Waste- and Refuse-Derived Fuels: Circular Energy Solutions from Waste Streams

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Abstract: This review explores the potential of waste-derived fuels (WDF) and refuse-derived fuels (RDF) as sustainable alternatives to conventional fossil fuels, addressing both energy recovery and waste management challenges. WDF and RDF are generated from diverse feedstocks—such as municipal solid waste (MSW), industrial by-products, and biomass—via mechanical, thermochemical, and biochemical processing. These fuels can be utilized in cement kilns, power plants, and industrial furnaces, contributing to reduced fossil fuel consumption. The manuscript classifies WDF and RDF into solid, liquid, and gaseous forms, examining their energy characteristics and combustion properties in comparison to coal, diesel, and natural gas. A detailed analysis of calorific value, moisture and ash content, and emissions profiles is provided to assess their performance. The environmental benefits, including decreased landfill usage, methane mitigation, and lower greenhouse gas emissions, are emphasized through life cycle assessments (LCA). Economic aspects such as production costs, energy substitution potential, and global market adoption trends are also discussed. Technological pathways including shredding, drying, gasification, pyrolysis, and anaerobic digestion are analyzed for their efficiency, capital investment requirements, and environmental impacts. The review also highlights current challenges—such as feedstock heterogeneity, emissions control, and public perception—and outlines future prospects enabled by technological advancements, regulatory support, and integration into circular economy frameworks. This comprehensive evaluation positions WDF and RDF as viable contributors to a low-carbon energy future, offering pathways for sustainable waste valorization and renewable energy generation.

Keywords: Waste-derived fuels (WDF), Refuse-derived fuels (RDF), Waste-to-energy (WTE), Energy recovery, Biofuels, Renewable fuels, Circular economy, Waste management.

1. INTRODUCTION

The rapid industrialization and urbanization of modern societies have led to a significant increase in waste generation, posing severe environmental and economic challenges. Traditional waste disposal methods, such as landfilling and open burning, contribute to pollution and greenhouse gas emissions while also wasting potential energy resources. In response, **waste-to-energy (WTE)** technologies have emerged as sustainable approaches for converting waste into usable energy forms such as electricity, heat, and fuels [1-3]. These technologies are increasingly integrated into waste management systems aimed at reducing landfill dependency and promoting resource efficiency [4, 5].

Among various WTE strategies, **Waste-Derived Fuels (WDF)** and **Refuse-Derived Fuels (RDF)** stand out as promising alternatives to fossil fuels. WDF encompasses fuels derived from municipal solid waste (MSW), industrial by-products, and biomass residues. RDF, a subset of WDF, refers to processed waste materials that undergo mechanical, thermal, or chemical treatment to enhance energy content and combustion efficiency [6-8]. RDF is optimized for use in cement kilns, industrial boilers, and power plants, thereby contributing to both energy recovery and waste diversion from landfills [9].

As illustrated in Figure **1**, the main WTE conversion pathways include mechanical pre-treatment, thermochemical processes (pyrolysis, gasification, incineration), and biochemical methods (anaerobic digestion, fermentation) [10, 11]. These technologies enable the transformation of heterogeneous waste streams into valuable fuel intermediates such as syngas, bio-oil, and methane. WDF and RDF offer significant environmental advantages over fossil fuels. The combustion of coal and petroleum releases high levels of CO, SO, NO_x, and particulates [12, 13]. In contrast, WDF and RDF—especially when derived from sorted waste—exhibit lower sulfur and ash content, and reduce methane emissions by diverting organics from landfills [14, 15]. Furthermore, WDF and RDF contribute to the **circular economy** by promoting resource efficiency, minimizing waste, and extending material lifecycles. This contrasts with the linear economy, which is based on extraction, use, and disposal [16]. By converting waste into fuels, these systems reduce raw material demand and the environmental burden of energy production.

Economically, WDF and RDF help industries reduce fuel costs and diversify energy sources. Their adoption is supported by regulatory incentives, tax benefits, and

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Received on 15-06-2025 Accepted on 20-07-2025 Published on 01-08-2025

E-ISSN: 2410-4701/25

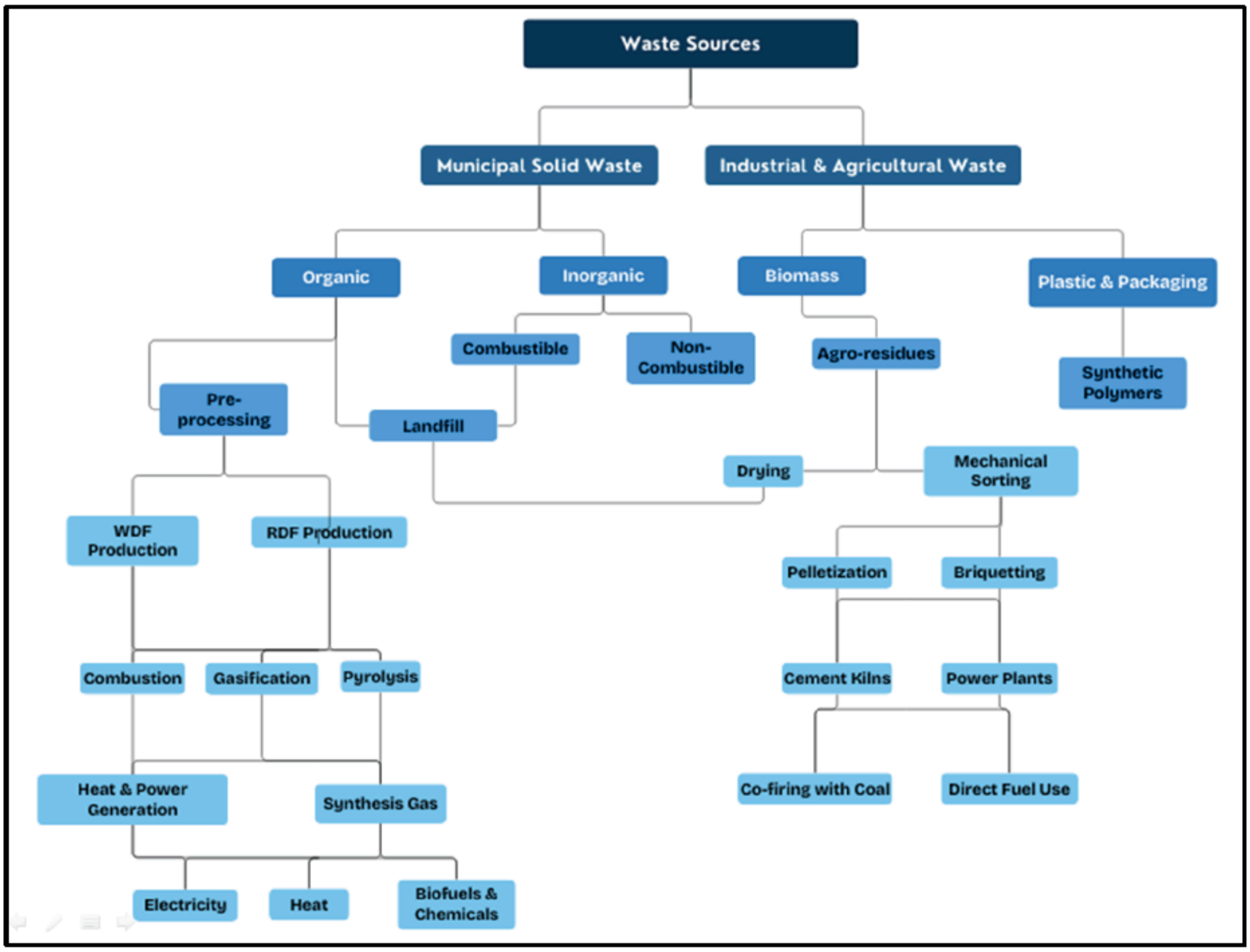

Figure 1: Schematic representation of waste-to-energy (WTE) conversion pathways, including mechanical, thermochemical, and biochemical routes. This diagram illustrates how various waste streams are transformed into waste-derived fuels (WDF) and refuse-derived fuels (RDF), supporting sustainable energy generation and landfill diversion.

renewable energy mandates. Notably, European countries have successfully integrated RDF in cement kilns and district heating, demonstrating its practical and policy-backed viability [17]. Despite their promise, challenges persist—particularly in terms of feedstock variability, inconsistent calorific value, and emissions control [18]. Investments in waste segregation, advanced processing technologies, and emissions treatment are essential. Innovations like AI-driven sorting and plasma gasification offer potential solutions, but require policy and financial support for industrial-scale deployment [19].

Objectives: This review offers a comprehensive analysis of WDF and RDF, focusing on classification, feedstocks, conversion technologies, energy performance, environmental benefits, economic viability, and regulatory context. It also outlines key challenges and future directions to enhance the scalability and impact of waste-derived fuels.

Structure: Section 2 classifies WDF and RDF by physical and chemical properties. Section 3 discusses feedstocks including MSW, industrial and agricultural waste. Section 4 details mechanical, thermochemical, and biochemical processing. Section 5 evaluates energy characteristics and industrial applications. Section 6 reviews environmental and economic aspects, while Section 7 addresses challenges and future directions. Section 8 concludes the manuscript with strategic recommendations. By presenting a consolidated assessment of WDF and RDF, this study contributes to ongoing efforts in sustainable waste valorization and low-carbon energy transitions. These fuels are poised to play a critical role in decarbonizing industries, reducing waste, and supporting circular economy goals. Table **1** provide comparative overview of waste-derived fuels (WDF and RDF) versus conventional fossil fuels in terms of calorific value, emissions, composition, availability, and environmental performance. This early comparison highlights the sustainability advantages and industrial relevance of WDF/RDF.

2. CLASSIFICATION OF WASTE-DERIVED FUELS

2.1. Types of Waste-Derived Fuels

Waste-derived fuels (WDF) represent a broad category of alternative energy sources obtained from

Table 1: Comparative overview of waste-derived fuels (WDF and RDF) versus conventional fossil fuels in terms of calorific value, emissions, composition, availability, and environmental performance. This early comparison highlights the sustainability advantages and industrial relevance of WDF/RDF

Parameter	WDF/RDF	Coal	Diesel/Natural Gas
Origin	Secondary resource from waste	Primary fossil fuel	Petroleum/natural gas reserves
Calorific Value (MJ/kg)	12–28	24–30	42–50 (diesel), 35–50 (NG)
Moisture Content (%)	5–35	5–15	<1
Ash Content (%)	3–20	5–20	<0.5
Emission Profile	Lower CO_2, SO_2, NO_x (if sorted well)	High SO_2, NO_x, CO_2	Low SO_2, moderate CO_2
Resource Availability	Readily available from MSW/agro-waste	Finite and regionally concentrated	Depleting fossil resources
Carbon Footprint	Lower (when sourced from biogenic waste)	High	Moderate
Circular Economy Potential	Strong (valorizes waste)	None	Limited
Cost Volatility	Low to moderate	High	High
Applications	Cement kilns, power plants, boilers	Power, steel, thermal plants	Transport, industry

various waste streams. These fuels are categorized based on their physical state into solid, liquid, and gaseous fuels, each possessing distinct characteristics, conversion processes, and applications. The classification of WDF is crucial in determining its suitability for different industrial and energy applications, with factors such as calorific value, combustion efficiency, and emission profiles playing a key role. By effectively utilizing waste as a resource, these fuels contribute to reducing landfill waste, lowering greenhouse gas emissions, and decreasing reliance on fossil fuels.

a) Solid Fuels: Pellets, Briquettes, and RDF

Solid waste-derived fuels are among the most widely used forms of WDF due to their ease of handling, storage, and direct applicability in combustion-based energy systems. The primary types of solid fuels derived from waste include pellets, briquettes, and refuse-derived fuel (RDF), all of which are produced through mechanical processing and densification techniques. Pellets are small, cylindrical solid fuels typically manufactured by compressing dried biomass or waste materials such as agricultural residues, wood chips, and sawdust [20]. These pellets have a high energy density, low moisture content, and uniform composition, making them an efficient and consistent fuel source. Pellets are commonly used in residential heating systems, industrial boilers, and co-firing applications in power plants, where they serve as a substitute for coal or traditional biomass. Due to their standardized size and composition, pellets exhibit improved combustion efficiency and lower emission levels compared to raw waste materials. Briquettes, similar to pellets, are compressed solid fuels but are larger in size and often made from a wider variety of waste feedstocks, including municipal solid waste (MSW), agro-industrial residues, and biomass. The densification process enhances their energy value and reduces the transportation and storage challenges associated with loose waste [21]. Briquettes are commonly used in small-scale industrial furnaces, kilns, and domestic cooking applications, particularly in regions where conventional fuel sources are expensive or scarce. The production of briquettes also helps in waste minimization by converting organic and combustible waste into a valuable energy resource.

Refuse-Derived Fuel (RDF) is a specific type of solid WDF that undergoes preprocessing to remove non-combustible fractions such as metals, glass, and inert materials. RDF typically consists of a mixture of plastics, paper, textiles, and organic waste that have been shredded, dried, and compacted into a higher-calorific fuel product. The refined nature of RDF makes it suitable for co-firing in cement kilns, industrial boilers, and gasification plants, where it serves as an alternative to fossil fuels. The use of RDF not only provides an efficient energy source but also reduces the environmental burden of waste disposal by diverting materials from landfills.

b) Liquid Fuels: Bio-Oils and Synthetic Fuels

Liquid waste-derived fuels are generated through thermochemical and biochemical processes that break down organic waste into liquid energy carriers. These fuels, including bio-oils and synthetic fuels, offer the advantage of compatibility with existing fuel infrastructure and can be used in transportation, heating, and industrial applications. Bio-oils are produced through processes such as pyrolysis and hydrothermal liquefaction, wherein biomass and waste materials are thermally decomposed in the absence of oxygen. Pyrolysis oil, also known as bio-crude, is a dark, viscous liquid with a high oxygen content and moderate energy density [22]. Although bio-oils require further upgrading and refining to be used in conventional engines, they hold significant potential as a sustainable alternative to petroleum-based fuels. These oils can be utilized in boilers, turbines, and blended with conventional fuels to reduce dependency on fossil fuels. Synthetic fuels, often referred to as Fischer-Tropsch (FT) fuels or advanced biofuels, are produced from waste-derived syngas through catalytic conversion processes [23]. These fuels mimic the properties of conventional gasoline, diesel, and jet fuel, making them a viable option for the transportation sector. Synthetic fuels offer a cleaner combustion profile with lower sulfur and particulate emissions, making them environmentally preferable to traditional liquid fuels. The production of synthetic fuels from waste materials, including plastic waste and biomass, has gained attention as a means to mitigate plastic pollution and enhance energy security.

c) Gaseous Fuels: Syngas and Biogas

Gaseous waste-derived fuels represent another crucial category of WDF, offering high energy efficiency and versatile applications in power generation, industrial heating, and vehicular use. The primary gaseous fuels derived from waste include syngas and biogas, both of which are produced through thermochemical and biochemical processes. Syngas (synthesis gas) is a mixture of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4) generated through gasification of solid waste materials such as biomass, municipal solid waste, and industrial residues [24]. Gasification involves partial oxidation of waste at high temperatures, producing a combustible gas that can be further processed into liquid fuels or used directly in gas turbines, internal combustion engines, and fuel cells. Syngas has gained recognition as a clean and flexible energy carrier, with applications in hydrogen production, synthetic fuel synthesis, and combined heat and power (CHP) systems. Its production from waste not only provides a renewable energy source but also contributes to reducing waste disposal challenges.

Biogas, in contrast, is generated through anaerobic digestion, a microbial process that breaks down organic waste in the absence of oxygen. Organic waste sources such as food waste, manure, sewage sludge, and agricultural residues are converted into biogas, which primarily consists of methane (CH_4) and carbon dioxide (CO_2). Biogas is widely used for electricity generation, heating, and as a substitute for natural gas in transportation [25]. Additionally, the by-product of anaerobic digestion, known as digestate, serves as a nutrient-rich fertilizer, further contributing to sustainable waste management practices. Upgraded biogas, known as biomethane, can be injected into natural gas grids, providing a renewable alternative to fossil-based natural gas.

The utilization of gaseous waste-derived fuels plays a significant role in decarbonizing the energy sector, particularly in rural and off-grid areas where traditional fuel sources are limited. The production of syngas and biogas from organic and industrial waste enhances energy resilience, reduces greenhouse gas emissions, and promotes a more circular economy by valorizing waste streams that would otherwise contribute to environmental pollution. Waste-derived fuels, whether in solid, liquid, or gaseous form, offer substantial potential for sustainable energy production. Solid fuels like pellets, briquettes, and RDF provide an efficient alternative to coal and biomass in combustion applications. Liquid fuels such as bio-oils and synthetic fuels pave the way for renewable alternatives to petroleum-based fuels, while gaseous fuels like syngas and biogas offer versatile applications in power generation and industrial processes [26]. The continued advancement of waste-to-energy technologies and policy support will be critical in unlocking the full potential of WDF, contributing to waste management solutions and the transition toward a low-carbon energy future.

2.2. Classification of Refuse-Derived Fuels (RDF)

Refuse-Derived Fuel (RDF) is a specific category of waste-derived fuel (WDF) that undergoes pre-processing to improve its combustion properties and energy content. RDF is typically produced from municipal solid waste (MSW) and industrial waste through a series of mechanical, thermal, or chemical treatments aimed at removing non-combustible materials such as metals, glass, and inert components. The remaining fraction, primarily composed of plastics, paper, textiles, and biomass residues, is then processed into a fuel suitable for industrial applications. Based on its quality, processing level, and calorific value, RDF is generally classified into two main categories: low-grade RDF and high-grade RDF. Each type serves different energy applications, ranging from direct combustion in power plants to conversion into advanced fuels. The classification of RDF is essential in determining its suitability for various end uses, optimizing its efficiency, and ensuring compliance with environmental regulations.

Low-Grade RDF: Directly Combusted for Power Generation

Low-grade RDF refers to RDF that undergoes minimal processing and retains a relatively high fraction of heterogeneous waste materials. This type of RDF is primarily used in direct combustion applications, such as co-firing in power plants, industrial boilers, and cement kilns. Due to its lower energy density and higher moisture and ash content, low-grade RDF is typically utilized in facilities equipped with advanced emissions control systems to mitigate the release of pollutants during combustion [27]. The production process of low-grade RDF involves mechanical separation, shredding, and drying of mixed waste streams to remove larger non-combustible fractions. However, the resulting fuel still contains varying levels of contaminants and lower energy content compared to traditional fossil fuels. Despite these limitations, low-grade RDF remains a viable alternative to coal and other conventional fuels in energy-intensive industries. One of the key benefits of using low-grade RDF is waste diversion from landfills, significantly reducing methane emissions and environmental pollution. Moreover, many power plants and cement industries have adapted their systems to accommodate RDF as a secondary fuel, leveraging its availability and cost-effectiveness [28].

However, the use of low-grade RDF poses certain challenges, particularly in terms of combustion efficiency and emissions management. The presence of chlorine, heavy metals, and other contaminants can lead to the formation of harmful emissions, necessitating the use of advanced flue gas treatment technologies. Additionally, variability in waste composition can impact the consistency of RDF's calorific value, requiring thorough quality control measures to maintain performance standards. As shown in Figure **2**, low-grade RDF serves as an entry-level waste-derived fuel option, offering immediate benefits in waste-to-energy applications while requiring further advancements to improve its efficiency and sustainability.

High-Grade RDF: Further Processed into Higher Calorific Value Fuels

High-grade RDF is an upgraded form of refuse-derived fuel that undergoes additional processing to achieve a higher calorific value, lower moisture content, and improved combustion properties. This type of RDF is designed for more advanced applications, including gasification, pyrolysis, and co-firing with higher efficiency in industrial and energy production systems. High-grade RDF is commonly used in waste-to-liquid (WTL) and waste-to-gas (WTG) processes, where it is converted into synthetic fuels, biochar, and syngas, providing a cleaner and more versatile energy output. The production of high-grade RDF involves further refinement and densification techniques, such as pelletization or briquetting, to enhance its fuel properties. By removing impurities and optimizing its composition, high-grade RDF exhibits higher energy density, improved combustion efficiency, and lower emissions compared to low-grade RDF [29]. Industries such as cement manufacturing, steel production, and advanced thermal power plants benefit from high-grade RDF as a cost-effective and environmentally friendly alternative to fossil fuels.

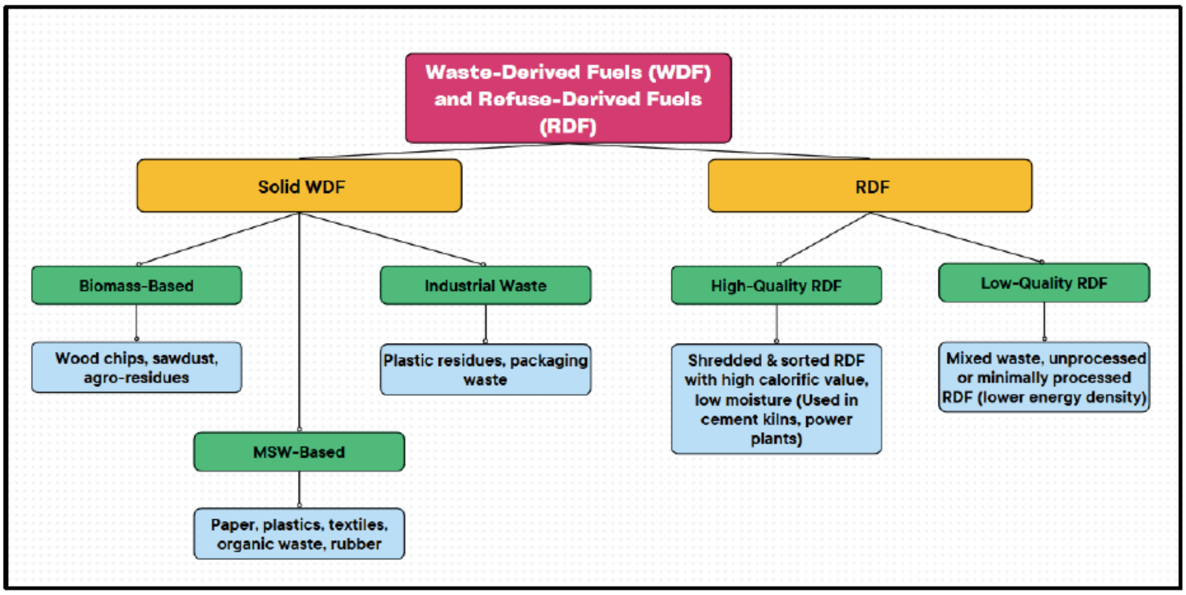

Figure 2: Flowchart outlining the classification of waste-derived fuels (WDF) and refuse-derived fuels (RDF) into solid, liquid, and gaseous forms. It also distinguishes between low-grade and high-grade RDF, providing insight into processing intensity, calorific value, and suitable end-use applications.

A critical advantage of high-grade RDF is its greater compatibility with advanced energy conversion technologies. Gasification, for instance, enables the production of clean syngas, which can be utilized for electricity generation, hydrogen production, or synthetic fuel synthesis. Similarly, pyrolysis of high-grade RDF produces valuable liquid biofuels that can be integrated into transportation fuel supply chains. These processes help in reducing greenhouse gas emissions, increasing energy efficiency, and enhancing resource recovery from waste materials [30]. Despite its advantages, the production of high-grade RDF requires greater investment in processing infrastructure and quality control systems. Strict regulations regarding RDF composition and emissions standards must be met to ensure its safe and efficient use. Additionally, high-grade RDF production facilities need to establish robust supply chains and waste segregation systems to maintain a consistent fuel output. As shown in Figure **2**, the classification of RDF into low-grade and high-grade categories plays a crucial role in determining its application potential and optimizing its utilization in different energy systems. The continued development of RDF processing technologies, coupled with supportive policies and industrial adoption, will be instrumental in scaling up the role of RDF in sustainable energy production.

2.3. Comparison with Conventional Fuels

Waste-derived fuels (WDF) and refuse-derived fuels (RDF) are increasingly being considered as viable alternatives to conventional fossil fuels due to their potential for waste valorization, reduced environmental impact, and enhanced energy security. The fundamental differences between these alternative fuels and conventional fossil fuels lie in their energy density, composition, and combustion characteristics, which directly affect their efficiency, emissions, and applicability in various industrial processes. One of the key aspects of evaluating the feasibility of WDF and RDF is their energy density, which determines the amount of energy released per unit mass of fuel [31]. While conventional fuels such as coal and natural gas typically exhibit higher energy densities, advanced processing techniques have enabled the production of high-grade RDF with comparable calorific values. Additionally, the composition of WDF and RDF varies significantly based on the feedstock and processing methods employed. Unlike fossil fuels, which are chemically uniform, WDF and RDF contain heterogeneous materials such as plastics, biomass, textiles, and paper, which influence their combustion behavior and emissions profile.

In terms of combustion characteristics, WDF and RDF can exhibit higher moisture and ash content than conventional fuels, affecting their combustion efficiency and requiring modifications in fuel handling, burner technology, and emission control systems. However, the co-firing potential of RDF in cement kilns, power plants, and industrial boilers has demonstrated promising results in reducing coal dependency while maintaining efficient combustion. As shown in Table **2**, the comparative properties of WDF, RDF, and conventional fuels highlight the key performance metrics that determine their suitability for large-scale energy applications.

This comparative analysis underscores the advantages and limitations of WDF and RDF in relation to traditional fossil fuels. While their lower carbon footprint and renewable nature make them attractive for sustainable energy transitions, challenges such as heterogeneous composition, variable calorific value, and emissions management necessitate further technological advancements and policy support.

3. SOURCES AND FEEDSTOCK FOR WDF AND RDF

The selection of feedstock plays a crucial role in the efficiency, energy potential, and sustainability of

Table 2: Comparative Properties of WDF, RDF, and Conventional Fuels

Property	WDF	RDF	Coal	Natural Gas	Diesel
Calorific Value (MJ/kg)	12-25	15-28	24-30	35-50	42-46
Moisture Content (%)	10-35	5-20	5-15	0-5	0.1-0.5
Ash Content (%)	5-20	3-15	5-20	<0.5	<0.1
Composition	Mixed organic and plastic waste	Paper, plastics, biomass, textiles	Carbon-rich solid	Methane (CH_4)	Hydrocarbons
Emission Levels	Moderate to high	Moderate to low	High SOx and NOx	Low CO_2 and NOx	Moderate CO_2
Combustion Efficiency	Moderate	High	High	Very high	Very high
Application	Boilers, gasifiers, cement kilns	Cement kilns, industrial furnaces, power plants	Power plants, steel industry	Heating, power generation	Transportation, industrial processes

waste-derived fuels (WDF) and refuse-derived fuels (RDF). The quality and composition of the raw materials influence the calorific value, emissions profile, and overall feasibility of waste-to-energy (WTE) processes. Municipal solid waste (MSW), industrial and agricultural waste, and biomass-based feedstocks are among the most commonly utilized sources for producing alternative fuels [32]. Each of these categories presents unique benefits and challenges that impact their potential as energy resources.

Municipal Solid Waste (MSW) as Feedstock

Municipal solid waste (MSW) is a diverse mix of organic and inorganic materials generated from households, commercial establishments, and institutions. The composition of MSW varies significantly based on geographic location, economic development, and waste management practices. Typically, MSW consists of:

- Biodegradable organic waste (40-60%) – Food scraps, yard waste, and paper-based materials.
- Plastics and packaging materials (10-30%) – Includes polyethylene, polypropylene, and polystyrene.
- Paper and cardboard (10-20%) – Newspapers, office paper, cartons.
- Textiles and rubber (5-10%) – Clothing, footwear, and synthetic fibers.
- Glass and metals (5-15%) – Beverage cans, aluminum foils, and construction debris.

A significant portion of MSW can be converted into WDF and RDF, with organic fractions contributing to biofuels and synthetic gas production, while plastics and paper-based waste provide high-calorific-value RDF suitable for industrial applications [33]. As shown in Figure **3**, the distribution of these components determines the efficiency and feasibility of different conversion pathways for waste-derived fuels.

One of the primary challenges in utilizing MSW as a feedstock is the heterogeneous nature of the waste stream. Effective waste segregation and sorting are essential to enhance the quality of RDF and reduce contamination. The main challenges include:

- Mixed waste disposal habits – Lack of source separation increases processing costs.
- Presence of non-combustible materials – Metals, glass, and high-moisture waste reduce fuel efficiency.
- Variability in calorific value – Differences in regional waste composition affect energy output.
- Hazardous contaminants – The presence of heavy metals and chlorine-containing plastics can lead to toxic emissions.

Addressing these challenges requires technological advancements such as automated sorting, sensor-based waste identification, and enhanced recycling policies to improve feedstock quality for RDF production.

Industrial and Agricultural Waste

Industrial activities generate substantial amounts of plastic waste and packaging residues, which can be converted into high-energy-density RDF. Plastics, particularly polyethylene (PE), polypropylene (PP), and polystyrene (PS), have high calorific values ranging from 30-45 MJ/kg, making them excellent candidates for co-firing in cement kilns, gasification, and pyrolysis [34]. However, their use as RDF comes with challenges, including:

- Chlorinated plastic emissions – PVC-based plastics release harmful dioxins and furans.
- Difficulty in recycling composite materials – Laminates and multi-layer plastics hinder processing.
- Microplastic concerns – Incomplete combustion can contribute to particulate pollution.
- Effective solutions include mechanical recycling, thermal depolymerization, and improved waste collection systems to ensure that non-recyclable plastics are efficiently converted into high-grade RDF.

Agricultural waste, including crop residues, husks, straws, and bagasse, serves as a valuable biofuel source with moderate-to-high energy potential. Common agro-residues used in RDF production include:

- Rice husk (14-17 MJ/kg) – Abundant in rice-producing regions and suitable for pelletization.
- Sugarcane bagasse (15-18 MJ/kg) – A byproduct of sugar production, often used in bioenergy.
- Corn stover (12-16 MJ/kg) – Rich in cellulose and hemicellulose, suitable for RDF processing.

As indicated in Table **3**, agro-waste-derived RDF provides a renewable alternative to fossil fuels, but its

Table 3: Common Waste Feedstocks and Their Energy Potential

Feedstock Type	Common Sources	Calorific Value (MJ/kg)	Challenges
MSW	Household, commercial, institutional waste	12-20	High variability, contamination
Plastics & Packaging	Industrial plastic waste, packaging residues	30-45	Emission concerns, recycling limitations
Agro-Residues	Rice husk, corn stover, bagasse	12-18	Moisture content, seasonal availability
Woody Biomass	Forestry waste, sawdust, wood chips	15-20	Collection and transportation costs
Algae Biomass	Microalgae, seaweed	20-30	High cultivation costs
Energy Crops	Miscanthus, switchgrass	16-22	Land use competition, processing complexity

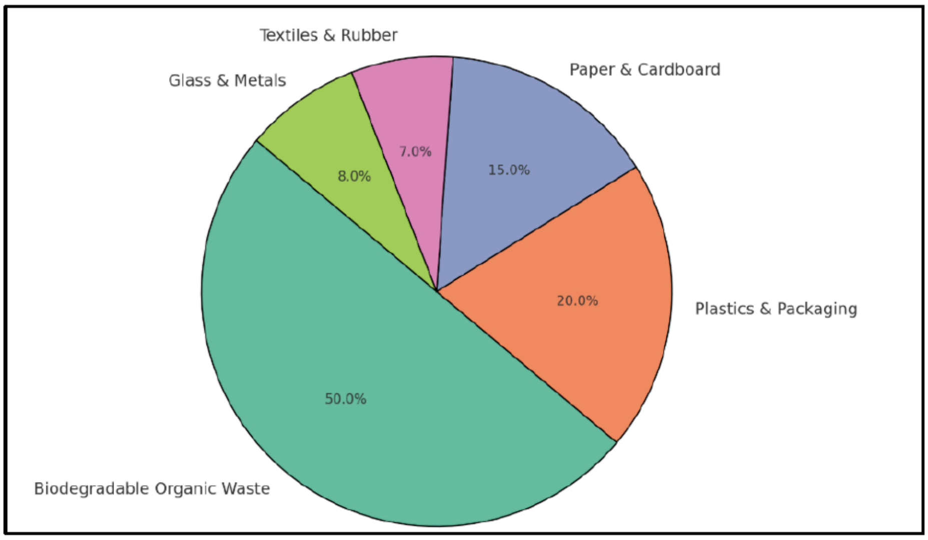

Figure 3: Pie chart illustrating the typical composition of municipal solid waste (MSW) used in WDF and RDF production. This breakdown highlights the proportion of organics, plastics, paper, textiles, and inorganics, which directly influences fuel quality, emissions, and energy content.

high moisture content, seasonal availability, and ash deposition issues require preprocessing techniques such as drying, torrefaction, and briquetting to improve fuel efficiency.

Biomass-Based Feedstock

Biomass-based feedstocks, including woody biomass, algae, and dedicated energy crops, offer significant potential for WDF and RDF production. Biomass is characterized by its renewability, carbon-neutral cycle, and compatibility with bioenergy systems. Some of the most common biomass feedstocks include:

- Wood chips and sawdust (15-20 MJ/kg) – Derived from forestry residues and widely used in pelletized RDF.
- Algae biomass (20-30 MJ/kg) – High lipid content makes it suitable for biofuel conversion.
- Miscanthus and switchgrass (16-22 MJ/kg) – Energy crops with high cellulose content for pyrolysis applications.

Compared to MSW and industrial waste, biomass feedstocks generally contain fewer contaminants, lower ash content, and higher combustion efficiency. However, land use competition, processing costs, and logistical challenges affect the large-scale adoption of biomass for RDF production.

The integration of biomass-derived RDF with existing bioenergy systems enhances overall energy efficiency and sustainability. Biomass feedstocks can be used in:

- Co-firing with coal – Reduces greenhouse gas emissions while maintaining high combustion efficiency.
- Biogasification and syngas production – Enables cleaner fuel synthesis and hydrogen generation.

- Thermochemical conversion (pyrolysis, gasification, hydrothermal liquefaction) – Produces liquid biofuels and synthetic gas for industrial applications.

The versatility and carbon-neutral nature of biomass-based RDF make it a promising option for reducing dependency on fossil fuels, improving waste valorization, and promoting a circular economy approach in energy systems.

4. PROCESSING AND CONVERSION TECHNOLOGIES

4.1. Mechanical Processing

Mechanical processing plays a crucial role in converting waste materials into high-quality waste-derived fuels (WDF) and refuse-derived fuels (RDF). Proper pre-processing ensures that waste is transformed into a uniform, energy-dense, and efficient fuel source suitable for industrial applications, such as co-firing in cement kilns, power plants, and gasification units. The three primary mechanical processing steps—shredding, drying, and sorting—significantly impact the fuel's combustion efficiency, handling properties, and environmental footprint [35]. Effective mechanical treatment of waste not only enhances energy recovery but also minimizes operational issues associated with inconsistent feedstock composition.

Shredding is a fundamental step in the mechanical processing of WDF and RDF, as it reduces the size of waste materials and increases their surface area, which is essential for efficient combustion. Large, irregularly shaped waste fractions are broken down into smaller, manageable pieces, improving fuel homogeneity and ensuring stable energy output. Proper shredding facilitates uniform feeding into combustion systems, preventing blockages and reducing wear on processing equipment. Various shredding technologies are used depending on the nature of the waste [36]. Single-shaft shredders are effective for general coarse shredding, while double-shaft and four-shaft shredders provide finer particle size reduction, especially for plastics and textiles. Hammer mills are commonly employed when producing fine RDF fractions for fluidized bed combustion. Shredding also enables the removal of oversized contaminants, such as metal scraps, glass, and non-combustible materials, which, if left untreated, could compromise the efficiency of RDF-based energy systems. Drying is another essential pre-treatment step that improves the combustion properties of RDF by reducing its moisture content [37]. High moisture levels in waste-derived fuels lower their calorific value and increase energy consumption during combustion, as excess energy is required to evaporate water before fuel ignition. Wet waste also leads to incomplete combustion, generating higher emissions of particulate matter and unburned hydrocarbons. Drying methods such as rotary dryers, belt dryers, and solar drying are used to remove excess moisture from RDF feedstocks. Rotary dryers utilize heated air to evaporate water quickly, whereas belt dryers operate at lower temperatures, making them ideal for organic waste [38]. Solar drying, though slower, is a sustainable and cost-effective option in regions with high solar radiation. By optimizing drying conditions, the calorific value of RDF can be increased from approximately 12–15 MJ/kg to 20–25 MJ/kg, making it comparable to conventional fossil fuels in terms of energy output [39].

Sorting is a critical step in ensuring that RDF consists of high-calorific-value components while eliminating non-combustible or hazardous materials. Effective sorting processes remove impurities that could negatively impact combustion efficiency and emissions. Magnetic separation is widely used to extract ferrous metals such as iron and steel, preventing these materials from entering RDF combustion systems. Similarly, eddy current separation targets non-ferrous metals, such as aluminum and copper, which can interfere with RDF processing [40]. Air classification is employed to separate lightweight combustibles, such as plastics and paper, from heavier materials like stones and glass, thereby improving RDF consistency. Optical sorting, which utilizes near-infrared (NIR) technology, further refines RDF composition by distinguishing between different types of plastics and organic fractions. These advanced sorting techniques help reduce environmental concerns by preventing the inclusion of hazardous materials, such as chlorine-containing plastics, which release harmful dioxins and furans upon combustion. Additionally, proper sorting enhances material recovery and recycling, diverting non-energy-efficient waste fractions from RDF production and ensuring a more sustainable waste-to-energy pathway.

Pre-processing requirements for high-quality RDF involve careful selection of feedstock and adherence to strict quality control measures. Not all waste materials are suitable for RDF production, and waste characterization is essential to assess factors such as moisture content, calorific value, and contamination levels. The best RDF feedstocks include plastics (excluding PVC and halogenated compounds), which provide high calorific values, as well as paper, cardboard, and biomass residues, which contribute to sustained energy release and renewable carbon sources [41]. Contaminants such as heavy metals, medical waste, and hazardous chemicals must be strictly removed to meet environmental regulations and ensure safe RDF combustion. The integration of advanced pre-processing technologies, including automated sorting, drying optimization, and high-efficiency shredding, enhances RDF quality, making it a viable alternative to conventional fossil fuels. Effective mechanical processing is therefore essential for optimizing RDF production and maximizing its role in sustainable energy systems.

4.2. Thermochemical Conversion

Thermochemical conversion is a key process in transforming waste-derived fuels (WDF) and refuse-derived fuels (RDF) into useful energy and chemical products. It involves breaking down organic waste components through the application of heat, enabling energy recovery from materials that would otherwise be discarded in landfills. The primary thermochemical processes—pyrolysis, gasification, and combustion—offer different advantages based on operating conditions, energy output, and emissions. These methods help reduce dependence on fossil fuels and contribute to a more sustainable waste management system by utilizing non-recyclable waste fractions for energy production. As illustrated in Figure **4**, thermochemical pathways convert heterogeneous waste streams into high-value energy products through distinct reaction mechanisms.

I. Pyrolysis: Decomposition of Organic Materials

Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen, breaking down complex organic waste into bio-oil, syngas, and biochar. It typically operates at temperatures ranging from 300°C to 700°C, depending on whether slow, fast, or flash pyrolysis is used [42]. Slow pyrolysis focuses on maximizing biochar yield, whereas fast and flash pyrolysis prioritize the production of bio-oil and syngas. This process is particularly effective for processing plastics, biomass, and organic waste fractions from WDF and RDF. The main products of pyrolysis serve different energy and industrial applications. Bio-oil is a high-energy liquid that can be refined into transportation fuels or burned for electricity generation. Syngas, a mixture of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and light hydrocarbons, can be utilized in gas turbines, fuel cells, or further converted into synthetic fuels [43]. Biochar, the solid residue left after pyrolysis, has applications in soil improvement, carbon sequestration, and energy production. Pyrolysis is favored for its low emissions, ability to handle mixed waste, and potential for chemical recovery, making it a vital component of advanced waste-to-energy strategies. However, it requires pre-treatment of feedstock, moisture reduction, and careful control of reaction parameters to maximize fuel quality and minimize impurities.

II. Gasification: Partial Oxidation to Produce Syngas

Gasification is a partial oxidation process that converts RDF and WDF into syngas, a valuable gaseous fuel that can be used for power generation, chemical synthesis, and hydrogen production. Unlike combustion, which completely oxidizes waste into carbon dioxide and heat, gasification preserves chemical energy by limiting the oxygen supply. It typically operates at temperatures between 700°C and 1,200°C, using air, oxygen, or steam as the gasifying agent. The primary product of gasification, syngas, contains hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and trace amounts of carbon dioxide (CO_2). Syngas has several applications, including direct combustion in gas turbines, conversion into synthetic natural gas (SNG) for pipeline distribution, and liquid fuel production through Fischer-Tropsch synthesis. It can also be utilized for hydrogen extraction, supporting the development of green hydrogen economies. Gasification offers higher energy efficiency than direct combustion and lower emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. Advanced gasification technologies, such as plasma gasification, operate at ultra-high temperatures (up to 5,000°C), ensuring complete molecular breakdown of waste and producing a cleaner syngas with minimal residues [43, 44]. However, gasification requires strict control over feedstock composition to prevent the release of hazardous substances, such as chlorine-containing plastics, which can lead to the formation of toxic dioxins and furans. Pre-sorting and drying of RDF feedstock are essential for optimizing gasification efficiency and maintaining compliance with environmental regulations.

III. Combustion: Direct Burning for Energy

Combustion is the most widely used thermochemical process for converting RDF and WDF into heat and electricity. It involves complete oxidation of waste-derived fuels in the presence of excess oxygen, producing heat, carbon dioxide (CO_2), water vapor, and ash residues. RDF combustion is commonly carried out in municipal solid waste incinerators, industrial power plants, and cement kilns, replacing conventional fossil fuels such as coal and oil. The primary advantage of direct combustion is its high energy conversion efficiency. Modern waste-to-energy (WTE) plants achieve 30-35% electrical efficiency and 80-90% total energy efficiency when integrated with district heating systems [45]. Additionally, combustion leads to significant volume reduction, decreasing waste mass by 80-90% and minimizing the need for landfill space. Unlike pyrolysis and gasification, combustion provides instantaneous energy recovery without the need for further processing. However, RDF combustion also poses environmental challenges, including the release of NO_x, SO_x, dioxins, and heavy metals if not properly controlled [46]. Advanced flue gas treatment systems, such as electrostatic precipitators, fabric filters, and wet scrubbers, are required to mitigate harmful emissions. Additionally, co-firing RDF with coal or biomass in industrial boilers helps reduce carbon footprint and enhance fuel efficiency. Proper sorting and pre-processing of RDF are essential to avoid burning toxic plastics, heavy metals, and hazardous waste, which can produce severe air pollution.

Thermochemical conversion plays a crucial role in the sustainable utilization of RDF and WDF by providing multiple energy recovery pathways. Pyrolysis offers bio-oil and syngas production, gasification enables clean energy generation from syngas, and combustion provides direct heat and electricity output. The selection of the appropriate conversion process depends on factors such as feedstock composition, energy requirements, and environmental considerations. As illustrated in Figure **4**, these processes transform waste streams into valuable energy carriers, reducing landfill dependency and supporting the global transition toward a circular economy and low-carbon energy systems.

4.3. Biochemical Conversion

Biochemical conversion plays a significant role in the utilization of organic waste for energy recovery, offering an environmentally friendly alternative to conventional fossil fuels. Unlike thermochemical processes such as pyrolysis and gasification, biochemical conversion relies on microbial activity to break down biodegradable materials into valuable biofuels. This method is particularly effective for processing high-moisture waste streams, including food waste, agricultural residues, sewage sludge, and organic fractions of municipal solid waste (MSW). The two primary biochemical conversion processes—anaerobic digestion and fermentation—enable the production of biogas, bioethanol, and biodiesel, providing sustainable energy sources with reduced carbon emissions. These processes align with circular economy principles by converting organic waste into usable energy while simultaneously minimizing landfill burden and environmental pollution.

I. Anaerobic Digestion: Biogas Production

Anaerobic digestion (AD) is a microbial-driven process that occurs in the absence of oxygen, breaking down organic matter into biogas and digestate. This process takes place in sealed anaerobic digesters, where bacteria and archaea facilitate the degradation of complex organic compounds. Anaerobic digestion occurs through four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each contributing to the conversion of waste into methane-rich biogas and a nutrient-rich byproduct [47]. During hydrolysis, complex organic molecules such as carbohydrates, proteins, and lipids are broken down into their simpler forms—sugars, amino acids, and fatty acids—by hydrolytic enzymes. This step is essential for making organic waste digestible by subsequent microbial communities. In the acidogenesis stage, these smaller molecules are further metabolized into volatile fatty acids (VFAs), alcohols, hydrogen (H_2), and carbon dioxide (CO_2) by acidogenic bacteria. The process continues with acetogenesis, where VFAs and alcohols are converted into acetic acid, hydrogen, and CO_2, preparing the intermediates for methane production [48]. Finally, methanogenesis is carried out by methanogenic archaea, which convert acetic acid and hydrogen into methane (CH_4) and CO_2, producing biogas that can be used for energy applications.

Biogas, the primary product of anaerobic digestion, typically contains 50-70% methane (CH_4), 30-40% carbon dioxide (CO_2), and trace amounts of hydrogen sulfide (H_2S) and ammonia (NH_3) [49]. It can be directly utilized for heat and electricity generation in combined heat and power (CHP) plants, upgraded to biomethane for grid injection, or converted into compressed natural gas (CNG) for vehicle fuel. The residual digestate, rich in organic matter and nutrients, serves as an excellent organic fertilizer for agricultural applications. Anaerobic digestion not only reduces methane emissions from landfills but also supports sustainable energy transitions by recovering energy from biodegradable waste. However, challenges such as substrate variability, slow digestion rates, and the need for efficient gas purification must be addressed to optimize AD efficiency and maximize biogas yield.

II. Fermentation: Bioethanol and Biodiesel Production

Fermentation is another biochemical conversion process that transforms organic waste into liquid biofuels such as bioethanol and biodiesel, offering a renewable alternative to gasoline and diesel. This process relies on microbial fermentation of sugars and lipids derived from various feedstocks, including lignocellulosic biomass, food waste, industrial residues, and algae. Fermentation can be classified into two major biofuel production pathways—ethanol fermentation and biodiesel transesterification—each contributing to sustainable energy production [50]. Bioethanol production through fermentation primarily utilizes sugar- and starch-based feedstocks such as crop residues, sugarcane bagasse, corn stover, and fruit waste. The process involves the enzymatic hydrolysis of cellulose and starch into fermentable sugars, followed by microbial conversion into ethanol by yeasts (*e.g.*, Saccharomyces cerevisiae) or bacteria (*e.g.*, Zymomonas mobilis). The general reaction follows the pathway:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

This reaction demonstrates the transformation of glucose ($C_6H_{12}O_6$) into ethanol (C_2H_5OH) and carbon dioxide (CO_2), with ethanol serving as a high-octane biofuel for blending with gasoline. Lignocellulosic ethanol production, derived from non-food biomass, is gaining traction due to its low carbon footprint and reduced reliance on edible crops. However, pretreatment challenges, enzymatic costs, and complex lignin structures remain barriers to large-scale production.

Biodiesel production, on the other hand, involves the transesterification of lipids (fats and oils) into fatty acid methyl esters (FAMEs), which serve as diesel substitutes. Feedstocks for biodiesel include waste cooking oil, animal fats, microalgae, and lipid-rich industrial byproducts. The transesterification process, catalyzed by acids or bases, converts triglycerides into biodiesel and glycerol:

Triglyceride+3Methanol→3Methyl Esters (Biodiesel)+ Glycerol (2)

Biodiesel is biodegradable, non-toxic, and emits lower particulate matter and sulfur oxides (SO_x) than conventional diesel. Additionally, algal biodiesel presents a promising alternative, given algae's high lipid content and rapid growth rate, making it a viable feedstock for sustainable fuel production [51]. However, challenges such as high cultivation costs, water usage, and feedstock availability must be addressed to improve commercial viability.

Biochemical conversion processes, including anaerobic digestion and fermentation, offer sustainable solutions for waste-derived fuel (WDF) and refuse-derived fuel (RDF) production. Anaerobic digestion provides a methane-rich biogas for energy applications, while fermentation enables bioethanol and biodiesel production from organic waste streams. These technologies contribute to renewable energy generation, greenhouse gas mitigation, and waste valorization, aligning with global efforts toward a circular bioeconomy [52]. However, continued advancements in process optimization, microbial engineering, and feedstock utilization are necessary to enhance efficiency and scalability. By integrating biochemical conversion with other waste-to-energy technologies, a more resilient and sustainable energy system can be achieved, reducing dependence on fossil fuels and promoting environmental stewardship.

Various processing technologies are employed for converting waste into energy, each with distinct advantages, limitations, and environmental implications. The selection of an appropriate processing technology depends on factors such as feedstock composition, energy efficiency, capital and operational costs, and environmental impact. Broadly, waste-derived fuel (WDF) and refuse-derived fuel (RDF) processing methods can be categorized into mechanical, thermochemical, and biochemical conversion technologies, each offering unique pathways for resource recovery.

Mechanical processing methods, such as shredding, drying, and sorting, serve as pre-treatment steps, enhancing fuel quality by reducing moisture content and particle size, thus improving combustion efficiency. Thermochemical processes, including pyrolysis, gasification, and combustion, primarily rely on heat-driven decomposition of organic matter, yielding syngas, biochar, and energy. Meanwhile, biochemical processes, such as anaerobic digestion and fermentation, utilize microbial activity to generate biofuels like biogas, bioethanol, and biodiesel, offering a sustainable alternative to fossil fuels. A comprehensive comparison of these processing technologies, considering factors such as efficiency, cost-effectiveness, and environmental footprint, is essential for selecting the most viable approach for waste-to-energy conversion. As shown in Table **4**, thermochemical processes generally offer higher energy yields, but they often require greater capital investment and emissions control systems. In contrast, biochemical processes provide low-carbon biofuels with minimal air pollution but may have slower conversion rates and high feedstock specificity. Mechanical processing, though not a direct energy conversion method, plays a crucial role in improving fuel quality and optimizing downstream processes.

5. ENERGY CONTENT AND PERFORMANCE OF WDF AND RDF

Waste-derived fuels (WDF) and refuse-derived fuels (RDF) have gained attention as alternative energy sources due to their ability to reduce dependency on fossil fuels while providing an efficient way to manage waste. The energy content and combustion characteristics of these fuels determine their suitability for various industrial applications, including their use in power generation, cement kilns, and district heating systems. The key factors influencing the energy

Table 4: Comparison of Different Processing Technologies in Terms of Efficiency, Costs, and Environmental Impact

Processing Technology	Efficiency (%)	Capital Cost	Operational Cost	Byproducts	Environmental Impact
Mechanical Processing (Shredding, Drying, Sorting)	Pre-treatment (not a direct energy conversion method)	Low	Low	RDF, separated recyclables	Minimal, but energy required for sorting
Combustion (Direct Burning)	20-40%	Medium	Medium	Ash, flue gases	High CO_2 and pollutant emissions, requires flue gas treatment
Pyrolysis	50-70% (liquid and gas fuels)	High	Medium	Bio-oil, syngas, char	Moderate emissions, requires upgrading for fuel use
Gasification	60-80% (syngas production)	High	High	Syngas, slag	Lower emissions than combustion, but requires gas cleanup
Anaerobic Digestion	40-60% (biogas energy yield)	Medium	Low	Biogas, digestate	Low emissions, methane leakage concerns
Fermentation (Bioethanol/Biodiesel Production)	30-50%	Medium-High	Medium	Bioethanol, biodiesel, CO_2	Low emissions, but feedstock-dependent

performance of WDF and RDF include their calorific value, fuel efficiency, combustion properties, and emissions profile [53]. Compared to traditional fuels such as coal and biomass, these alternative fuels offer competitive energy outputs with lower environmental footprints. As illustrated in Figure **5**, the calorific values of WDF and RDF vary depending on feedstock composition, moisture content, and processing techniques, influencing their suitability for diverse industrial applications.

The calorific value of a fuel represents the amount of energy released during combustion and is a critical parameter in evaluating the performance of WDF and RDF. The calorific value is typically measured in megajoules per kilogram (MJ/kg) and varies significantly depending on the composition of the waste feedstock. Fossil fuels like coal have high calorific values, typically ranging between 20-30 MJ/kg, while biomass-based fuels, such as wood pellets and agricultural residues, have a lower calorific value, averaging 15-20 MJ/kg [54]. WDF and RDF, depending on their composition and processing, can achieve calorific values in the range of 12-25 MJ/kg, making them competitive substitutes for fossil fuels. As shown in Figure **5**, the calorific values of high-quality RDF can approach those of coal, making it a viable fuel for industrial co-firing. However, factors such as moisture content, volatile matter, and the presence of non-combustible materials can impact the overall efficiency of WDF and RDF. Pre-processing methods like shredding, drying, and pelletization significantly improve fuel quality by reducing moisture content and increasing energy density. Additionally, the homogenization of waste feedstock through mechanical sorting and blending enhances combustion uniformity, ensuring a more stable energy output in industrial applications [55].

The combustion performance of WDF and RDF depends on several key factors, including ash content, volatile matter, and emissions characteristics. Ash content is a critical parameter, as high ash levels can lead to slagging, fouling, and increased maintenance costs in combustion systems. Coal typically contains 5-15% ash, whereas WDF and RDF can have 10-25% ash, depending on their feedstock. The presence of inorganic components such as silica, alkali metals, and chlorine can influence the formation of ash deposits and impact the efficiency of boilers and kilns. Another essential factor in combustion performance is the volatile matter content, which affects the ignition and flame stability of the fuel. RDF, particularly from municipal solid waste, often has higher volatile matter content (50-70%) than coal (20-35%), leading to faster ignition and combustion rates [56]. This property makes RDF highly suitable for fluidized bed combustion (FBC) systems, which operate efficiently with fuels containing high volatile matter.

The emissions profile of WDF and RDF is another important consideration. Compared to fossil fuels, these alternative fuels generally produce lower sulfur dioxide (SO_2) emissions, as they contain minimal sulfur compounds. However, certain waste-derived fuels, particularly those containing plastics, treated wood, or synthetic materials, may release higher levels

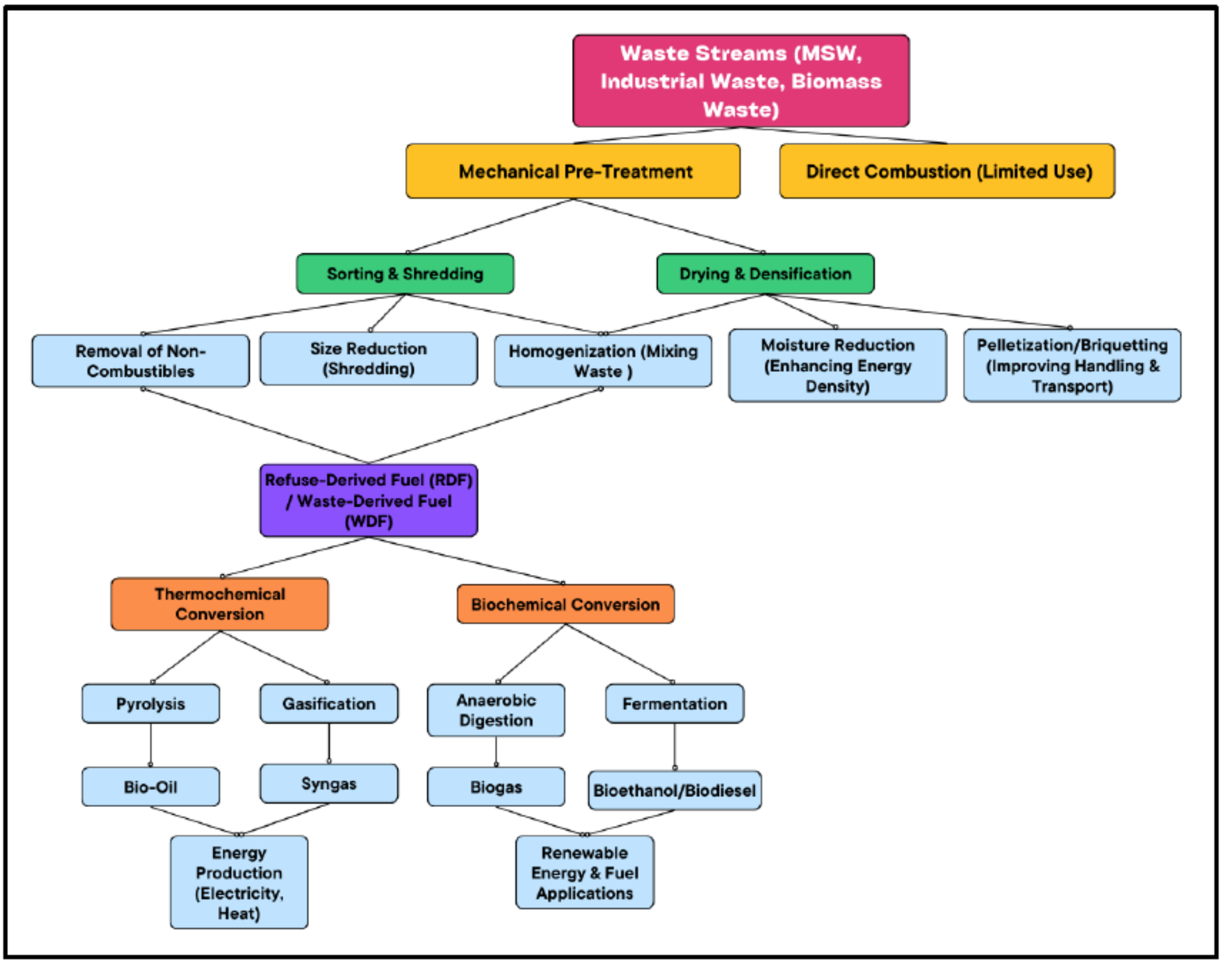

Figure 4: Flow diagram of the WDF and RDF production chain, showing major mechanical, thermochemical, and biochemical processing stages. The figure demonstrates how raw waste is pre-treated, converted, and refined into usable energy carriers, underscoring the technological diversity of waste-to-fuel pathways.

of chlorine and dioxins. Emission control systems, including flue gas treatment, electrostatic precipitators, and selective catalytic reduction (SCR), are necessary to mitigate the environmental impact of RDF combustion [57]. Co-firing RDF with coal in modern combustion systems equipped with pollution control technologies significantly reduces emissions, making it a cleaner alternative for energy production.

The increasing demand for sustainable and cost-effective fuels has positioned WDF and RDF as attractive options for various industrial sectors, including cement kilns and power plants. These industries require high-energy fuels and can accommodate a range of fuel compositions, making them ideal candidates for WDF and RDF utilization.

Cement kilns are among the largest energy consumers in industrial operations and have successfully integrated RDF as a partial replacement for coal and petroleum coke. The high operating temperatures (1400-1500°C) in cement kilns allow for the complete combustion of RDF, minimizing the formation of pollutants such as dioxins and furans [58]. Additionally, the alkaline environment inside the kiln helps neutralize acidic gases, reducing the need for additional flue gas treatment. Using RDF in cement kilns provides multiple benefits, including:

- Reduced reliance on fossil fuels, lowering operational costs.
- Lower CO□ emissions, contributing to climate change mitigation.
- Efficient disposal of non-recyclable waste, diverting materials from landfills.

Many cement plants have adopted waste-to-energy strategies, incorporating RDF into their fuel mix, often achieving 30-50% substitution rates. The success of RDF in cement kilns demonstrates its economic and environmental feasibility, making it a promising option for sustainable industrial fuel use.

Coal-fired power plants are another major sector where RDF and WDF can be used as substitute fuels, particularly through co-firing strategies. Co-firing RDF with coal in pulverized coal boilers or fluidized bed

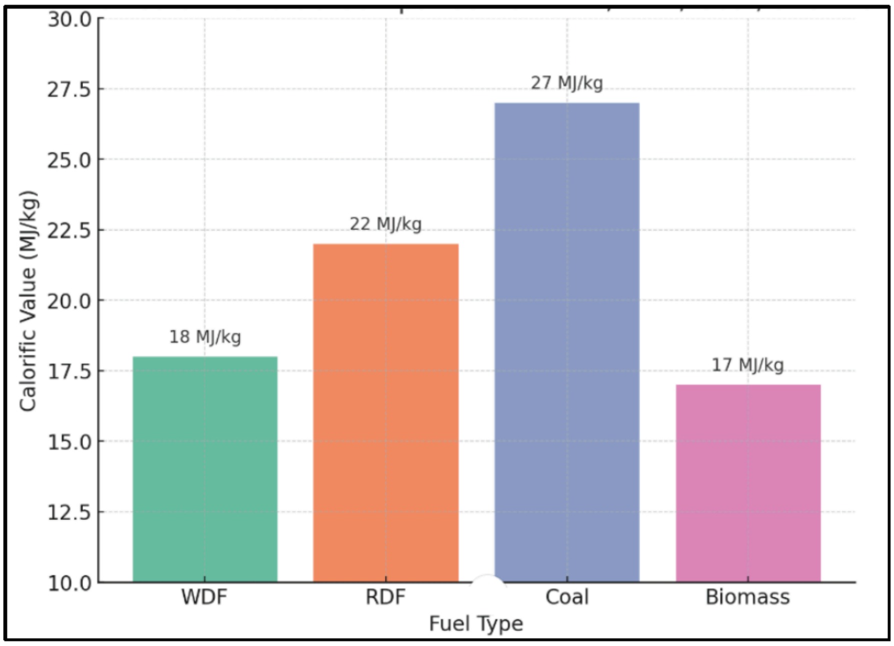

Figure 5: Comparative bar chart depicting calorific values of WDF, RDF, coal, and biomass. This figure underscores the energy potential of waste-derived fuels relative to traditional fossil and renewable biomass sources, emphasizing their suitability for industrial energy applications.

systems helps reduce carbon emissions and fuel costs, while maintaining a stable energy supply. The key advantages of using RDF in power generation include:

- Lower carbon footprint compared to coal, reducing greenhouse gas emissions.
- Diversification of energy sources, improving energy security.
- Utilization of local waste resources, promoting circular economy principles.

However, challenges such as feedstock variability, ash deposition, and emissions control must be addressed for widespread adoption. Many power plants are investing in advanced combustion technologies, such as integrated gasification combined cycle (IGCC) and fluidized bed combustion (FBC), to optimize RDF performance and minimize environmental impact.

The energy content and combustion performance of WDF and RDF make them viable alternatives to traditional fossil fuels in various industrial applications. While calorific values and fuel efficiency determine their competitiveness with coal and biomass, combustion properties such as ash content, volatile matter, and emissions profile influence their practical implementation. Cement kilns and power plants represent key industries that can benefit from RDF and WDF utilization, offering cost-effective and environmentally sustainable energy solutions. Advancements in fuel processing, emission control technologies, and co-firing strategies will further enhance the role of WDF and RDF in future energy systems, contributing to global efforts toward sustainable waste management and renewable energy integration.

6. ENVIRONMENTAL AND ECONOMIC ASPECTS

6.1. Environmental Benefits

Waste-derived fuels (WDF) and refuse-derived fuels (RDF) present significant environmental benefits by addressing critical challenges such as waste management, carbon emissions reduction, and resource conservation. As alternative energy sources, they contribute to a more sustainable approach to energy production and waste disposal, helping to mitigate environmental impacts associated with traditional fossil fuels. The primary environmental advantages of using WDF and RDF stem from their ability to reduce landfilling and decrease CO_2 and pollutant emissions, which are crucial for minimizing the ecological footprint of both waste management and energy generation processes.

One of the most pressing environmental issues globally is the management of municipal solid waste (MSW). With landfills filling up rapidly and limited space available, the environmental consequences of poor waste disposal practices, such as the release of harmful leachates, methane emissions, and land degradation, are significant. By utilizing WDF and RDF as energy sources, waste that would otherwise end up in landfills is diverted, contributing to waste reduction and resource recovery. When MSW is processed into RDF, non-recyclable materials are converted into a usable fuel, significantly reducing the volume of waste sent to landfills [59]. This process not only minimizes the burden on waste disposal infrastructure but also leads to a decrease in landfill methane emissions. Methane, a potent greenhouse gas, is released when organic waste decomposes anaerobically in landfills. By diverting waste for RDF production, the amount of organic material decomposing in landfills is reduced, thus mitigating the environmental impact of methane emissions, which have a much higher global warming potential than CO_2. In addition, the energy recovery from RDF further reduces the environmental strain on landfills, making waste management more circular and sustainable.

The environmental benefit of using WDF and RDF as fuels extends beyond landfill diversion to reducing carbon emissions and other pollutants. Fossil fuel combustion is one of the primary sources of carbon dioxide (CO_2), contributing significantly to climate change. In contrast, WDF and RDF offer a lower-carbon alternative, as they primarily consist of waste materials that would otherwise decompose in landfills or be incinerated without energy recovery [60]. The use of RDF in co-firing systems (such as those in cement kilns and power plants) has been shown to result in lower CO_2 emissions compared to the combustion of coal. By substituting fossil fuels with waste-derived alternatives, the overall carbon footprint of energy production is reduced, contributing to climate change mitigation efforts. Moreover, WDF and RDF combustion tends to produce lower sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions compared to coal, which are key contributors to acid rain and air pollution. However, it is essential to note that certain types of waste, such as plastics, can lead to the release of chlorine and dioxins during combustion. Therefore, appropriate emission control systems, such as flue gas treatment technologies and scrubbers, are necessary to mitigate the environmental impact of RDF combustion. These systems help to ensure that the environmental benefits of RDF use are maximized, while pollutant emissions are kept within regulatory limits.

The use of WDF and RDF also contributes to the reduction of greenhouse gas emissions in other sectors, such as transportation and bioenergy production, by displacing the need for petroleum-based fuels and contributing to the production of bioethanol, biodiesel, and biogas. These biofuels, produced via biochemical or thermochemical processes, have a much lower carbon intensity than their fossil fuel counterparts, further helping to reduce overall emissions. The environmental benefits of WDF and RDF extend across multiple domains, from reducing landfill usage and mitigating methane emissions to decreasing carbon footprints and lowering pollutant emissions in energy production. By promoting a more circular economy, these waste-derived fuels offer a sustainable and environmentally-friendly alternative to fossil fuels, contributing to both waste management and the transition to a low-carbon future.

6.2. Life Cycle Assessment (LCA) of WDF and RDF

A Life Cycle Assessment (LCA) is a comprehensive tool used to evaluate the environmental impacts of a product or process over its entire life cycle, from resource extraction to disposal. For waste-derived fuels (WDF) and refuse-derived fuels (RDF), LCA helps to analyze the environmental benefits and challenges associated with their production and use as alternative energy sources. The assessment includes several key stages: waste collection, processing, energy recovery, and emissions. By considering each of these stages, LCA provides valuable insights into the carbon footprint, resource efficiency, and overall environmental impact of using WDF and RDF for energy generation.

I. Waste Collection

The first stage in the LCA of WDF and RDF involves waste collection, which includes the gathering and transportation of municipal solid waste (MSW), industrial waste, and biomass materials to processing facilities. Waste collection typically accounts for a significant portion of the environmental impact due to the fuel consumption of waste collection vehicles, the need for transportation infrastructure, and the emissions associated with the movement of waste [61]. Factors such as collection efficiency, distance to processing facilities, and fuel type used by collection vehicles influence the environmental impact at this stage. Efficient waste sorting and segregation at the source can reduce the need for additional transportation and processing efforts, minimizing the carbon footprint.

II. Processing

Once waste is collected, it is processed into RDF through various mechanical and thermal treatments. This processing stage includes shredding, drying, sorting, and, in some cases, pelletization. Processing helps to remove contaminants, reduce moisture content, and increase energy density, thereby enhancing the overall quality of the fuel. Mechanical processing is energy-intensive, requiring electricity and sometimes fossil fuels. The environmental impact of this stage largely depends on the type of waste being processed and the energy inputs used for the processing operations. For example, plastic-rich waste requires more energy-intensive processes compared to biomass-rich waste. Additionally, the use of renewable energy in the processing phase can significantly reduce the environmental impact [62]. At this stage, the efficiency of the sorting and separation process can also influence the energy recovery potential of the resulting RDF. A high-quality RDF, containing fewer contaminants, leads to a cleaner and more efficient combustion process, thereby improving the overall energy recovery and reducing emissions from later stages.

III. Energy Recovery

The next stage involves the energy recovery process, where the RDF is burned in a combustion system, co-fired in cement kilns, or utilized in power plants for energy generation. This is the stage where the maximum energy output is realized, as the calorific value of the RDF is converted into usable energy, usually in the form of electricity or heat. The combustion efficiency and the design of the energy recovery system are critical factors affecting this stage's environmental performance. Technologies like fluidized bed combustion, integrated gasification combined cycle (IGCC), and high-efficiency boilers are often used to optimize energy recovery from RDF. While energy recovery from RDF has clear environmental advantages over landfilling, it is not without its own environmental impacts. CO_2 emissions are produced during combustion, though these are generally lower compared to fossil fuels. Additionally, the burning of RDF may release pollutants such as NO_x, SO_2, and particulate matter, depending on the waste composition and combustion conditions [63]. Flue gas treatment technologies and emission control systems are essential to mitigate these impacts and ensure compliance with environmental regulations. These systems help minimize the harmful emissions from the combustion process and further improve the sustainability of RDF as an energy source.

IV. Emissions

The final stage in the LCA of WDF and RDF involves the emissions that result from each of the earlier stages, including both direct emissions from energy recovery and indirect emissions from waste collection, transportation, and processing. The most significant emissions associated with RDF combustion include CO_2, CO, NO_x, and particulate matter. The overall impact of these emissions depends on the waste feedstock's composition and the effectiveness of pollution control technologies used during the combustion process [64]. LCA also takes into account the emissions associated with transportation of waste and processed RDF, as well as the energy consumption during processing. An essential feature of LCA is its holistic approach, which ensures that all emissions and energy use are accounted for across the entire life cycle, not just during the final energy recovery phase. By identifying areas of high environmental impact, LCA can help optimize the overall sustainability of WDF and RDF use, such as improving processing technologies, increasing transportation efficiency, or incorporating renewable energy sources at various stages.

The Life Cycle Assessment (LCA) of WDF and RDF is a valuable tool for evaluating their environmental performance across multiple stages, from waste collection to energy recovery and emissions. By understanding the environmental impacts at each phase, LCA provides a comprehensive framework for optimizing the production and use of WDF and RDF. It helps in identifying potential improvements in waste processing, energy efficiency, and emissions control, ultimately enhancing the sustainability of WDF and RDF as renewable energy sources and promoting more circular waste management practices.

6.3. Economic Feasibility and Market Trends

The economic feasibility and market trends surrounding the production and adoption of refuse-derived fuels (RDF) are pivotal in determining the sustainability and long-term viability of this alternative energy source. As the world increasingly shifts toward renewable energy solutions, RDF presents a cost-effective means to recover energy from waste, simultaneously addressing issues related to waste management and carbon emissions. However, for RDF to become a mainstream alternative to fossil fuels, understanding its cost structure and global market trends is crucial.

The production of RDF involves several stages, including waste collection, sorting, processing, and energy recovery, each of which incurs costs. The capital investment required for establishing RDF production facilities is one of the major economic considerations. These facilities need specialized equipment for shredding, sorting, drying, and compressing waste materials, which involves significant upfront costs. Furthermore, operational costs—including energy consumption, labor, and transportation—add to the total expense. However, the economic advantages of RDF come from its ability to substitute fossil fuels in energy generation, such as in co-firing in cement kilns and power plants, which can help reduce fuel costs over time. One of the primary benefits of RDF is its lower cost compared to fossil

Table 5: Comparative summary of Waste-Derived Fuels (WDF), Refuse-Derived Fuels (RDF), and fossil fuels based on calorific value, emissions, environmental impact, cost, and scalability. This highlights the sustainability and techno-economic positioning of WDF and RDF relative to conventional energy sources

Parameter	WDF	RDF	Fossil Fuels (Coal/Diesel/NG)
Source	Biogenic and non-recyclable waste	Preprocessed MSW/industrial waste	Geological reserves (finite)
Calorific Value (MJ/kg)	12–25	15–28	24–50 (coal/diesel/NG)
Moisture Content (%)	10–35	5–20	<5
Ash Content (%)	5–20	3–15	0.1–20
Carbon Emissions	Lower (esp. from biogenic content)	Moderate to low	High
SOx/NOx Emissions	Moderate (waste-dependent)	Controlled with pre-sorting	High
Cost (per MJ)	Low–moderate (waste-based, local sourcing)	Moderate (processing and quality control)	High and volatile
Environmental Impact	Circular economy aligned; reduces landfill	High resource recovery; moderate emissions	GHG-intensive; extraction, transport, pollution
Infrastructure Need	Moderate	Moderate to high (advanced processing)	Existing, but carbon-intensive
Scalability	High (local availability, policy-driven)	High (with investment and regulations)	Established, but unsustainable

fuels, particularly when waste is locally sourced and transportation distances are minimized. The costs of producing RDF can also be offset by government incentives and subsidies promoting renewable energy and waste-to-energy (WTE) technologies. In some regions, the revenue generated from the sale of RDF to energy producers or through carbon credits can further improve the economic feasibility of its production [65]. However, the economic competitiveness of RDF depends largely on the price of fossil fuels in the market and the efficiency of the RDF production process.

The global adoption of RDF has been growing, particularly in Europe, Asia, and North America, where there is an increasing demand for alternative energy sources and better waste management practices. In Europe, for example, countries like Germany, Sweden, and the Netherlands have been at the forefront of RDF adoption, largely driven by stringent waste management policies and incentives for renewable energy production [66]. The use of RDF in co-firing in cement kilns and power plants is becoming more common, as it provides a way to reduce the carbon footprint of traditional fuel sources. The market for RDF is expected to expand significantly, driven by the increasing availability of waste, technological advancements in waste sorting and processing, and the need for sustainable energy solutions. As waste-to-energy projects gain momentum globally, the demand for RDF as a substitute for coal and other fossil fuels is expected to increase. However, challenges remain, such as the need for investment in infrastructure, regulatory frameworks, and overcoming the perception of RDF as a low-value fuel. Despite these challenges, the trend toward circular economies and sustainable waste management practices is likely to drive continued growth in RDF adoption worldwide.

7. CHALLENGES AND FUTURE PERSPECTIVES

Despite the demonstrated potential of WDF and RDF, their widespread adoption faces several critical barriers. Among these, the most pressing challenge is the heterogeneity and inconsistency of feedstock, which directly affects fuel quality, energy output, and emissions control. This issue is compounded by the lack of effective source segregation and preprocessing infrastructure, particularly in developing economies. Additionally, emissions management remains a regulatory bottleneck, especially with regard to toxic outputs like dioxins from plastic-containing RDF. These technical barriers are further aggravated by high capital costs, limited public awareness, and market volatility.

In contrast, several innovations show strong promise in overcoming these barriers. Notably, AI-driven sorting systems, plasma gasification, and hydrothermal carbonization present advanced technological pathways to improve RDF quality and reduce environmental impact. Likewise, policy-based instruments—such as carbon credit schemes, waste import restrictions, and renewable energy mandates—can catalyze industrial RDF uptake. The integration of RDF into circular economy models and its co-firing with biomass or coal in existing infrastructure are also strategically important. Therefore, future success will depend on targeted investments in preprocessing infrastructure, emissions control technologies, and enabling policy frameworks.

Challenges

a) Waste Collection and Segregation Issues

- Lack of proper waste segregation at the source complicates the quality and efficiency of RDF production.
- Inefficient collection systems lead to higher transportation costs and energy consumption.
- Contamination of recyclable materials impacts the overall fuel quality.

b) High Initial Capital Investment

- Establishing RDF production facilities requires significant capital investment for specialized equipment, infrastructure, and processing plants.
- Operational costs, including energy usage and labor, are high, especially in the early stages.

c) Energy and Emissions Control

- Managing emissions (*e.g.*, CO_2, NO_x, and particulate matter) during RDF combustion requires expensive pollution control technologies.
- Proper waste composition control is necessary to avoid releasing harmful substances like dioxins and furans.

d) Inconsistent Quality of Feedstock

- The variability in the composition of waste can affect the calorific value and combustion characteristics of RDF.
- Inconsistent waste streams lead to difficulties in achieving stable energy output and fuel performance.

e) Market and Economic Factors

- Price volatility in fossil fuels can impact the cost-competitiveness of RDF in energy markets.
- The lack of incentives or subsidies in certain regions may hinder the widespread adoption of RDF.

f) Public Perception and Acceptance

- Public awareness of RDF benefits remains limited, and there may be resistance to its use due to misconceptions about its safety and effectiveness.
- The perception of RDF as a low-value fuel may deter investment in production and utilization technologies.

Future Perspectives

a) Technological Advancements

- Improved sorting and processing technologies can increase the efficiency and fuel quality of RDF, reducing contaminants and enhancing energy recovery.
- Advances in combustion technologies (*e.g.*, fluidized bed combustion and gasification) will improve the efficiency and environmental performance of RDF energy generation.

b) Integration with Circular Economy Models

- As countries adopt circular economy principles, RDF production can play a crucial role in waste-to-energy systems, promoting sustainable waste management and resource recovery.
- Increasing integration of RDF into industrial processes (*e.g.*, cement production, power generation) will boost its market potential.

c) Policy and Regulatory Support

- Governments are likely to introduce incentives, subsidies, and regulatory frameworks to encourage the use of RDF and other waste-derived fuels.
- Policies supporting waste diversion from landfills and carbon credit schemes will enhance the financial viability of RDF.

d) Global Market Expansion

- The increasing demand for renewable energy will drive the global adoption of RDF, particularly in regions with abundant waste resources like Asia and Europe.
- The potential for RDF to replace coal and other high-carbon fuels in industrial processes will further enhance its adoption in power plants and cement kilns.

e) Collaboration and Research Initiatives

- Collaborative efforts between governments, industries, and academic institutions will accelerate research on advanced RDF technologies, waste segregation techniques, and emissions control systems.

- Public-private partnerships can facilitate the development of infrastructure and market structures for RDF production and utilization.

8. CONCLUSION

In conclusion, waste-derived fuels (WDF) and refuse-derived fuels (RDF) present a promising solution to address the growing challenges of waste management and energy generation in a sustainable manner. The utilization of waste materials as fuel not only helps in reducing the environmental burden of landfilling but also provides an alternative to conventional fossil fuels, thus contributing to energy security and the reduction of greenhouse gas emissions. Through various processing technologies, including mechanical, thermochemical, and biochemical methods, waste can be converted into valuable energy, offering significant economic, environmental, and social benefits.

However, despite the advantages, there are notable challenges that must be overcome, including high initial capital investments, variability in feedstock quality, and the management of emissions during energy recovery. Additionally, market dynamics, public perception, and policy support play critical roles in determining the extent of RDF adoption globally. Technological advancements in sorting, processing, and combustion methods, coupled with greater integration into circular economy models, will improve the efficiency and environmental footprint of RDF production.

Looking to the future, the global market for RDF is set to grow, driven by the increasing demand for sustainable energy solutions, stricter waste management regulations, and the need to reduce dependence on fossil fuels. Policymakers, industries, and researchers must continue to collaborate to optimize RDF production processes, reduce costs, and improve its performance as an energy source.

Ultimately, the adoption of WDF and RDF presents an opportunity to transition towards a more sustainable and circular economy, where waste is seen as a resource, not a burden. By addressing the challenges and capitalizing on the opportunities, RDF can play a key role in the future of energy systems, driving us toward a more sustainable and environmentally responsible future.

To ensure the global scaling of RDF technologies, strong policy support is essential. Governments should implement enforceable waste segregation mandates, introduce landfill diversion targets, and promote RDF through renewable energy credits, feed-in tariffs, or carbon pricing mechanisms. Internationally harmonized standards for RDF classification and quality can also facilitate cross-border trade and investment in RDF infrastructure.

Furthermore, financial incentives such as tax exemptions, subsidies for RDF co-firing systems, and green public procurement policies can lower adoption barriers. The establishment of public-private partnerships (PPPs) will be critical to mobilize capital and accelerate deployment. Integrating RDF with national circular economy roadmaps and climate action plans can also ensure long-term alignment with sustainability targets.

Finally, capacity building, technology transfer, and international collaboration—particularly in emerging economies—are key to replicating successful RDF models. By translating these insights into pragmatic action, RDF can evolve from a niche alternative to a cornerstone of global energy and waste management systems.

ACKNOWLEDGEMENT

During the preparation of this work the authors used ChatGPT (version 3.5) in order to polish language and avoid grammatical errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

DECLARATION OF COMPETING INTEREST

It is declared that this article is original and written by the stated authors. There is no conflict of interest between the authors.

CONFLICTS OF INTEREST OR COMPETING INTERESTS

No conflicts of interest exist among the authors.

DATA AND CODE AVAILABILITY

All the data is presented in the manuscript. No supplementary data is needed.

SUPPLEMENTARY INFORMATION

No supplementary data is required as no additional material omitted from the main manuscript.

ETHICAL APPROVAL

All the authors have worked in accordance with ethical standard and approved by Netaji Subhas University of Technology.

FUNDING

No funding was provided for the manuscript

AUTHORS CONTRIBUTIONS

Peeyush Phogat: Writing - original draft, Conceptualization, Data Collection and Formal analysis.

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