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Integrating biomass into petrochemical processes: A review of feedstock options and conversion routes

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ABSTRACT

Integrating biomass-derived feedstocks into petrochemical processes in Iran is a potential path toward environmental sustainability, enhancing sustainable energy and material production in the country. Iran possesses extensive fossil reserves. There is a growing demand to develop a diversified energy matrix due to greenhouse gas emissions and worldwide climate concerns. Biomass, a renewable resource, provides a sustainable path for the production of energy as well as chemical feedstocks. This study illustrates the potential of converting available biomass and waste into fuels and petrochemical intermediates, identifying technologies such as gasification, anaerobic digestion, and hydrothermal carbonization. It also examines Iran's biomass resources, technological options, and strategic opportunities for integrating biomass-derived streams into the petrochemical value chain. The study addresses the challenges related to infrastructure development, feedstock logistics, and process optimization, noting that biomass integration offers significant economic and environmental benefits. Integrating biomass as a renewable energy and chemical feedstock supports Iran's long-term sustainability goals while reducing dependence on fossil fuels and feedstocks. This approach also promotes rural and industrial development.

Introduction

Using petrochemical waste to produce biomass in Iran has become increasingly important for environmental preservation and meeting renewable energy demands. The process of converting waste products of the petrochemical industry into useful biomass can serve as a source of energy and fuel in other applications. Fossil fuel use is a primary cause of global warming and air pollution. Oil reserves are non-renewable and unevenly distributed globally; thus, adopting renewable energy is essential to reduce reliance on crude oil [1].

The release of greenhouse gases, primarily carbon dioxide, is a serious environmental problem that needs to be addressed [2]. Approximately 40% of global CO_2 emissions originate from factories (7.6

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Gt per year) and their associated power station emissions (3.9 Gt per year). The petrochemical, oil refinery, cement, glass, and metal-processing sectors are estimated to be the largest sources of these emissions [3].

Petrochemical industries, which have expanded in oil- and gas-producing nations, are major sources of hazardous waste containing toxic compounds [4]. Approximately 80% of the waste in the petroleum industry is hazardous, containing toxic organic compounds and heavy metals. The petrochemical industry generates a variety of solid wastes and sludge that can be defined as hazardous waste by the presence of highly toxic organic constituents and heavy metals. Petrochemical waste in the Pars Special Energy Zone of southern Iran is classified as hazardous and non-hazardous based on its physicochemical characteristics. These wastes are further classified as high-calorific-value organic waste, recyclable inorganic waste, and non-recyclable inorganic waste. Their treatment includes material recycling, energy recovery through incineration, and landfill disposal [5].

1.1. Iran's Energy Context

Iran, a developing nation situated in the south of the Caspian Sea, ranks as one of the leading nations in the availability of both renewable and non-renewable resources [6]. It generates a significant portion of its energy from non-renewable fossil fuels and natural gas reserves. The need to diversify energy sources is evident, as renewable resources contribute less than 1% to total energy consumption (Figure 1) [7]. Because of the abundant fossil fuel reserves, there is limited adoption of low-pollution renewable resources. The country is situated in a high-potential zone for generating renewable energy. By harnessing resources such as biomass, hydropower, wind, solar, and geothermal energy, it can reduce fossil fuel dependency and decrease pollution levels.

Greenhouse gases contribute to global warming and have diverse impacts on the environment and humanity. The threat of global climate change has increased, with fossil fuels being the primary contributor to greenhouse gas emissions [6]. Additionally, approximately one-third of annual CO_2 emissions are absorbed by oceans, gradually increasing water acidity and negatively affecting the biodiversity of marine ecosystems [8]. In 2009, Iran's CO_2 emissions from fossil fuels were approximately 527 million tonnes. Figure 2 illustrates the trend in Iran's CO_2 emissions over the past decade.

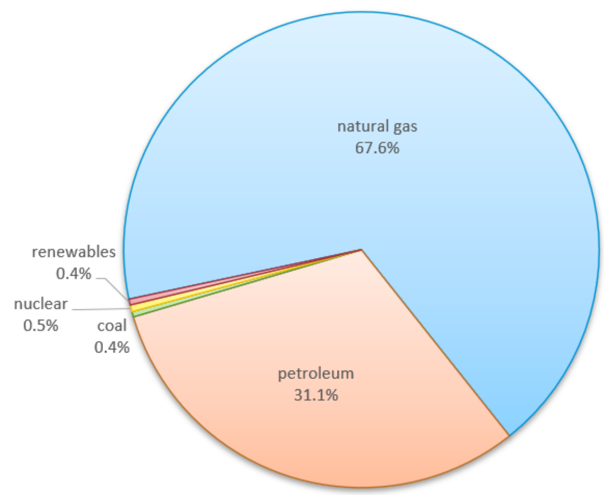

Figure 1. Iran's total primary energy consumption, 2022 [7]

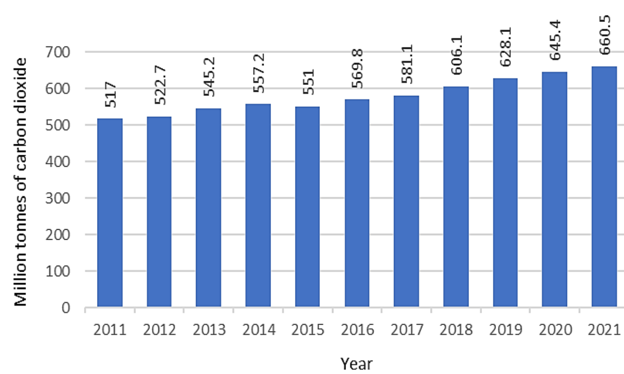

Figure 2. Carbon dioxide emissions from energy in Iran from 2011 to 2021 [9]

Alternative energy sources and production methods must be considered to address these issues. Energy production using biomass offers several significant benefits compared to fossil fuels, including minimizing greenhouse gas emissions, safeguarding the national security of energy, boosting rural development, and providing sustainable fuel for the future [10]. The transition to renewable energy sources—such as solar, wind, hydropower, biomass, and geothermal—should be prioritized in future studies, given Iran's significant potential in this area and the need to address global warming. The government should also encourage private sector investment in renewable energy [11]. It is estimated that most developed nations will use biomass waste to meet over 50% of their total energy requirements by 2050 [12].

This study aims to examine the possibility of converting waste in the petrochemical sector into biomass and integrating biomass into Iran's petrochemical energy matrix.

Environmental and industrial needs for biomass use are outlined in this article, highlighting Iran's low renewable energy share, high CO_2 emissions, and significant hazardous petrochemical waste. This research explores how gasification, anaerobic digestion (AD), and hydrothermal carbonization (HTC) can be applied within the country's petrochemical infrastructure. It examines how local biomass and waste resources can be converted into fuels or petrochemical intermediates, identifies the most suitable technologies for the country's context, and evaluates the environmental and economic implications of such integration.

The objectives include assessing available biomass resources and their characteristics, evaluating the performance and applicability of conversion technologies, and identifying practical integration pathways for petrochemical processes. Based on the literature and national context, the study hypothesizes that (i) Iran's biomass resources are sufficient for petrochemical inputs, (ii) existing infrastructure supports partial biomass integration, and (iii) such integration will provide environmental and strategic benefits, particularly in emissions reduction and rural development. By addressing these aspects, this research provides a framework to facilitate energy diversification within Iran's petrochemical sector.

2. Methodology

This study employed a systematic literature review and qualitative analytical framework to assess the potential for integrating biomass-derived feedstocks into Iran's petrochemical processes. The approach was designed to synthesize existing knowledge on biomass resources, conversion technologies, and integration pathways, while evaluating their applicability within the national context. No primary data collection or empirical modeling was conducted; instead, the analysis relied on secondary data from peer-reviewed publications, government reports, and international energy databases to ensure a robust, evidence-based foundation.

2.1. Data Sources

Data were sourced from a wide array of academic and institutional publications, focusing on biomass utilization, petrochemical processes, and Iran's energy landscape. Key sources include:

- Peer-reviewed journals (e.g., *Renewable and Sustainable Energy Reviews*, *Energy Conversion and Management*, and *Journal of Cleaner Production*) for technological reviews, environmental impacts, and economic assessments [6, 13–17].
- International energy reports from the U.S. Energy Information Administration (EIA) [7], BP Statistical Review of World Energy [9], and the International Energy Agency (IEA) [18] for emission trends, energy consumption statistics, and projections.
- Iranian-specific studies and reports from the Ministry of Power [19], National Petrochemical Company (NPC) [20], and regional analyses (e.g., Pars Special Economic Energy Zone waste characterization [5]; biofuel potential assessments [6, 10, 21]).
- Additional datasets on global and regional biomass potentials from sources like the Food and Agriculture Organization (FAO) and World Bank, integrated via cited works [e.g., Refs. [12, 22]]. The literature was selected using keyword searches (e.g., "biomass integration petrochemical Iran" and "waste-to-energy (WTE) Iran") in databases such as Scopus, Web of Science, and Google Scholar, prioritizing publications from 2000 onward for relevance to modern sustainability goals.

2.2. Time Horizon

The analysis covers historical data from 2003 to 2024 (e.g., energy consumption trends [7, 9] and CO_2 emissions [6, 11]) to establish baseline conditions, with forward-looking projections extending to 2030-2050.

This horizon aligns with Iran's national energy planning (e.g., expected growth in primary energy demand at 2.6% annually to 2030 [6]) and global decarbonization targets (e.g., biomass meeting >50% of energy needs in developed nations by 2050 [12]).

Projections incorporate scenarios for technology scale-up and policy shifts, drawing from techno-economic models in the literature (e.g., production costs for biomass-derived petrochemicals in 2030-2050 [17]).

2.3. Analytical Framework

The study adopts a multi-criteria qualitative framework combining elements of Life Cycle Assessment (LCA) principles for environmental evaluation, Cost-Benefit Analysis (CBA) for economic implications, and comparative technology assessment inspired by Multi-Criteria Decision Analysis (MCDA). These are specifically mentioned in the following subsections.

2.3.1. LCA-Inspired Environmental Assessment

Environmental benefits (e.g., Greenhouse Gas (GHG) reductions and carbon neutrality) are evaluated across the biomass lifecycle, from feedstock sourcing and conversion (gasification, AD, HTC) to integration and end-use in petrochemical processes, using metrics like energy efficiency (>90% recovery in integrated HTC-AD systems [23–25]) and emission offsets (e.g., 55.83% GHG cuts from biofuels [16]). This draws on LCA studies in the references [e.g., Refs. [25-27]] to quantify trade-offs without full quantitative modeling.

2.3.2. CBA for Economic and Strategic Evaluation

Techno-economic indicators such as Capital Expenditure (CAPEX), Operating Expenditure (OPEX), Internal Rate of Return (IRR), and Net Present Value (NPV) are synthesized from the literature [e.g., Refs. [17, 25, 28–33], comparing biomass pathways against fossil baselines. Strategic factors like energy security, rural development, and export potential are assessed qualitatively via CBA frameworks [e.g., Refs. [6, 22, 34]].

2.3.3. MCDA-Inspired Comparative Analysis

Technologies (gasification, AD, HTC) are compared using a structured matrix across criteria including CAPEX/OPEX, IRR/NPV, GHG mitigation, energy efficiency, and constraints, weighted implicitly by Iran's context (e.g., wet biomass prevalence favoring AD/HTC [35, 36]). Site selection examples (e.g., analytic network process (ANP) model for microalgae refineries [35]) inform integration pathways. This framework facilitates a holistic evaluation, hypothesizing biomass sufficiency and benefits (as stated in the Introduction), while identifying challenges. Limitations include reliance on secondary data, which may overlook site-specific variabilities; future work could incorporate primary modeling (e.g., Mixed-Integer Nonlinear Programming (MINLP) optimization [36]).

3. Environmental and Industrial Imperatives for Biomass Utilization in Iran

Biomass is a renewable energy resource because CO_2 released during its combustion or thermal conversion processes does not increase atmospheric CO_2 levels. Biomass is a plant-derived material that undergoes photosynthesis, among other processes. Plants absorb the atmospheric CO_2 released from the decomposition of other organic matter, forming part of a closed-loop system. Light absorption, CO_2 fixation, and the conversion to organic material by vegetation are crucial across various scientific disciplines. This process enables terrestrial and aquatic organisms to use the energy derived from biomass. As a result, using biomass releases CO_2 into the atmosphere, which plants subsequently use to regenerate biomass [37–39].

Biomass is a source of carbon from the biosphere rather than fossilized carbon stored over millions of years. Biomass refers to any organic material used in a non-fossilized form, such as crops, shrubs, trees, animal by-products, animal and human waste, food waste, and other readily decomposable waste streams.

These materials can be replenished cyclically within years or decades. Biomass is a versatile resource capable of producing renewable sources of electricity, heat, transportation fuels, chemical feedstocks, and more under suitable conditions

[13]. Petrochemical waste can be converted to bioenergy, reducing dependence on fossil fuels, curbing climate change, and enhancing the quality of air [14].

4. Biomass Resources and Waste Potential in Iran

In view of the abundance of various types of biomass resources in Iran, the Ministry of Power conducted a study to assess the viability of using them as a renewable fuel resource.

The reported biomass components are animal waste, urban waste, urban wastewater biogas, methane wastewater from industrial sources, and agricultural and wood waste [19].

Iran also has high potential for biofuel production from various biomass feedstocks, such as municipal wastewaters, woodland and forestry wastes, and animal and poultry waste. These feedstocks are prioritized due to their availability and potential to reduce greenhouse gas emissions and produce cleaner fuels [21].

Given the high agricultural waste rate in Iran, the government must effectively manage these resources. One of the best examples is the production of biofuels using crop residuals. The benefits of using biofuels as a substitute for traditional fuel are:

(1) Reducing greenhouse gas emissions,

(2) Decreasing fossil fuel consumption,

(3) Enhancing national energy security,

(4) Promoting rural development

(5) Ensuring a renewable fuel supply in the future.

Ethanol provides a high energy yield, making it highly favorable compared to other renewable fuels [19].

There are various technologies available to convert biomass into energy, including gasification, bioethanol production, anaerobic digestion to produce biogas, biodiesel production, and combustion. In Iran, biogas production using anaerobic digestion is the preferred choice owing to its efficiency and the least water consumption [15].

Biomass waste is a renewable energy resource that can be converted into bioenergy through various technologies [40].

Biomass is decomposed by microorganisms or is burned and transformed into ash through thermal incinerators, as well as kiln co-incineration, converting the chemical energy into mechanical or electrical energy.

If the biomass undergoes natural biocomposting processes, it emits carbon in the form of methane or CO_2 back into the environment. Figure 3 illustrates the general closed loop of biomass energy flow [41].

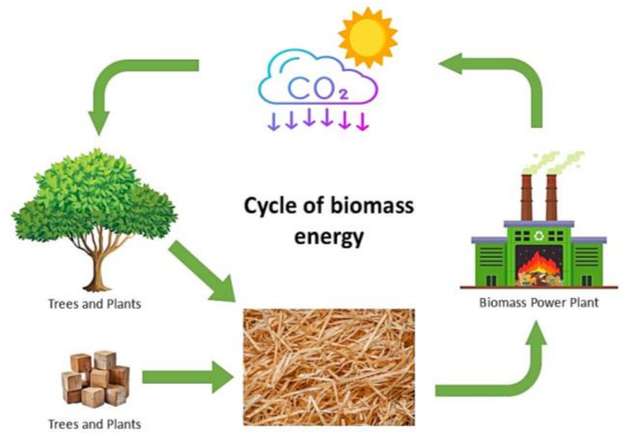

Figure 3. The general cycle of biomass energy [22]

5. Technological Pathways for Biomass Conversion and Integration into Petrochemical Processes

There are various technologies to convert biomass into fuel and chemicals. Gasification is a major one, generating hydrogen-rich syngas that can be directly used in the petrochemical sector for the production of ammonia, methanol, and various other chemicals [42, 43].

Gasification is a process similar to combustion, in which biomass is burned at elevated temperatures with insufficient oxygen for complete combustion. Products include a gas (the desired product) and a solid whose composition is determined by the biomass involved [13].

There are many routes for the conversion of syngas derived from biomass into petrochemical feedstocks. For example, consider the olefins conversion chain where olefins like ethylene and propylene are converted into polymers (such as polyethylene, polypropylene, and PVC), the glycols (such as ethylene glycol and propylene glycol), as well as a host of ordinary products such as acetone, acetic acid, petrol additives, and surfactants. The olefins can be made by converting naphtha through a Fischer-Tropsch process, followed by cracking in a standard naphtha cracker into ethylene and propylene. Alternatively, a methanol-to-olefins (MTO) conversion can make use of methanol, a syngas product [44].

Syngas purity is one of the factors that impacts the optimization of conversion pathways [45]. Another significant aspect is the H_2 to CO ratio in the syngas [44]. Other technologies include bioethanol and biogas production via biochemical processes, which have also been recognized as potential opportunities in Iran [16]. In addition, hydrothermal carbonization stands out as a promising approach to the conversion of waste biomass to energy and material, in keeping with the circular bioeconomy concept [46].

Electrochemical processing of lignocellulosic biomass into platform chemicals is also being investigated as a green replacement for conventional petrochemical processes [47]. Agricultural waste, e.g., lignocellulosic biomass, is also a good raw material for the production of biofuels, biocomposites, and bioplastics [48]. Bioethanol production using agricultural waste can substitute for harmful fuel additives such as Methyl Tertiary Butyl Ether (MTBE) in gasoline, promoting fuel security and minimizing environmental footprint [14].

Waste-to-energy conversion in Iran can also avoid the combustion of fossil fuels, ubsequently decreasing CO_2 emissions and bringing economic benefits through the petrochemical exports [26]. In the context of electricity, biogas that is generated in waste-to-energy facilities, as well as waste itself, can also be viewed as an opportunity [49]. Basic petrochemicals, including ethylene, propylene, and aromatics, are the feedstock of the chemical industry. At present, they are mainly manufactured through traditional process routes using naphtha (crude oil derivative) and ethane (natural gas derivative) [50, 51].

Recently, conventional feedstock routes using methane, coal, and biomass to generate base petrochemicals have gained significant interest [17]. Most biomass and coal-based pathways are more economical compared with the majority of the oil and natural gas-based pathways. The ranges of their production costs differ by approximately \$100–200/t for High-Value Chemicals (HVCs), and in some instances, the differences are considerably higher. The cost of CO_2 emissions is pronounced for coal-based pathways; it is also quite pronounced in the case of the biomass-based pathways, but comparatively moderate in the case of the oil- and natural gas-based pathways [17].

Compared with the amount of attention focused on the use of biomass as fuel or heat supply, far less attention has been focused on biomass as a chemical feedstock. But as traditional feedstocks become more constrained in a world where nations are striving to achieve goals of lowering carbon dioxide emissions, the question arises whether burning biomass is optimal [13].

The prime petrochemical feedstocks are naphtha-type crude fractions, heavier oils, and natural gas. The tasks regarding biomass involve finding a cost-effective method of making such feedstocks for use with current petrochemical technology, or making alternative feedstocks (e.g., sources of carbon) that would have to be processed differently. The climate change advantage is from the short carbon cycle of biomass, i.e., the greater part of the CO_2 emitted from the conversion and use of biomass is balanced by the CO_2 fixed by the recent growth of such biomass [13].

Research shows that anaerobic digestion (AD) of biomass waste from petrochemical industries can produce significant amounts of biogas, which can be conditioned and potentially supplied to natural gas pipelines for use as a feedstock in petrochemical facilities [52]. Partial substitution can be achieved in petrochemical processes while biomass products are being investigated and optimized. For instance, bio-oil can be co-processed with traditional crude oil in Fluid Catalytic Cracking (FCC) processes to produce hydrocarbons. By doing so, fewer oxygenated hydrocarbons are yielded compared to a pure bio-oil stream, but more coke is formed compared with the FCC of traditional crude oil [53].

5.1. Theoretical Framework for Technology Integration

A robust theoretical framework for integrating gasification, anaerobic digestion, and hydrothermal carbonization within the petrochemical value chain is grounded in complementary process selection, synergistic integration, and supply chain optimization, enabling circular, low-carbon, and economically viable operations [23, 36, 54–56].

Gasification is well-suited for dry or pretreated biomass, converting it into syngas (CO, H_2, CH_4), which can be directly used as a renewable feedstock for petrochemical synthesis or energy generation. In contrast, AD is optimal for wet biomass, producing biogas (mainly CH_4 and CO_2) and digestate, both of which can be further valorized through downstream applications. HTC treats wet biomass at moderate temperatures to yield hydrochar and nutrient-rich process water; these outputs can then be fed into AD or gasification systems for further energy and material recovery [23, 55]. Integration of these technologies, whether sequentially (e.g., HTC followed by gasification or AD) or in parallel, enhances energy yields and carbon conversion, while minimizing waste streams [23, 54–56]. Such combinations align with circular economy principles by enabling multi-stream valorization of biomass and waste into energy, chemicals, and reusable materials [36, 55, 56]. To ensure operational and economic feasibility, this framework also emphasizes supply chain design, covering feedstock sourcing, transportation, siting, and distribution, with consideration of both environmental and financial objectives [36]. Additionally, advanced tools like MINLP are critical for simultaneously optimizing process configurations and logistics, facilitating alignment with the petrochemical sector's decarbonization targets through renewable intermediates such as syngas, biogas, and hydrochar [36, 55, 56].

5.2. Comparative Analysis of Biomass Conversion Technologies

Gasification provides high energy efficiency and hydrogen-rich syngas, valuable for petrochemical synthesis, but typically requires higher CAPEX and advanced syngas cleaning [28–31]. Anaerobic digestion is the most cost-effective option for wet biomass, with low CAPEX/OPEX, though it produces lower-energy-density biogas and leaves digestate that must be managed [23, 32, 33, 56, 55]. HTC efficiently treats wet biomass at lower temperatures than gasification and yields hydrochar and process water that can be further valorized via AD or gasification; commercial scale-up and process-water/hydrochar valorization remain key hurdles [24, 25, 55, 57–59]. Economically, gasification can deliver favorable IRR/NPV at large integrated scales despite higher CAPEX [28–31] AD's low CAPEX/OPEX suits decentralized applications, but returns can be constrained by energy yield and digestate costs [23, 32, 33, 56, 55], and HTC's moderate CAPEX improves when integrated with AD or other routes, especially in supply-chain-optimized settings [25, 36, 57]. Environmentally, gasification can reach ~80% energy efficiency with substantial GHG reductions when displacing fossil syngas [28-31] AD is highly effective in mitigating GHGs from wet wastes, particularly when biogas is upgraded and used as renewable fuel [23, 32, 33, 56, 55].

HTC coupled with AD can recover >90% of feedstock energy and further cut GHGs by valorizing both solid and liquid fractions, with Life Cycle Assessments showing integrated HTC-AD systems outperform standalone options [23-25].

A concise comparison of gasification, anaerobic digestion, and hydrothermal carbonization across CAPEX/OPEX, IRR/NPV, GHG mitigation, energy efficiency, and key constraints is provided in Table 1.

6. **Economic and Strategic Implications of Biomass Integration**

Biomass has the potential to reduce greenhouse gas emissions and dependence on fossil fuels while replacing fossil-based energy and chemicals with renewable alternatives. Using biomass for biofuels can cut greenhouse gas emissions by as much as 55.83% in certain cases, and incorporating biomass into the petrochemical sector can have benefits beyond its cost [16].

In addition, biomass use can create jobs in rural areas and lead to a circular economy through resource value maximization and waste minimization [34, 22].

Iran's primary energy demand is expected to grow at an average annual rate of 2.6% over 2003-2030, down from about 5% over the past decade. This growth is expected, provided the gradual elimination of energy subsidies (currently 10 percent of Gross Domestic Product (GDP)). Iran has the world's second-largest natural gas reserves. Gas output is expected to total 240 billion cubic meters (bcm) by 2030. Electricity generation is expected to increase from 153 terawatt-hour (TWh) in 2003 to 359 TWh by 2030; hence, the need for 54 gigawatt (GW) new generating capacity, and total investment in power infrastructure will cost $92 billion.

It is renewable energies, specifically biofuels, that can provide Iran with an increased share of non-fossil energy sources, and thus, reduce fossil fuel consumption [6]. Iran's energy consumption, as illustrated in Figure 4, ranks among the highest in the world, comparable to the U.S. and China. However, it exceeds that of India, even though it is lower than that of the U.S. and China. This situation highlights the potential for alternative energy sources, such as biomass.

Generally, WTE for municipal solid waste (MSW) can decrease greenhouse gas emissions and, at the same time, retain economic advantages, as it balances energy conversion and waste consumption to achieve an optimal state [26]. Government support and investments have increased, while the technology has improved and costs have decreased; this will lead to the consideration of more WTE in developing markets [60, 61]. In the energy sector, bioenergy and biomass have always been a sustainable alternative in renewable energy [62–64].

The potential of using the available energy sources for providing electricity in Isfahan (Iran) has been investigated, where the three main energy sources are wind, solar, and biomass. In considering the system's life cycle and economic performance, biomass was identified as the most efficient and economically viable energy source [27]. Important criteria in selecting a suitable location for biomass refineries include air temperature, access to salt water, startup costs, availability of human resources, and proximity to the petrochemical industry [35].

6.1. Petrochemical Industry Context

The petrochemical industry is the third most energy-intensive industry in Iran, accounting for 16% of the country's total energy consumption. The history of Iran's petrochemical industry dates back to 1963 with the establishment of a fertilizer plant in the city of Shiraz. One year later, the state-owned NPC came into being. There are two petrochemical Special Economic Zones in Iran, Maahshahr and Assaluyeh, located in southern Iran along the Persian Gulf.

Table 1. Concise comparison of biomass conversion options for petrochemical integration.

Process	CAPEX / OPEX	IRR / NPV	GHG reductions	Energy efficiency	Ref
Gasification	High CAPEX; OPEX elevated by tar control & syngas cleanup	Favorable at large, integrated scales	High when displacing fossil syngas; integration dependent	Up to ~80% with suitable integration	[28–31]
AD	Low CAPEX/OPEX; costs for digestate handling	Constrained by lower energy yield & digestate costs	High for wet wastes; upgrading biogas boosts benefits	Lower product energy density	[23, 32, 33, 56, 55]
HTC	Moderate CAPEX; economics improve with valorization/integration	Improves when integrated	High with AD coupling (valorizes solid & liquid)	>90% energy recovery when HTC+AD valorize both fractions	[24, 25, 29, 55, 57–59]

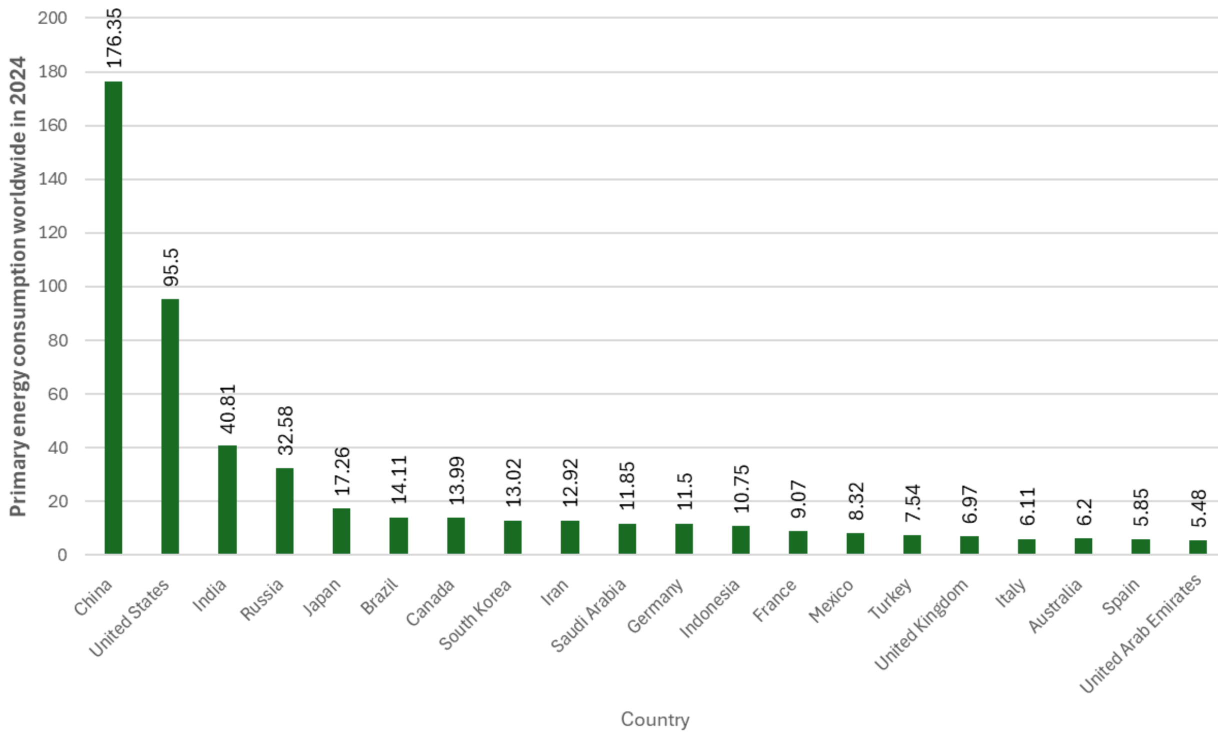

Figure 4. Global primary energy consumption in 2024 by country [18]

The country's biggest petrochemical complex is Bandar Imam Petrochemicals, followed by Marun, Borzuyeh, Shiraz, Pars, Razi, Arak, and Bou Ali Sina [20].

A notable example of biomass utilization in Iran, as illustrated by recent research, is the establishment of microalgae-based biomass refineries optimized through strategic site selection. A study conducted by Pashmi et al. evaluated potential refinery locations using an ANP model based on environmental, economic, social, and logistical criteria, ultimately identifying Bushehr as the optimal site. The selection of Bushehr was primarily influenced by its favorable conditions for algae cultivation, including abundant sunlight, saline water, and sufficient carbon dioxide emissions, making it an ideal hub for biomass production. Economically, the optimized transportation routes associated with Bushehr significantly reduced supply chain expenses, enhancing the viability and competitiveness of bioenergy production. From an environment perspective, cultivating algae in this region offered substantial benefits, such as reducing atmospheric CO_2 levels, purifying wastewater, and removing heavy metals. All of these factors contributed positively to local environmental conditions. Thus, this case study demonstrated a practical pathway toward converting petrochemical industry waste into valuable biomass energy, aligning effectively with Iran's broader sustainability and energy diversification goals [35].

7. Challenges and Future Directions for Biomass in Iran's Petrochemical Industry

The integration of biomass into Iran's petrochemical industry remains a promising yet demanding area, as infrastructure development and logistics planning for biomass collection and transportation are key factors that need to be addressed [13]. Factors such as optimizing conversion processes and implementing cooperative stakeholder mechanisms within value chains are also necessary to realize the full potential of biomass use [34]. Further research and development directed towards better conversion efficiencies and broader biomass applications in industrial practice are needed [65, 43]. This depiction of systemic and technical challenges, which include social and research challenges, is reflected in Figure 5, where challenges are classified into biomass-related, process-related, and overlapping issues [53].

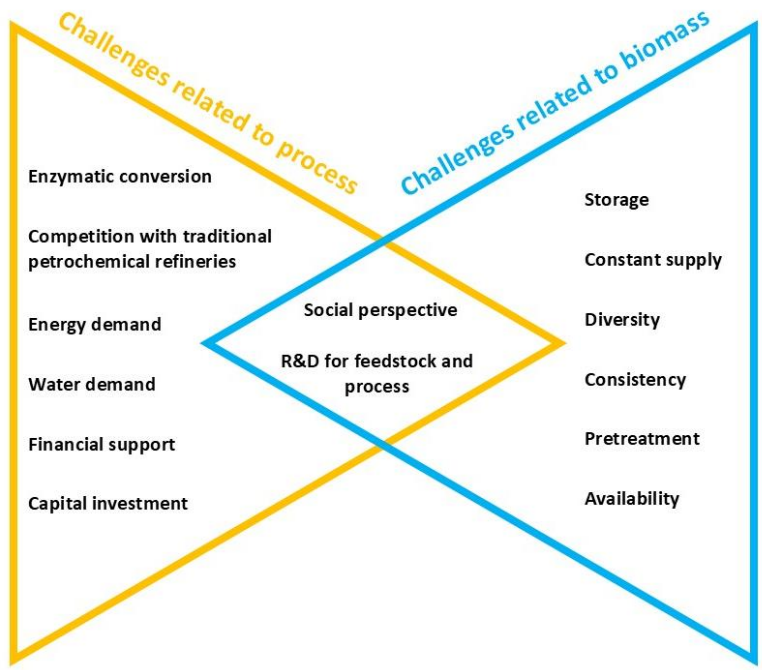

Figure 5. Main challenges for biofuel production in biorefineries [53]

A central issue driving the planning of research, development, and commercialization of biomass-to-chemicals activities is whether biomass can compete based on direct substitution or by performing the same functions as petrochemicals without replicating their molecular structures [66]. Direct substitution of biomass-derived olefins for petrochemical olefins has been discussed by Rudd and colleagues [67]. Studies indicate that petrochemical olefins are still tenable despite competing with biomass, even at elevated prices of petroleum and natural gas liquids, owing to the adverse stoichiometry of the biomass-to-petrochemical reactions [67]. It offers the best opportunities for direct substitution in industrialized nations where biomass is a significant resource, via petrochemicals produced through a multiple-reaction method (derived from petrochemical olefins) [67]. Therefore, in line with today's energy and environmental goals, renewable sources like biomass are gaining attention. Biomass includes all kinds of organic material from plants or animals, especially the biodegradable parts of agricultural, forestry, industrial, and household waste, as well as products derived from processing such materials [68].

7.1. Policy, Industry, and Research Directions

The integration of biomass into Iran's industrial processes offers a pathway to sustainable energy production and environmental improvement, necessitating targeted policy and industry actions alongside focused research to overcome existing challenges. The Iranian government should introduce subsidies and tax exemptions to offset high capital expenditures for technologies like gasification and HTC. By enforcing stricter waste segregation policies, a steady supply of biomass feedstocks, such as municipal solid waste and agricultural residues, is ensured. Fostering public-private partnerships to fund decentralized AD facilities promotes rural development and reduces greenhouse gas emissions. Industry stakeholders, particularly in major complexes, should adopt hybrid systems combining HTC with AD or gasification, optimize supply chains using tools like MINLP, and prioritize syngas purification to meet industrial standards. These actions will enhance economic viability and compatibility with existing processes. Future research should focus on improving conversion efficiencies through advanced catalysts, exploring underutilized feedstocks like microalgae, developing cost-effective logistics models for Iran's infrastructure, and quantifying socioeconomic benefits via life cycle assessments to inform policy design. These concerted efforts will support Iran's energy diversification goals, reduce fossil fuel dependency, and contribute to global climate action.

5. Conclusion

The conversion of petrochemical industry waste to bioenergy in Iran presents a viable and impactful pathway for sustainable energy production and environmental improvement. By leveraging the country's substantial biomass resources, such as agricultural residues, animal waste, and municipal solid waste, and applying proven technologies like gasification, anaerobic digestion, and biochemical conversion, it is possible to reduce greenhouse gas emissions, improve air quality, and decrease reliance on fossil fuels. Furthermore, integrating biomass into petrochemical processes offers a dual advantage of addressing waste management issues while producing valuable chemical feedstocks. Despite existing challenges in infrastructure, economic incentives, and policy frameworks, the environmental and economic benefits of this approach are significant. Future efforts should prioritize technological innovation, investment in biomass infrastructure, and cross-sector collaboration to ensure the successful implementation of biomass strategies. This transition not only supports Iran's energy diversification goals but also contributes to global climate action and sustainable development.

Abbreviations

AD	Anaerobic digestion
ANP	Analytic network process
bcm	Billion Cubic Meters
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
EIA	Energy Information Administration
FAO	Food and Agriculture Organization
FCC	Fluid catalytic cracking
GDP	Gross domestic product
GHG	Greenhouse Gas
Gt	Giga Tons
GW	Gigawatt
HTC	Hydrothermal carbonization
HVC	High-value chemicals
IEA	International Energy Agency
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
MINLP	Mixed-Integer Nonlinear Programming
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
MTO	Methanol-to-olefins
NPC	National petrochemical company
NPV	Net Present Value
OPEX	Operating Expenditure
PVC	Polyvinyl chloride
RES	Renewable energy source
TWh	Terawatt-hour
WTE	Waste-to-energy

Authors contribution

All authors contributed equally to the conception, design, analysis, and manuscript preparation.

Conflict of interest

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