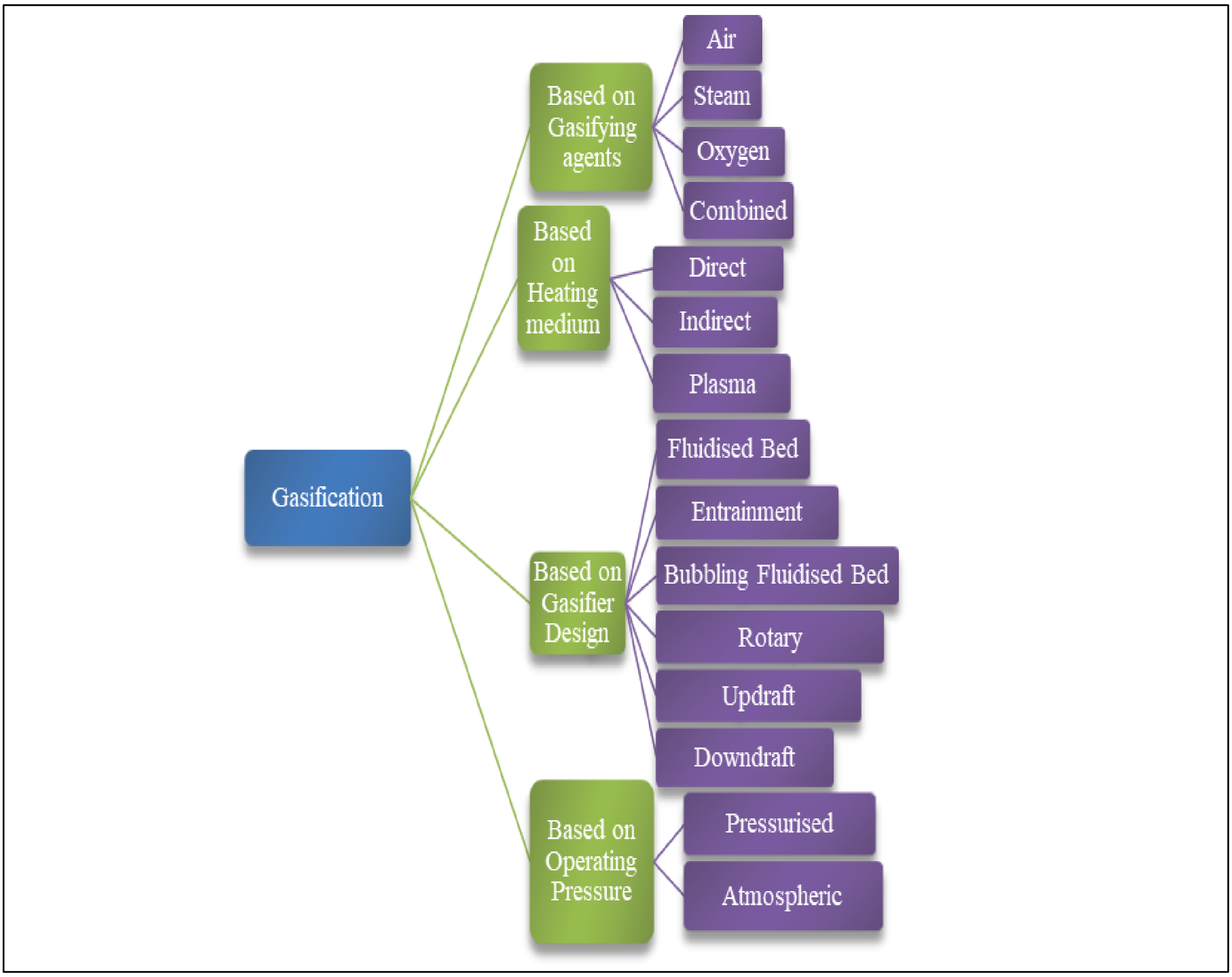


Fig 3 Types of Gasification

➢ *Key Highlights of Co-gasification of MSW:*

- *Feedstock Synergies:*

✓ MSW combined with biomass or agricultural residues offers improved syngas quality due to the high volatile content of these feedstocks.
✓ Coal acts as a stabilizing agent for MSW gasification, addressing its variability in calorific value.

- *Gasifier Types:*

✓ Fluidized bed gasifiers are widely used due to their flexibility in handling diverse feedstocks and high conversion efficiency.
✓ Plasma gasifiers provide superior tar reduction, making them ideal for syngas applications with stringent purity requirements.

- *Performance Metrics:*

✓ Cold Gas Efficiency (CGE) ranges from 65% to 85%, with higher efficiencies observed in plasma systems.
✓ Tar content varies significantly, with plasma gasifiers achieving the lowest values (<1 g/Nm³).

- *Operating Conditions:*

✓ Operating temperatures span 800-1,500°C, depending on the feedstock and gasifier type.
✓ Elevated pressures, such as those in entrained flow systems, facilitate higher syngas yields but require more advanced designs.

Table 2 Summary of Operating Conditions and Performances of Waste Co-Gasification Systems

Feedstock Combination	Gasifier Type	Temperature (°C)	Pressure (MPa)	Syngas Composition (H_2/CO)	Cold Gas Efficiency (CGE)	Tar Content (g/Nm³)	Reference
MSW + Biomass	Fluidized Bed	800-900	Atmospheric	1.2-1.5	75-80%	1-3	[4]
MSW + Coal	Fixed Bed	900-1,000	0.5-1.0	0.8-1.2	65-70%	3-5	[25]
MSW + Plastic Waste	Plasma Gasifier	1,200-1,500	Atmospheric	1.5-2.0	80-85%	<1	[39]
MSW + Sewage Sludge	Entrained Flow	1,000-1,200	2.0-3.0	1.0-1.3	70-75%	2-4	[40]
MSW + Agricultural Residues	Bubbling Fluidized Bed	850-950	Atmospheric	1.2-1.4	72-78%	1-2	[41]

IV. INNOVATIVE WASTE VALORIZATION PROCESS FOR METHANOL PRODUCTION

Proposed Process for Methanol Production from MSW is illustrated in Figure 4. All equipment’s legends are shown on left side. The process described that after being sun-dried and pretreated, the municipal solid waste (MSW) undergoes separation to remove metallic components using a magnetic separator. This widely applied technique utilizes either permanent magnets or electromagnets. Permanent magnets do not require an external power source, making them energy-efficient but with limited capacity. Electromagnets, in contrast, offer higher performance and flexibility but require electricity. The efficiency of metallic separation depends on the magnetic strength, conveyor belt width, and waste layer thickness. Stronger magnets and optimized belt design improve separation efficiency, ensuring high-quality feedstock for subsequent processes. The metallic-free MSW is then shredded in a hammer mill, where rotating hammers crush the material inside a high-speed chamber. Crushing occurs through repeated hammer impacts, collisions with the chamber walls, and particle-to-particle impacts. This reduces waste size to approximately 25 mm (1 inch), suitable for further processing. The shredded waste is transferred to a hopper designed to handle the volume of MSW and fitted with a screw conveyor. The conveyor operates at a calibrated speed to regulate MSW flow into the gasifier. The gasifier is a core component designed to convert MSW into synthesis gas (syngas). Operating at high temperature and low pressure, MSW enters at ambient temperature and is progressively dried as it moves through different temperature zones. In the presence of steam, the waste undergoes gasification, yielding syngas, tar and char. The char exits the gasifier through an auger conveyor, while the tar vaporizes due to high temperatures. A calcined dolomite catalyst bed decomposes tar, enhancing syngas quality.

The hot syngas, exiting the gasifier at high temperature, passes through a waste heat boiler to recover energy. A series of heat exchangers, including a superheater, evaporator, and economizer, utilize this energy to generate high-pressure steam. Approximately 90% of the energy from syngas is recovered, and the cooled syngas exits the boiler at relatively low temperature, ready for further purification. To remove particulates larger than 3 microns, the syngas is directed into a cyclone separator. Dirt and debris collect at the separator's base, while clean syngas exit from the top. This step achieves a separation efficiency of about 75%. The purified syngas is compressed using a centrifugal compressor. During this process, the gas temperature rises and the hydrogen (H_2) and carbon monoxide (CO) ratio of need to be optimized in this step for methanol synthesis in the reactor. The reactor operates with $Cu/ZnO/Al_2O_3$ catalysts under isothermal conditions. Methanol is synthesized by hydrogenating carbon oxides via an exothermic reaction. Cooling jackets maintain temperature stability, ensuring catalyst longevity and selectivity. Methanol yields exceed 99.6%, minimizing byproducts. The liquid methanol mixture undergoes partial separation in a flash drum at 50°C and 2 bar pressure. Volatile components, such as CO, CO_2, and H_2, are separated, while methanol and heavier components remain in the liquid phase. Crude methanol is fed into a distillation column, and methanol is concentrated in the vapor phase, with 99.2% pure methanol collected at the top as the primary product. The remaining liquid is refluxed into the column for further purification. The bottom product, primarily water with trace methanol, is discharged.

Figure 4 shows systematic process, integrating advanced thermal and catalytic technologies, ensures efficient MSW-to-methanol conversion with minimal environmental impact.

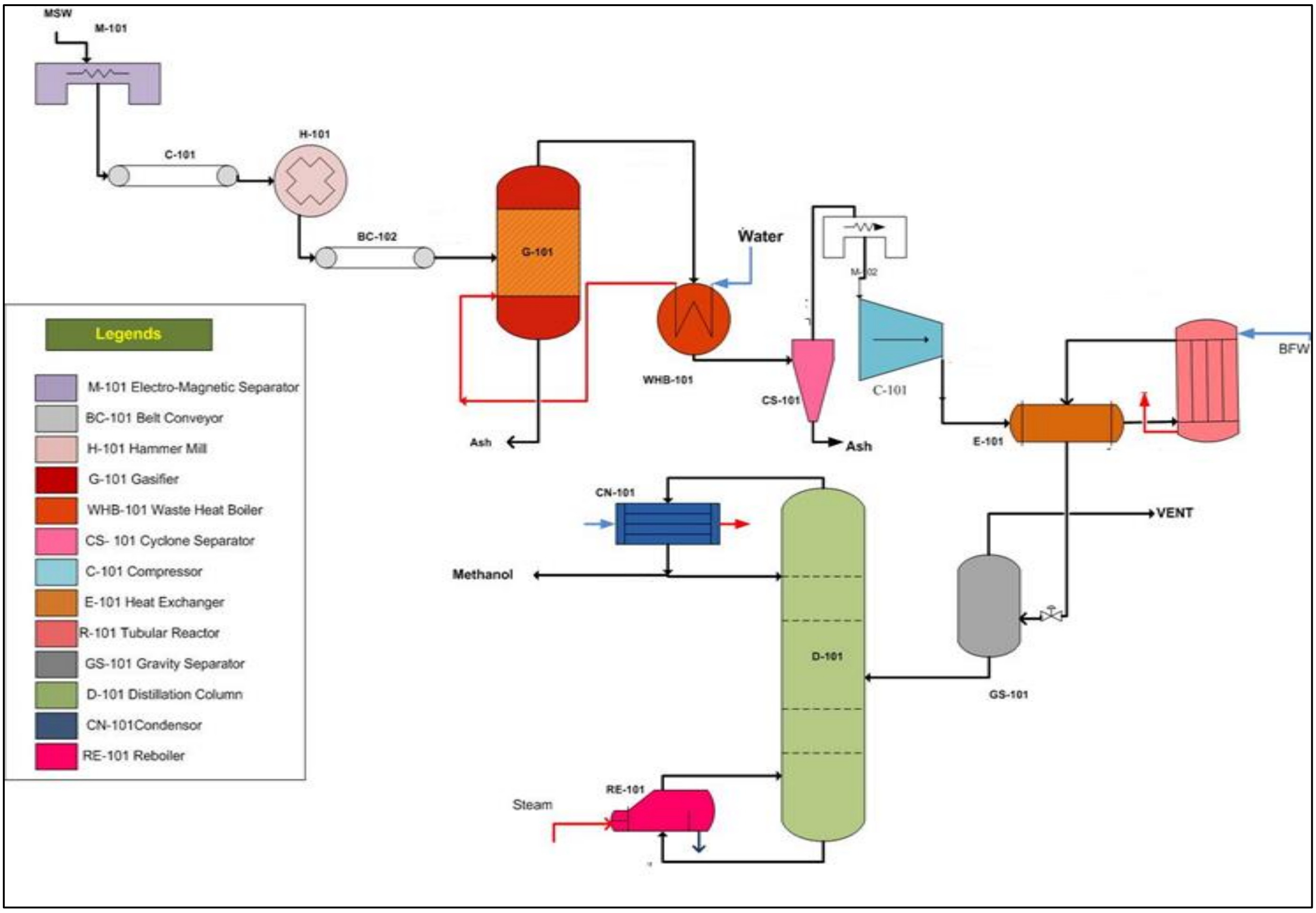


Fig 4 Waste to Methanol Process Overview

- *Economic and Environmental Benefits of Methanol Production from MSW*

Methanol production from municipal solid waste (MSW) offers significant economic and environmental advantages, making it a key solution for sustainable waste management and clean energy production. Economically, methanol serves as a versatile chemical feedstock and a valuable fuel for various industries, including transportation, power generation and manufacturing. Its production from MSW transforms waste liabilities into economic assets by reducing landfill dependency and creating revenue streams through methanol sales [10]. Additionally, advanced waste-to-energy systems can generate employment opportunities in waste collection, gasification plant operation, and methanol distribution networks, particularly in developing regions [26].

Environmentally, converting MSW to methanol aligns with global efforts to reduce greenhouse gas emissions and combat climate change. Gasification-based methanol production avoids the methane emissions typically associated with landfilling organic waste [13]. Furthermore, it minimizes air pollution compared to conventional incineration processes, as gasification systems can achieve higher thermal efficiencies with lower pollutant generation [24]. The process also supports circular economy principles by recovering valuable energy and reducing waste accumulation. For instance, the European Union's Circular Economy Action Plan highlights methanol production as a key strategy for achieving sustainable resource management [22].

To fully realize these benefits, policy frameworks must focus on promoting investment in waste-to-methanol technologies through subsidies, tax credits, and carbon trading systems. Integrating methanol production with municipal waste management policies can further enhance waste valorization efforts, contributing to energy security and environmental sustainability [25].

- *Cradle to Grave Life Cycle:*

A cradle-to-grave approach addresses the entire lifecycle of municipal solid waste (MSW), from its generation to final disposal, ensuring sustainability at every stage. Policies embracing this approach focus on waste segregation, advanced gasification methods, and methanol production to reduce environmental impact. Japan's Waste Management Law exemplifies such comprehensive strategies, promoting lifecycle-based waste valorization [29]. Similarly, the European Union's Circular Economy Action Plan integrates extended producer responsibility to minimize waste generation [22]. Implementing cradle-to-grave principles strengthens global policy frameworks, aligning methanol production from MSW with sustainability targets and significantly reducing greenhouse gas emissions [24].

V. ENHANCING POLICY FRAMEWORKS FOR METHANOL PRODUCTION FROM MUNICIPAL SOLID WASTE (MSW)

- *The Role of Comprehensive Policies in Scaling Methanol Production from MSW*

Municipal Solid Waste (MSW) management has evolved from being a basic sanitation service to a critical component of sustainable urban development. Methanol production from MSW is a transformative solution that addresses waste disposal challenges while contributing to energy sustainability. However, realizing its potential requires robust and integrated policy frameworks that address technical, financial, and environmental aspects.

A comprehensive policy framework must begin with efficient waste collection and segregation at the source. Countries like Japan and Sweden have demonstrated the importance of clear regulations and public awareness campaigns for successful waste segregation [22,29]. Policies promoting segregation improve the quality of feedstock for methanol production, enhancing process efficiency and yield. Additionally, financial mechanisms such as subsidies, tax credits, and grants can reduce the high capital costs of establishing methanol production facilities. For instance, the European Union (EU) incentivizes waste-to-energy projects through its Horizon 2020 program, encouraging technological innovation and investment in renewable fuels [42].

Moreover, carbon trading systems like the EU Emissions Trading System (ETS) have become essential tools for monetizing the environmental benefits of MSW-to-methanol conversion. These systems reward industries for reducing greenhouse gas emissions, making methanol production economically viable in the long run [31]. In developing nations, however, weak regulatory enforcement and infrastructure gaps limit the scalability of such initiatives. Strengthening public-private partnerships and providing access to international financing mechanisms are critical for overcoming these barriers [24].

Public policies must also align with international climate goals, such as the United Nations Sustainable Development Goals (SDGs). Methanol production from MSW supports SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by promoting renewable energy solutions and reducing carbon footprint [43]. Policies focused on cross-border collaborations, knowledge sharing, and technology transfer can further accelerate the adoption of this technology globally.

- *Integrating Methanol Production into Circular Economy Policies*

The integration of methanol production into circular economy strategies offers an innovative approach to waste valorization. Circular economy policies aim to minimize waste generation and maximize resource recovery, aligning perfectly with waste-to-methanol technologies. The European Commission’s Circular Economy Action Plan is a leading example, emphasizing waste reduction, material recycling, and energy recovery [10]. Methanol, as a clean-burning fuel and a precursor for various chemicals, provides a sustainable outlet for MSW, reducing landfill dependency and lowering environmental pollution [25].

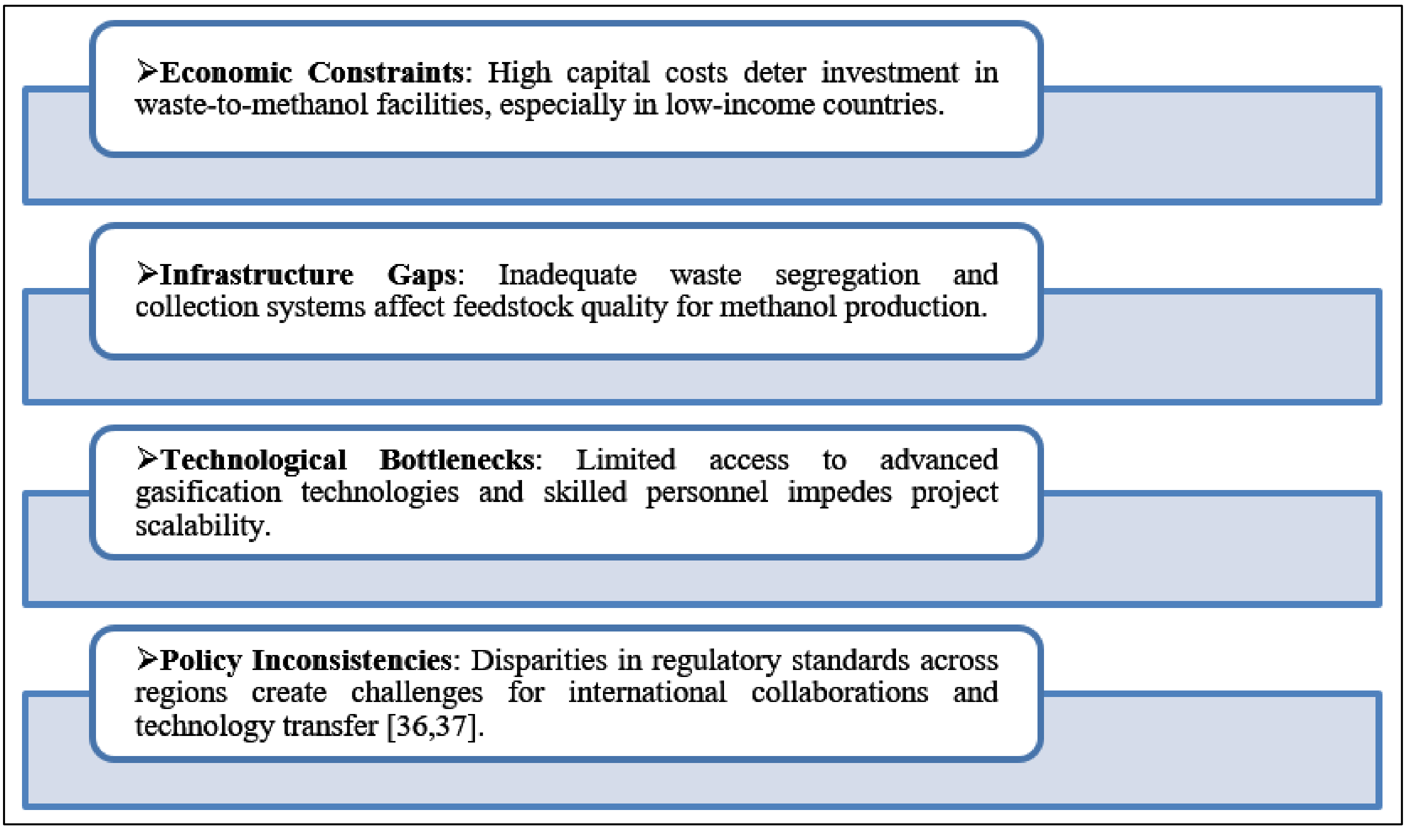
Economic instruments like extended producer responsibility (EPR) have proven effective in supporting circular economy initiatives. EPR policies require manufacturers to take responsibility for the disposal and recycling of their products, encouraging industries to adopt sustainable waste management practices [26]. These policies can be adapted to incentivize industries to collaborate with methanol production facilities, ensuring a steady supply of feedstock while reducing waste accumulation.

Furthermore, advancements in waste-to-energy technologies, including gasification and pyrolysis, have made methanol production from MSW more efficient and scalable. Policies must prioritize research and development (R&D) to optimize these processes. Countries like South Korea and Germany have invested heavily in R&D, resulting in improved gasification systems that yield higher-quality syngas [13]. Public funding for pilot projects and demonstration plants can accelerate the commercialization of these technologies, bridging the gap between laboratory research and industrial-scale applications.

Another critical policy consideration is the standardization of methanol production processes and product quality. International standards can facilitate trade and ensure that methanol derived from MSW meets the requirements for use in fuel applications and chemical industries. Collaborative efforts by organizations such as the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) can play a pivotal role in developing these standards [36,45].

- *Challenges in Policy Implementation*

While policy frameworks exist, their implementation often faces barriers such as:



- **Economic Constraints**: High capital costs deter investment in waste-to-methanol facilities, especially in low-income countries.
- **Infrastructure Gaps**: Inadequate waste segregation and collection systems affect feedstock quality for methanol production.
- **Technological Bottlenecks**: Limited access to advanced gasification technologies and skilled personnel impedes project scalability.
- **Policy Inconsistencies**: Disparities in regulatory standards across regions create challenges for international collaborations and technology transfer [36,37].

Fig 5 Challenges in Policy Implementation

Developing countries face unique barriers such as limited waste segregation infrastructure and inconsistent policy implementation. India's Swachh Bharat Mission and China's waste management initiatives highlight the potential for integrating MSW-to-methanol systems through public-private partnerships and financial subsidies [38,24]

VI. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

The development of a robust policy framework for methanol production from municipal solid waste (MSW) is essential for addressing global waste management challenges and advancing clean energy solutions [46]. Methanol production offers dual benefits: reducing landfill dependency and providing a sustainable alternative to fossil fuels. However, the successful implementation of this technology requires targeted policy interventions that address technical, economic and environmental barriers.

A key policy consideration is the establishment of incentives to promote investment in waste-to-methanol technologies. Financial support mechanisms, such as subsidies, tax exemptions and carbon credits, are critical for offsetting the high capital costs associated with gasification plants and methanol production facilities.

Another significant aspect of policy design is integrating methanol production into existing waste management systems. Policies must prioritize waste segregation at the source to ensure high-quality feedstock for gasification processes. Additionally, standards for gasifier design, syngas composition and methanol purity are necessary to streamline operations and promote international trade [23,30]. These standards can also enhance public confidence and attract private-sector participation.

In conclusion, a comprehensive policy framework must address the financial, technical, and environmental dimensions of methanol production from MSW. However, its success depends on the establishment of robust policy frameworks that integrate financial incentives, technological advancements, and international cooperation. By embedding methanol production within broader circular economy strategies and aligning policies with global climate goals, nations can create a sustainable pathway for waste valorization and renewable energy generation. A coordinated global approach, supported by investments in infrastructure, research and development, and capacity-building initiatives, will be essential for unlocking the full potential of methanol production from MSW.

RECOMMENDATIONS FOR FUTURE WORK

To advance the implementation of methanol production from municipal solid waste (MSW), future work should focus on optimizing technical processes, strengthening policy frameworks and enhancing public-private collaborations.

On the technical front, research should prioritize the development of cost-effective and efficient gasification technologies that can handle the heterogeneous nature of MSW. Innovations in catalyst design, particularly for tar reduction and syngas purification, are critical for improving methanol yield and quality. Pilot projects integrating advanced process controls and real-time monitoring systems will further aid in scaling up these technologies.

Policy initiatives must aim to harmonize global standards for gasification and methanol synthesis, enabling technology transfer and international trade. Introducing carbon credit mechanisms and renewable energy certificates can incentivize investment in waste-to-methanol projects. Additionally, education campaigns and waste segregation programs at the community level should be implemented to improve feedstock quality.

Collaboration between governments, industries and academic institutions is essential for bridging knowledge gaps. Joint ventures can facilitate the establishment of demonstration plants and foster innovation through shared expertise. Emphasis should also be placed on evaluating the environmental and economic impacts of these projects to ensure long-term sustainability.

By addressing these areas, methanol production from MSW can emerge as a transformative solution for global waste and energy challenges.

REFERENCES

[1]. World Bank. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. https://hdl.handle.net/10986/30317

[2]. Olah, G. A., Goeppert, A., & Prakash, G. K. S. (2011). Beyond Oil and Gas: The Methanol Economy. Wiley-VCH. https://doi.org/10.1002/anie.200462121

[3]. Boerrigter, H., & Rauch, R. (2006). Review of Applications of Biomass Gasification https://www.researchgate.net/publication/228622716

[4]. Arena, U. (2012). Process and Technological Aspects of Municipal Solid Waste Gasification: A Review. Waste Management https://doi:10.1016/j.wasman.2011.09.025

[5]. Bridgwater, A. V. (2003). Renewable Fuels and Chemicals by Thermal Processing of Biomass. Chemical Engineering Journal. https://doi:10.1016/S1385-8947(02)00142-0

[6]. Consonni, S., & Viganò, F. (2012). Waste Gasification vs. Conventional Waste-to-Energy: A Comparative Evaluation of Efficiency and Environmental Impact. Waste Management. https://doi:10.1016/j.wasman.2011.09.025

[7]. Basu, P. (2010). Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press. https://doi:10.1016/C2009-0-64825-8

[8]. Chen, D., Yin, L., Wang, H., & He, P. (2014). Pyrolysis Technologies for Municipal Solid Waste: A Review. Waste Management https://doi:10.1016j.wasman.2014.04.013

[9]. Arena, U., & Di Gregorio, F. (2014). Energy Recovery from Waste: A State-of-the-Art Review. Waste and Biomass Valorization. https://doi:10.1007/s12649-014-9357-7

[10]. Ellen MacArthur Foundation. (2019). Circular Economy in Action: Closing the Loop on Methanol. https://ellenmacarthurfoundation.org/resources/

[11]. European Commission. (2020). The Role of Renewable Fuels in Achieving Net-Zero Emissions by 2050. https://ec.europa.eu/research/

[12]. Kumar, S., et al. (2017). Challenges and Opportunities Associated with Waste-to-Energy Technologies. Renewable Energy. https://doi:10.1016/j.renene.2016.09.065

[13]. Hoornweg, D., & Bhada-Tata, P. (2012). What a Waste: A Global Review of Solid Waste Management. https://doi.org/10.1596/978-1-4648-1329-0

[14]. Rezaei, M., et al. (2015). Catalytic Conversion of Syngas to Methanol: A Review of Recent Developments. Renewable and Sustainable Energy Reviews. https://doi:10.1016/j.rser.2015.01.002

[15]. Malkow, T. (2004). Novel and Innovative Pyrolysis and Gasification Technologies for Energy Efficient and Environmentally Sound MSW Disposal. Waste Management. https://doi:10.1016/j.wasman.2004.02.018

[16]. Bai, M., et al. (2020). Methanol Economy in China: Current Practices and Future Perspectives. Energy Policy. https://doi:10.1016/j.enpol.2019.111257

[17]. Ducharme, A. (2021). India's Roadmap to Waste-to-Energy Projects. Journal of Clean Energy. https://doi:10.1016/j.jclepro.2020.124973

[18]. United Nations. (2015). Sustainable Development Goals. https://sdgs.un.org/goals

[19]. IEA (International Energy Agency). (2021). Global Energy Review: Tracking Sustainable Development. https://www.iea.org/reports/global-energy-review-2021

[20]. Yang Y, Liew RK, Tamothran AM, Foong SY, Yek PNY, Chia PW, et al. Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-020- 01177-5

[21]. EPA (2021). "Facts and Figures about Materials, Waste, and Recycling." https://www.epa.gov

[22]. European Commission. (2020). *Circular Economy Action Plan*. https://ec.europa.eu

[23]. Eurostat (2020). "Waste Statistics - Municipal Waste." https://ec.europa.eu/eurostat

[24]. Kumar, S., et al. (2022). *Waste-to-Energy Technologies in India: Challenges and Opportunities*. Renewable Energy. https://doi:10.1016/j.renene.2021.09.048

[25]. Zhang, Y., et al. (2020). "Municipal Solid Waste Management in China: Status and Challenges." Waste Management. https://doi:10.1016/j.wasman.2020.01.015

[26]. Al-Khatib, I. A., et al. (2021). "Solid Waste Management Trends in the Middle East." Environmental Monitoring and Assessment. https://doi:10.1007/s10661-020-08736-6

[27]. Hoornweg, D., & Bhada-Tata, P. (2012). *What a Waste: A Global Review of Solid Waste Management*. World Bank. https://doi:10.1596/978-1-4648-1329-0

[28]. Ministry of Environment Japan (2020). "Annual Report on the Environment in Japan." https://www.env.go.jp
[29]. Ministry of Environment Japan. (2020). Waste Management Policies in Japan. https://www.env.go.jp
[30]. Ellen MacArthur Foundation. (2019). The Role of Renewable Fuels in Decarbonization. https://ellenmacarthurfoundation.org
[31]. European Commission. (2021). EU Emissions Trading System (EU ETS). https://ec.europa.eu/clima/policies/ets_en
[32]. Government of India. (2021). Swachh Bharat Mission: Urban Framework. https://sbm.gov.in
[33]. Rezaei, M., et al. (2015). Catalytic Conversion of Syngas to Methanol: A Review. Renewable and Sustainable Energy Reviews. https://doi:10.1016/j.rser.2015.01.002
[34]. Basu, P. (2010). Biomass Gasification and Pyrolysis: Design and Theory. Academic Press. https://doi:10.1016/C2009-0-64825-8
[35]. Netherlands Government. (2020). Top Sectors Policy for Sustainable Innovation. https://www.government.nl
[36]. IEA (International Energy Agency). (2021). Global Energy Review. https://www.iea.org
[37]. UN Environment. (2018). *International Policies on Waste-to-Energy Technologies*. Retrieved from: https://www.unep.org
[38]. Sajid, M., et al. (2022). "Gasification of municipal solid waste: Progress, challenges, and prospects." Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2022.112815
[39]. Molino, A., et al. (2016). "Gasification of Plastic Waste as Waste-to-Energy or Waste-to-Syngas Recovery Route." Renewable and Sustainable Energy Reviews. https://doi:10.1016/j.rser.2016.01.006
[40]. Xie, Q., et al. (2014). "Co-Gasification of Municipal Solid Waste and Sewage Sludge in an Entrained Flow Gasifier." Bioresource Technology. https://doi:10.1016/j.biortech.2013.11.093
[41]. Kumar, S., et al. (2021). "Co-Gasification of Agricultural Residues and MSW: Insights and Challenges." Renewable Energy. https://doi:10.1016/j.renene.2021.03.001
[42]. European Commission. (2021). Horizon 2020 and Renewable Energy Investments. https://ec.europa.eu
[43]. United Nations. (2015). Sustainable Development Goals. https://sdgs.un.org/goals
[44]. Al-Khatib, I. A., et al. (2021). Solid Waste Management Trends in the Middle East. Environmental Monitoring and Assessment. https://doi:10.1007/s10661-020-08736-6
[45]. IRENA. (2020). The Role of Standards in Advancing Renewable Energy. https://www.irena.org
[46]. Ducharme, A. (2021). India's Roadmap to Waste-to-Energy Projects. Journal of Clean Energy. DOI: 10.1016/j.jclepro.2020.124973