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Review

State of the Art of Biomethane Production in the Mediterranean Region

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Abstract

The Mediterranean region is increasingly confronted with intersecting environmental, agricultural, and socio-economic challenges, including biowaste accumulation, soil degradation, and high dependency on imported fossil fuels. Biomethane, a renewable substitute for natural gas, offers a strategic solution that aligns with the region's need for sustainable energy transition and circular resource management. This review examines the current state of biomethane production in the Mediterranean area, with a focus on anaerobic digestion (AD) technologies, feedstock availability, policy drivers, and integration into the circular bioeconomy (CBE) framework. Emphasis is placed on the valorisation of regionally abundant feedstocks such as olive pomace, citrus peel, grape marc, cactus pear (*Opuntia ficus-indica*) residues, livestock manure, and the Organic Fraction of Municipal Solid Waste (OFMSW). The multifunctionality of AD—producing renewable energy and nutrient-rich digestate—is highlighted for its dual role in reducing greenhouse gas (GHG) emissions and restoring soil health, especially in areas threatened by desertification such as Sicily (Italy), Spain, Malta, and Greece. The review also explores emerging innovations in biogas upgrading, nutrient recovery, and digital monitoring, along with the role of Renewable Energy Directive III (RED III) and national biomethane strategies in scaling up deployment. Case studies and decentralised implementation models underscore the socio-technical feasibility of biomethane systems across rural and insular territories. Despite significant potential, barriers such as feedstock variability, infrastructural gaps, and policy fragmentation remain. The paper concludes with a roadmap for research and policy to advance biomethane as a pillar of Mediterranean climate resilience, energy autonomy and sustainable agriculture within a circular bioeconomy paradigm.

Keywords: anaerobic digestion; Mediterranean agriculture; circular bioeconomy; agricultural residues; OFMSW; renewable energy sources; sustainability

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1. Introduction

The Mediterranean basin is widely recognised as one of the most climate-vulnerable regions in the world, facing mounting challenges from prolonged drought periods, rising temperatures, increasing water scarcity, and a persistent dependency on fossil fuel imports [1,2]. These environmental pressures are further compounded by demographic factors such as high population density and the generation of substantial quantities of organic waste from agricultural, livestock, agro-industrial, and urban sectors [3]. In this context, organic waste streams represent an underutilised yet strategic resource for renewable energy production within the framework of the circular bioeconomy (CBE), supporting both environmental sustainability, and economic resilience.

Among the available renewable energy technologies, anaerobic digestion (AD) has emerged as a mature, flexible, and scalable solution for the treatment of organic substrates. Through this biological process, biodegradable waste is transformed into biogas and digestate. Biogas, in turn, can be valorised through Combined Heat and Power (CHP) systems or upgraded to biomethane, a renewable and grid-compatible alternative to natural gas, which can also be used as a sustainable transport fuel [4–8]. The deployment of AD technologies contributes to multiple sustainability objectives, including the reduction in greenhouse gas (GHG) emissions, the valorisation of local waste streams, and the enhancement of energy security in a region highly dependent on energy imports [9,10].

Foundational research in this field includes the study of Comparetti et al. (2012) [11], who evaluated the energy recovery potential from livestock and agro-industrial residues, establishing a baseline for the development of AD-based energy strategies in Mediterranean rural areas. Attard et al. (2017) [7] further demonstrated the viability of AD systems in Mediterranean island contexts, where such technologies align with local renewable energy and waste management objectives. In more recent years, Greco et al. (2022) [12] highlighted the socio-economic and environmental co-benefits associated with small-scale biowaste AD plants, particularly in peri-urban and urban-rural interface zones.

Complementary valorisation pathways have also been investigated. Greco et al. (2019a) [13] examined manure pyrolysis as an alternative route for waste conversion, while Comparetti et al. (2017) [14] and Greco et al. (2019b) [15] explored nutrient recycling from cactus pear residues as a circular approach to agri-food by-product management. Additional studies by Campiotti et al. (2019) [16] have emphasised the role of renewable energy, including biomethane, in reducing the environmental footprint of Mediterranean greenhouse production systems.

In this integrated context, biomethane production is not only a pathway to clean energy but also an enabler of sustainable rural development, especially when implemented in multifunctional farming systems that integrate energy, nutrient cycling, and waste management [8,17]. Furthermore, Greco et al. (2020, 2021) [18,19] demonstrated that compost and vermicompost derived from digestate can successfully replace peat in growing media, thus contributing to closing the organic matter loop and enhancing soil fertility.

Taken together, these studies underscore the role of biomethane production via AD as a strategic driver for sustainable energy transitions, resource circularity, and climate resilience in Mediterranean agri-food systems.

Building on this foundation, the present review analyses the current state of biomethane production across the Mediterranean region. Particular attention is given to the development and deployment of AD technologies, the availability and regional distribution of feedstocks, and the evolving policy and regulatory frameworks supporting their adoption within the circular bioeconomy paradigm. Moreover, the review highlights emerging innovations in biogas upgrading technologies, nutrient recovery, and digital process monitoring, as well as the implications of the Renewable Energy Directive III (RED III) and national biomethane roadmaps for future scaling up.

Table 1 summarises representative examples of AD plants operating in Mediterranean countries, detailing the primary feedstock sources, plant capacities, and biogas valorisation pathways. These examples illustrate how region-specific organic residues are integrated into circular bioeconomy systems, supporting sustainable energy generation and promoting agricultural and rural development.

Table 1. Overview of selected anaerobic digestion (AD) plants in the Mediterranean region, highlighting dominant feedstocks and pathways of biogas valorisation. The listed examples illustrate region-specific integration of agricultural residues into bioenergy systems and the alignment with local circular bioeconomy strategies.

Country	Region	Plant Name/Project	Feedstocks Used	Biogas Valorisation	Notes
Italy	Emilia-Romagna, Sicily	Azienda Agricola Speranza, ILSA Biometano	Livestock manure, olive pomace, grape marc	Upgrading to biomethane gas grid injection	Feed-in tariff incentives under the Biometano Decree
Spain	Catalonia, Murcia	Ecobiogas Murcia, AEMA Biogás	Citrus peel, OFMSW, agro-industrial waste	CHP and partial upgrading	Industrial parks use heat and electricity locally
France	Occitanie, Provence	Agribiométhane, Méthabaz	Livestock manure, pruning biomass, winery waste	Grid injection (GRDF), vehicle fuel	Strong national support through long-term purchase contracts
Greece	Thessaly, Crete	Bioenergy Thessaly pilot, Heraklion Coop	Dairy manure, olive mill waste, fruit waste	Electricity production (CHP)	EU-funded pilot under Horizon 2020 and innovation grants
Tunisia	Cap Bon, Kairouan	Biogas CapBon, PommeVerte Pilot	Tomato waste, cattle slurry, fruit residues	CHP (local use in farms)	GIZ and EIB pilot; digestate used as organic fertiliser in orchards

2. Biomethane Production Technologies

Biomethane production in the Mediterranean region is primarily based on anaerobic digestion (AD), a well-established and versatile biotechnology that enables the biological conversion of organic matter into biogas and digestate under anaerobic conditions (Figure 1). This process is adaptable to various scales and feedstocks, making it particularly suited to the diversified agricultural, livestock, and agro-industrial contexts of Mediterranean countries.

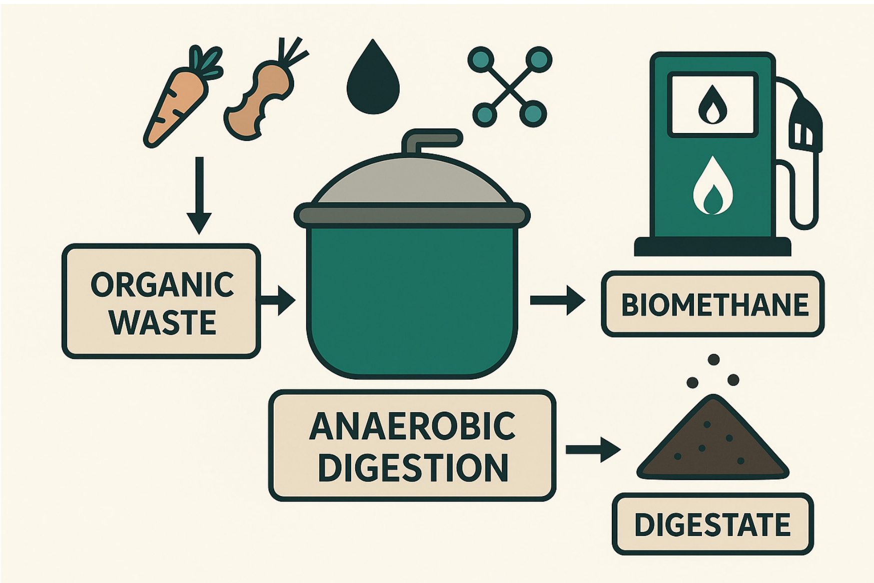

Figure 1. Schematic representation of the anaerobic digestion process aimed at converting organic waste into biomethane and digestate.

The efficiency and stability of the AD process are influenced by a complex interplay of physicochemical and biological parameters. Among the most critical factors are the biochemical composition of the feedstock—especially the carbon-to-nitrogen (C/N) ratio—along with operational conditions such as pH, hydraulic retention time (HRT), and the activity of microbial consortia that drive the sequential stages of anaerobic conversion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Environmental temperature plays a decisive role in modulating microbial kinetics. In Mediterranean climates, thermophilic digestion (50–60 °C) is often favoured due to the elevated ambient temperatures, promoting faster reaction rates and more efficient pathogen inactivation. Nevertheless, thermophilic systems demand greater energy input and precise operational control compared to mesophilic processes, posing challenges in terms of energy balance and process stability [20,21].

A major bottleneck for biomethane production in the Mediterranean context is the heterogeneous nature of available biomass, particularly lignocellulosic residues derived from crop production and agro-industrial processing. These include straw, vineyard, and orchard pruning residues and fruit-processing by-products, which are inherently recalcitrant to microbial degradation. To address this, various pre-treatment technologies are being increasingly implemented to enhance the bioavailability of complex substrates. Mechanical comminution, steam explosion, thermal hydrolysis, and chemical conditioning (alkaline or acidic) are among the techniques employed to disrupt lignocellulosic structures, increase the accessible surface area, and facilitate enzymatic hydrolysis, ultimately improving methane yields [22,23].

Co-digestion strategies represent another key optimisation approach, particularly relevant in the Mediterranean agri-food sector. By combining livestock manure—an abundant resource that provides buffering capacity, essential micronutrients, and a natural microbial inoculum—with high-energy agro-industrial residues such as olive mill wastewater, citrus peels, and winery grape marc, it is possible to achieve a more balanced nutrient composition and stimulate synergistic microbial interactions. Co-digestion not only enhances process stability and methane production but also supports the integrated management of organic waste streams within agro-industrial clusters, thereby promoting industrial symbiosis and regional waste valorisation [24,25].

Beyond energy production, the anaerobic process generates a nutrient-rich digestate, which can be valorised as an organic fertiliser or soil amendment. The application of digestate in agriculture contributes to nutrient recycling and soil fertility improvement, aligning with circular bioeconomy principles. This dual role of AD—producing renewable biomethane while recycling nutrients—positions the technology as a cornerstone of sustainable energy and waste management strategies in Mediterranean agriculture. In this context, decentralised energy solutions and distributed resource recovery systems are increasingly vital to building climate-resilient and energy-independent farming communities, particularly in light of ongoing climate change challenges and evolving energy transition policies [3,26].

Raw biogas, as produced by anaerobic digestion, typically consists of 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2), along with trace amounts of hydrogen sulphide (H_2S), ammonia (NH_3), siloxanes, and water vapour. To transform this raw biogas into biomethane—a high-purity renewable gas suitable for grid injection or as a vehicle fuel—it is necessary to remove CO_2 and these contaminants. This upgrading process not only increases the methane concentration but also ensures compliance with pipeline specifications and protects end-use equipment from corrosion or fouling.

Several upgrading technologies are currently available, each with distinct operational characteristics and suitability depending on plant scale, feedstock variability, and economic considerations. The most widely applied methods include Pressure Swing Adsorption (PSA), water scrubbing, chemical absorption using amines, membrane separation, and cryogenic upgrading.

Pressure Swing Adsorption (PSA) systems operate based on the selective adsorption of gas components onto porous media under varying pressure conditions. PSA is particularly effective for plants with stable biogas flow rates and allows for reliable methane recovery [27,28]. Water scrubbing, a physical absorption process, exploits the greater solubility of CO_2 and H_2S in water relative to methane. It is widely applied in small- to medium-scale AD plants due to its relative simplicity, moderate operational costs, and minimal chemical use, making it a favourable option in decentralised Mediterranean agricultural contexts.

Chemical absorption, typically using amine solutions, provides high selectivity and methane purity by chemically binding CO_2. This technology is well-suited to large-scale facilities where the higher operational and maintenance costs are justified by economies of scale and the need for consistently high-purity biomethane [27,28].

Membrane separation technologies are gaining increasing traction for agricultural biogas upgrading. These systems rely on the differential permeability of gas molecules through polymeric or ceramic membranes, allowing for the selective separation of CO_2 from CH_4. Membrane systems are highly modular, energy-efficient, and easy to integrate into existing AD plants. Their compact footprint and scalability make them particularly attractive for decentralised, small- to medium-scale agricultural plants in the Mediterranean region, where space and economic efficiency are key considerations [29,30].

Cryogenic upgrading, which separates gas components through selective condensation and liquefaction at very low temperatures, achieves biomethane with exceptionally high purity. However, it is energy-intensive and economically viable primarily for large-scale or centralised operations, particularly those producing liquefied biomethane (Bio-LNG) for transport and storage applications.

Beyond these established technologies, several emerging approaches are expanding the potential for biomethane upgrading, particularly in distributed and small-scale systems. Biological methanation is an innovative process where hydrogen reacts with CO_2 under the action of methanogenic archaea, producing additional methane. This approach not only upgrades biogas but also integrates renewable electricity through power-to-gas applications, improving the overall energy system flexibility.

Additionally, compact, containerised upgrading solutions are being deployed in small cooperative networks and multifunctional farms. These modular systems offer scalable, plug-and-play solutions that require minimal infrastructure investment, enabling local energy production and consumption. Such systems are well suited to Mediterranean agricultural landscapes, where energy autonomy, circular resource management, and cost-effectiveness are essential for sustainable rural development [31,32].

Together, these advancements in upgrading technologies are facilitating the wider deployment of biomethane as a renewable energy carrier, supporting the transition towards decentralised energy systems and circular bioeconomies in Mediterranean agricultural regions.

3. Feedstocks in the Mediterranean Region

The Mediterranean region, characterised by favourable agro-climatic conditions and exceptional agricultural biodiversity, offers a diverse range of organic feedstocks suitable for biomethane production through anaerobic digestion (AD). The utilisation of these bioresources is consistent with the principles of the circular bioeconomy, fostering sustainable rural development in territories often challenged by water scarcity, energy dependency, and fragmented agricultural landscapes.

Among the most promising energy crops, cactus pear (*Opuntia ficus-indica*), a Crassulacean Acid Metabolism (CAM) species well adapted to arid environments, has been extensively studied. Comparetti et al. (2017) [14] demonstrated that the cladodes of *O. ficus-indica* serve as an efficient substrate for AD, yielding methane-rich biogas and nutrient-dense digestate suitable for soil improvement. Agro-industrial residues also provide a significant resource base. By-products from winemaking, such as grape marc, along with olive oil production residues like pomace and wastewater, and citrus fruit processing wastes such as peels, represent abundant and locally available feedstocks. Their integration into AD systems not only facilitates the reduction in organic waste but also contributes to decentralised energy production across rural and peri-urban areas [33,34].

Livestock manure continues to play a foundational role in Mediterranean AD systems, owing to its stable composition, buffering capacity, and balanced nutrient content. Studies by Greco et al. (2019a) and Attard et al. (2023) [13,17] have shown its critical role in island contexts, where the need for local energy autonomy is pronounced. Furthermore, co-digestion strategies that combine livestock manure with agro-industrial by-products such as tomato processing waste, olive pomace, and grape marc have proven effective in enhancing methane production. These combinations optimise the carbon-to-nitrogen (C/N) ratio of the feedstock mix and increase overall biodegradability, leading to more stable and productive AD processes [19,21].

In addition to these widely used feedstocks, emerging attention has been given to underutilised biomass streams. Pruning residues from orchards and vineyards, unsold fruit and vegetables from local markets, and biomass from invasive plant species such as *Ailanthus altissima* are increasingly being investigated as supplementary substrates for AD [35–37]. These resources are particularly well suited for small-scale or cooperative AD plants, which promote local energy self-sufficiency, reduce the environmental impact of organic waste, and diversify rural incomes. Such initiatives align with the objectives of the European Renewable Energy Directive and the Circular Economy Action Plan, both of which encourage the sustainable management of bioresources and the development of local energy systems.

Despite these advances, the number of studies specifically focusing on Mediterranean feedstocks for biomethane production remains limited when compared to the research output from Northern and Central Europe. While the scientific literature on the topic is expanding, further investigations are required to assess the availability, seasonal fluctuations, and local sustainability of these feedstocks. According to a bibliometric analysis by Zhou (2022) [38], Italy and Spain currently lead biomethane research in the region, but significant gaps remain in southern Mediterranean countries, where research efforts and technology deployment are still emerging.

Feedstock pretreatment represents a critical area for improving AD efficiency in the Mediterranean context. Various thermal processes, such as hot water or steam application, have been evaluated to enhance the biodegradability of lignocellulosic residues like pruning waste. Alkaline treatments, using sodium hydroxide (NaOH) or lime, have been applied to olive pomace and grape marc to disrupt lignocellulosic structures and improve microbial accessibility [39]. Biological pretreatment methods, such as the application of white-rot fungi, have also been explored to degrade lignin components, thus facilitating higher methane yields [40]. These pretreatment strategies contribute not only to increasing methane production but also to reducing the inhibitory effects of compounds such as limonene and polyphenols, which are commonly present in citrus peel and olive mill effluents [36,37]. Moreover, co-digestion with livestock manure or food waste further mitigates the presence of toxic substances and promotes the stability of microbial communities, improving overall process performance.

Digestate, the residual material from the anaerobic process, has shown substantial agronomic potential when applied to Mediterranean soils. Field experiments conducted in Sicily, Spain, and Tunisia have demonstrated that digestate enhances soil organic matter content, improves water retention capacity, and increases crop yields, particularly in degraded soils suffering from fertility loss [19]. These findings support the role of biomethane systems as a nexus between renewable energy production and sustainable agriculture, contributing to soil restoration and climate-resilient farming practices.

Table 2 provides a comprehensive summary of the principal feedstocks available in the Mediterranean region, outlining their agricultural or industrial origins, key biochemical characteristics, and representative countries where their use has been studied. The table is supported by data from the published literature and technical sources [14,41–44], reflecting both scientific research and applied case studies.

Table 2. Major Mediterranean feedstocks for biomethane production, including origin, biochemical composition, and countries of use based on key references.

Feedstock	Origin	Key Components	Countries	References
Olive pomace	Olive oil production	Lipids, cellulose	Italy, Spain, Greece	[41,42,44]
Citrus peel	Citrus processing	Sugars, pectin	Italy, Tunisia	[45,46]
Winery grape marc	Grape processing	Sugars, lignin	France, Italy, Spain	[43]
Cactus pear residues	Pruning and fruit industry	Mucilage, polysaccharides	Morocco, Tunisia	[14]
OFMSW	Municipal waste	Organic residues	All	[3,45]
Livestock manure	Dairy and pig farms	Organic matter, N	Spain, Italy	[13,17,44]
Agro-industrial wastewater	Canning, dairy, brewery	Mixed organic load	Greece, Turkey	[41]

Recent investigations have reported promising methane yields from the co-digestion of citrus peel and olive mill wastewater, two abundant agro-industrial by-products generated across the Mediterranean region. Methane production values typically range from 250 to 380 cubic meters of CH_4 per tonne of volatile solids (VSs). These substrates are characterised by a high content of readily biodegradable organic compounds, including simple sugars, organic acids, and essential oils, which contribute to substantial biogas production. However, despite their favourable biodegradability, these by-products also contain inhibitory substances—such as limonene in citrus peel and polyphenols in olive mill wastewater—that can negatively affect microbial activity during anaerobic digestion if not properly managed [46,47].

To mitigate these inhibitory effects, co-digestion strategies have been successfully employed. The addition of livestock manure or food waste to citrus peel and olive mill wastewater not only dilutes toxic compounds but also improves the overall nutrient balance of the feedstock mixture. This synergistic effect enhances microbial diversity and resilience, stabilising the anaerobic digestion process and improving methane yields [43,48]. Such integrated approaches reflect best practices for optimising methane production from challenging agro-industrial residues.

Beyond energy recovery, the process generates a nutrient-rich digestate, containing essential macro- and micronutrients with recognised agronomic value. When applied as a biofertiliser, this digestate contributes to soil fertility improvement, aligning with the European Union's sustainability goals for nutrient recycling and the reduction in dependency on synthetic chemical fertilisers. Field-scale experiments in Mediterranean areas have demonstrated that digestate derived from citrus and olive waste mixtures effectively enhances soil organic matter content, water retention capacity, and crop productivity. These benefits are particularly evident in degraded soils typical of many Mediterranean agricultural landscapes [44,49].

Figure 3 highlights the methane yields obtained in recent co-digestion trials using citrus peel and olive mill wastewater, where values between 250 and 380 m^3 CH_4 per tonne of VS were achieved. These studies confirm that co-digestion plays a critical role in mitigating the inhibitory effects of certain feedstocks, thereby enhancing overall biogas production efficiency [46–48].

In conclusion, while numerous Mediterranean feedstocks present significant potential for biomethane generation, additional research is necessary to fully assess their seasonal availability, scalability, and compatibility with various pretreatment technologies. Addressing these knowledge gaps will facilitate the broader deployment of biomethane systems, supporting climate-neutral energy strategies and fostering sustainable development pathways throughout the Mediterranean region.

4. Potential Biomethane Production in the Mediterranean Region

The Mediterranean region holds substantial and diversified potential for biomethane production, owing to the abundant availability of organic residues derived from agricultural, agro-industrial, municipal, and livestock activities. Agricultural by-products such as olive pomace and wastewater, grape marc, citrus peel, and tomato processing residues represent highly fermentable substrates, capable of yielding between 250 and 450 cubic meters of methane (CH_4) per tonne of volatile solids (VSs) [22,36]. In Greece and Italy alone, the olive oil industry annually generates over 2 and 5 million tonnes of olive pomace, respectively, while Spain surpasses 3 million tonnes [50]. Similarly, the winemaking sectors of France, Italy, and Greece collectively produce more than 6 million tonnes of grape marc each year, particularly concentrated in the September–October harvest period.

These lignocellulosic residues, although rich in fermentable carbohydrates, are often deficient in nitrogen, necessitating co-digestion with livestock manure or food waste to optimise nutrient balance and ensure process stability [23,43]. In Southern Spain and Portugal, integrated anaerobic digestion (AD) facilities have demonstrated that co-digestion of olive mill residues with pig slurry can increase methane yields by 15 to 20 percent [51]. Nevertheless, despite these positive examples, logistical constraints persist in fragmented rural landscapes, particularly in southern Italy and inland Greece, where more than 40 percent of the theoretical manure potential remains underutilised [7].

The Organic Fraction of Municipal Solid Waste (OFMSW) is also becoming a key biomethane resource in urban centres such as Barcelona, Rome, and Marseille. In these cities, biogas yields from OFMSW range between 100 and 250 cubic meters of CH_4 per ton, with enhanced performance observed when food service sector waste is included in the feedstock mix [3,52]. France and Italy have implemented dedicated biowaste collection schemes in major urban districts, achieving capture rates exceeding 70 percent and ensuring a stable feedstock supply for medium- and large-scale digesters. Portugal is actively expanding separate biowaste collection zones in Lisbon and Porto, aiming to boost biomethane output by 25 percent by 2030.

Among emerging bioenergy crops, cactus pear (*Opuntia ficus-indica*), extensively cultivated in Sicily, southern Spain, and Tunisia, is showing strong potential for biomethane production, especially in arid and semi-arid zones. Cladodes and fruit processing residues from this crop have demonstrated methane yields of 300 to 350 cubic meters of CH_4 per tonne of VS, with the additional advantage of low water and nutrient requirements [14,53]. Citrus peel from Calabria and Valencia, along with orange pulp from Moroccan juice industries, also represents a promising carbon source, although these residues require pretreatment to reduce limonene content and avoid inhibition of methanogenic activity [46,54].

Municipal sewage sludge is another important substrate, particularly in Mediterranean cities such as Athens, Palermo, and Madrid, where it is increasingly co-digested with food industry by-products, including brewery and dairy residues [29]. Cross-sector integration models are gaining traction in France, where regional hubs collect food industry waste and municipal sewage sludge for joint anaerobic digestion and biogas upgrading, fostering synergies within the circular bioeconomy framework [55].

When considered in aggregate, the combined biomethane production potential from agro-industrial residues, OFMSW, livestock manure, cactus biomass, and sewage sludge exceeds 8 billion cubic meters of methane per year across the Mediterranean region. Realising this potential, however, will require coordinated improvements in biomass collection logistics, the adoption of effective pre-treatment strategies, and the deployment of advanced biogas upgrading technologies. If successfully implemented, this renewable capacity could significantly reduce regional dependence on fossil gas imports, contribute to national and EU decarbonisation targets, and strengthen rural bioeconomies through integrated biorefinery models in Italy, France, Spain, Greece, and Portugal.

Figure 2 illustrates the estimated annual biomethane production potential in billion cubic meters of methane per year, derived from organic feedstock availability in selected Mediterranean countries. Italy leads with a projected potential of 2.5 billion cubic meters of CH_4 per year, followed by Spain with 2.0 billion, France with 1.5 billion, Greece with 1.0 billion, and Portugal with 0.8 billion cubic meters of CH_4 per year. These figures reflect the combined contribution of agricultural residues, agro-industrial by-products, OFMSW, and livestock manure and highlight the importance of co-digestion strategies in maximising regional biomethane capacity.

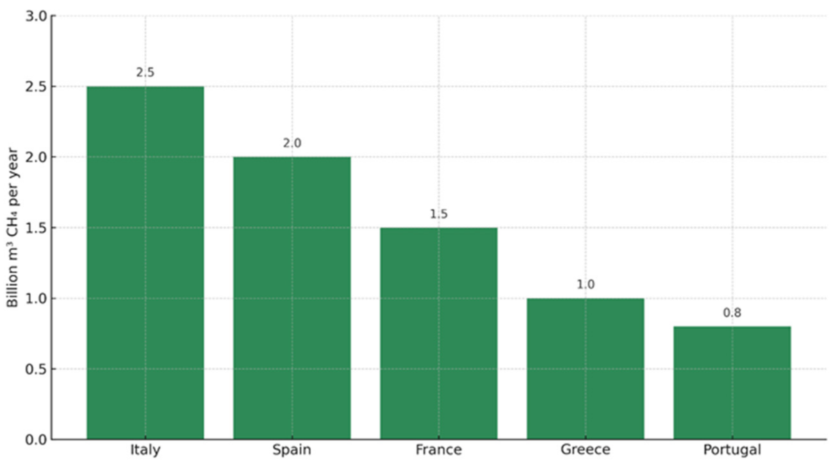

Figure 2. Estimated biomethane production potential in selected Mediterranean countries (Italy, Spain, France, Greece, and Portugal).

5. Policy and Economic Drivers

The policy and economic framework supporting biomethane production in the Mediterranean region is shaped by a complex interplay of European Union directives, national renewable energy strategies, and local incentive mechanisms. Collectively, these instruments aim to accelerate the deployment of renewable energy, promote the valorisation of organic waste, and strengthen the resilience of rural economies.

At the European Union level, the Renewable Energy Directive II (Directive (EU) 2018/2001) and its revision, RED III (Directive (EU) 2023/2413), have set ambitious renewable energy targets. RED III mandates that by 2030, at least 42.5 percent of the EU's final energy consumption must be derived from renewable sources, with a specific sub-target of producing 35 billion cubic meters of biomethane per year [35,56,57]. However, despite these policy goals, EU-wide biomethane production remains relatively modest, reaching just over 3.5 billion cubic meters per year as of 2022, underscoring both the challenge and the untapped potential for growth [58].

In response to this production gap, the EU launched the Biomethane Industrial Partnership (BIP) in 2022 to facilitate large-scale deployment. This initiative promotes investment, technological innovation, and regional collaboration, particularly in rural and agricultural areas where biomethane production can contribute to economic revitalisation and energy self-sufficiency. Complementary to these efforts, the EU Methane Strategy (2020) highlights biomethane as a crucial pathway for methane emission reductions, particularly through the anaerobic digestion of livestock manure and organic waste streams [59].

At the national level, Mediterranean countries are progressively incorporating biomethane into their broader climate and energy policies. Italy currently leads the Mediterranean region, with 44 operational biomethane plants as of early 2024 and over 200 additional projects in the development pipeline. The Italian Biometano Decree provides financial incentives, including feed-in premiums and support for grid injection and transport sector use of biomethane [60]. Spain, with 17 biomethane plants operational in 2023, anticipates significant growth through its Strategic Framework for Energy and Climate, which includes incentives for expanding gas grid infrastructure and facilitating biomethane injection [61].

In France, while not exclusively Mediterranean, biomethane production is well established, particularly in the southern regions bordering the Mediterranean coast. The country operates more than 400 biomethane plants and has set a national target of producing 7 terawatt-hours (TWh) of biomethane per year by 2030, supported by robust grid injection incentives [62]. Greece, although still in the early stages of development, has launched several pilot plants and feasibility studies supported by EU cohesion funds and national clean energy strategies [62]. Tunisia, through international cooperation initiatives, has also initiated pilot biomethane projects, focusing primarily on agricultural waste valorisation. Technical assistance and financing from agencies such as the German Agency for International Cooperation (GIZ) and the European Investment Bank have supported these initial efforts [62].

In this evolving policy environment, decision-support tools have become increasingly important for guiding both policy design and investment strategies. Asciuto et al. (2023) [8] developed an integrated assessment model for evaluating the feasibility of biogas plants in Mediterranean island contexts. This tool combines technical, environmental, and economic criteria, demonstrating how decentralised anaerobic digestion systems can align with the objectives of the circular bioeconomy.

Public–private partnerships, along with European funding programmes such as Horizon Europe, LIFE, and the Common Agricultural Policy (CAP), are playing a critical role in supporting the biomethane sector. These instruments help reduce investment risks and promote the deployment of small- and medium-scale AD systems, which are particularly suited to the fragmented agricultural landscapes and rural economies characteristic of the Mediterranean region [62].

6. Environmental and Agronomic Benefits

Biomethane production through anaerobic digestion (AD) represents not only a renewable energy pathway but also a key contributor to agronomic improvement and environmental sustainability in Mediterranean agricultural systems. As illustrated in Figure 3, AD supports climate-smart and circular agriculture by addressing both energy production and resource recycling challenges. By capturing methane emissions that would otherwise be released from the decomposition of unmanaged organic waste streams—including livestock manure, crop residues, and agro-industrial by-products—AD mitigates one of the most potent greenhouse gases. This reduction in methane emissions directly contributes to the climate neutrality targets set forth in the European Green Deal and the "Fit for 55" package, aligning biomethane production with broader strategies to decarbonise the agricultural and waste management sectors [3,63].

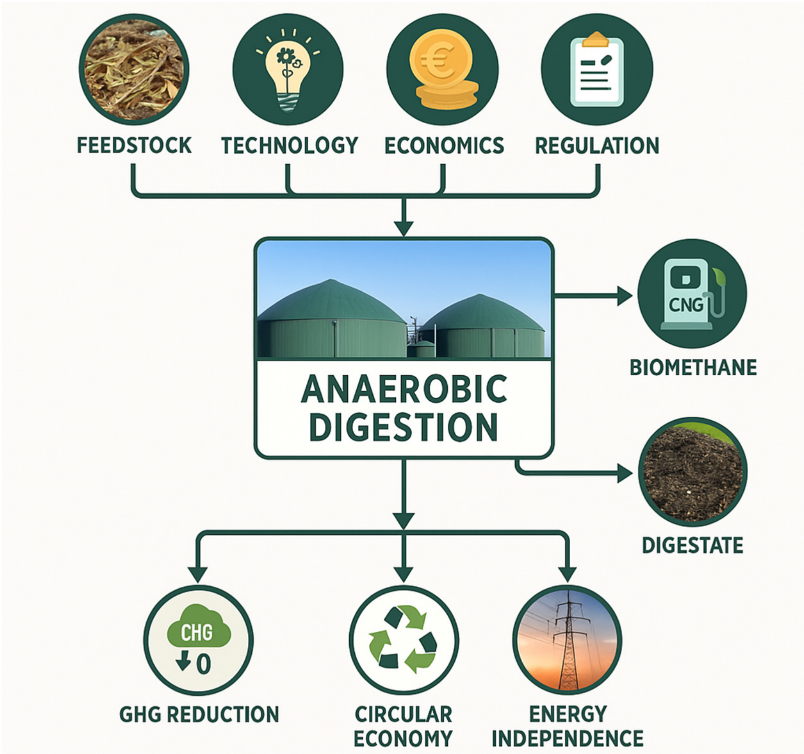

Figure 3. Agronomic and environmental benefits of anaerobic digestion and biomethane production in Mediterranean agriculture.

A central environmental and agronomic benefit of AD lies in the production of digestate, a nutrient-rich co-product in either liquid or solid form. Digestate contains essential plant nutrients, including readily available nitrogen in both ammonium and organic forms, phosphorus, potassium, micronutrients, and residual organic carbon. Its application to agricultural soils has been widely demonstrated to enhance fertility and structure, promote microbial activity, and increase water retention capacity. These benefits are particularly valuable in Mediterranean regions, where soils are frequently exposed to drought stress, nutrient depletion, and erosion risk.

Field studies conducted across southern Europe have consistently shown that the application of digestate can increase crop yields and reduce the reliance on synthetic mineral fertilisers, thereby contributing to nutrient circularity and lowering the environmental footprint of agricultural production. Notably, digestate from co-digestion processes often exhibits an improved carbon-to-nitrogen (C/N) balance and slower nutrient mineralisation rates compared to synthetic fertilisers, enhancing nitrogen-use efficiency and reducing nutrient losses. The reuse of digestate not only closes the nutrient loop but also decreases the dependency on fossil-based mineral fertilisers, in line with European Union objectives for reducing crop input costs and promoting more sustainable nutrient management practices.

In high-input production systems, such as Mediterranean greenhouse horticulture, digestate can be efficiently used in fertigation systems, supplying crops with both nutrients and irrigation water and thereby enhancing resource-use efficiency [16]. Additionally, composted digestate serves as a renewable alternative to peat in horticultural substrates. This practice not only improves substrate sustainability but also contributes to the protection of fragile peatland ecosystems, reducing carbon emissions associated with peat extraction. Research by Greco et al. (2020, 2021) [18,19] confirmed the agronomic suitability of compost and vermicompost derived from digestate for the cultivation of aromatic and medicinal plants such as sage (*Salvia officinalis*), with no adverse effects on crop yield or quality.

From a life cycle perspective, the environmental performance of biomethane production systems improves significantly when they are powered by on-site renewable energy sources. The integration of solar photovoltaic (PV) systems or biomass boilers into farm-scale AD plants enables on-site heat and electricity generation, reducing external energy inputs and lowering overall greenhouse gas (GHG) emissions. Farms adopting such diversified energy strategies benefit from enhanced energy autonomy, lower production costs, and improved environmental sustainability [32]. Moreover, co-digestion strategies involving a mix of livestock manure, food waste, and crop residues enhance the stability of the bioreactor, increase methane yields, and improve both the quality and consistency of the digestate produced.

Taken together, these environmental and agronomic synergies demonstrate the transformative potential of biomethane production for Mediterranean agriculture. Anaerobic digestion enables the integrated management of organic waste, renewable energy generation, and soil restoration, fully aligning with agroecological principles and bioeconomy objectives. This holistic approach reinforces the role of biomethane as a cornerstone technology in the transition toward more resilient and sustainable Mediterranean farming systems.

While the agronomic potential of digestate as a biofertiliser is widely recognised, its suitability for land application is closely linked to its chemical, biological, and physical quality. This consideration becomes particularly critical when the anaerobic digestion (AD) process involves the co-digestion of industrial effluents, such as olive mill wastewater, citrus peel residues, winery by-products, or municipal biowaste. These substrates may introduce a range of contaminants into the digestate, including polyphenols, limonene, heavy metals such as zinc (Zn), copper (Cu), lead (Pb), and cadmium (Cd), as well as residual antibiotics, microplastics, and pathogenic microorganisms [63].

Recent studies conducted in the Mediterranean context have drawn attention to these environmental risks. Pognani et al. (2019) [64], for example, analysed digestate derived from the co-digestion of food waste and agro-industrial effluents in northern Italy and observed elevated concentrations of copper and zinc, in some cases exceeding the thresholds established by Italian fertiliser legislation. The presence of winery residues in the feedstock was identified as a significant contributor to these elevated metal concentrations. Similarly, Vavouraki et al. (2020) [65] investigated digestate composition and reported considerable variability in polyphenol content depending on the proportion of olive mill pomace in the feedstock mixture. Their findings highlighted the need for post-treatment or dilution strategies to ensure the digestate could be safely applied to agricultural soils without phytotoxic effects. Conversely, research by Nayak and Bhushan (2019) [66] demonstrated that with appropriate composting and stabilisation techniques, digestate from Moroccan citrus and olive residues could meet the safety and quality standards set by EU Regulation 2019/1009, enabling its use in nutrient recycling.

In response to these concerns, Mediterranean countries have developed regulatory frameworks and quality assurance systems designed to safeguard soil and environmental health. In Italy, Legislative Decree 75/2010 classifies digestate into distinct categories based on feedstock origin and mandates compliance with strict limits for heavy metals, pathogens such as *E. coli* and *Salmonella*, and organic contaminants. Similar regulatory systems have been adopted in Spain and France, where digestate quality control is integrated into national fertiliser catalogues and biofertiliser certification programmes, including R.E.N.A.R.E. in Spain, the MAGRAMA guidelines, and ADEME protocols in France. These frameworks require routine analysis of digestate parameters such as pH, dry matter content, carbon-to-nitrogen (C/N) ratio, heavy metal concentrations, nitrogen content, and microbial load prior to its authorisation for agricultural use.

To further mitigate contamination risks and ensure environmental safety, best practices have been developed focusing on the segregation of waste sources, thorough characterisation of feedstocks prior to digestion, and the application of post-digestion treatments. Composting is frequently employed to stabilise digestate and reduce phytotoxicity, while techniques such as ammonia stripping, membrane filtration, and biochar addition are used to remove excess nutrients and contaminants. These approaches not only improve the chemical and microbiological stability of the digestate but also support its regulatory compliance, enhancing its value as a biofertiliser. Moreover, by promoting the safe and circular use of organic matter, these practices contribute to protecting soil health and water resources in line with the sustainability goals of the circular bioeconomy.

7. Biomethane in the Circular Bioeconomy

Anaerobic digestion (AD) plays a pivotal role within the circular bioeconomy (CBE), providing a sustainable solution for the valorisation of organic waste streams while simultaneously producing renewable energy and bio-based products. In the broader framework of the European Union's energy transition, AD is gaining strategic importance, particularly in light of recent geopolitical tensions. Energy dependency on third countries such as Russia, Algeria, and Libya, compounded by the ongoing instability in Ukraine, has underscored the vulnerability of fossil gas imports [3,55]. Against this backdrop, the production of biomethane through AD offers a pathway to enhance regional energy self-sufficiency, reduce exposure to external energy shocks, and strengthen the resilience of local economies.

By converting agricultural residues, livestock manure, and municipal biowaste into biomethane, AD systems provide a renewable substitute for fossil natural gas, supporting both energy transition goals and rural development objectives [67]. Equally important is the role of digestate, the nutrient-rich by-product of the AD process, which contributes to closing nutrient cycles and reducing reliance on synthetic chemical fertilisers [61]. Digestate application in agriculture improves soil fertility, enhances organic matter content, and promotes microbial biodiversity, all of which are critical factors in maintaining the health and productivity of Mediterranean agroecosystems. Recent studies have demonstrated the agronomic benefits of digestate and compost, particularly in enhancing soil structure and sustaining crop yields under Mediterranean climatic conditions [68,69].

A growing body of research highlights the potential of stabilised digestate and vermicompost as renewable alternatives to peat in soilless cultivation systems. This application is particularly relevant for the production of nutraceutical and aromatic crops such as sage (*Salvia officinalis*), oregano (*Origanum vulgare*), and rosemary (*Rosmarinus officinalis*), which are widely cultivated in Mediterranean regions [15,18,19]. The use of digestate-based substrates supports optimal plant growth and qualitative parameters while also reducing environmental pressures linked to peat extraction and habitat degradation. In this way, the integration of AD into agricultural and agro-industrial supply chains enhances environmental sustainability, fosters resource circularity, and contributes to the resilience of regional bioeconomies.

Figure 4 illustrates the integrated model of biomethane production within the circular bioeconomy. Agricultural, livestock, and food industry biowaste—including manure and slurry—are processed through AD systems, producing biomethane and digestate. The biomethane serves as a renewable energy carrier for grid injection or transport fuel, while the digestate is utilised as a biofertiliser or as a substitute for peat in horticultural substrates. This closed-loop approach simultaneously supports soil health, renewable energy generation, and the cultivation of aromatic crops, contributing to the reduction in external energy dependency and enhancing the sustainability of Mediterranean farming systems.

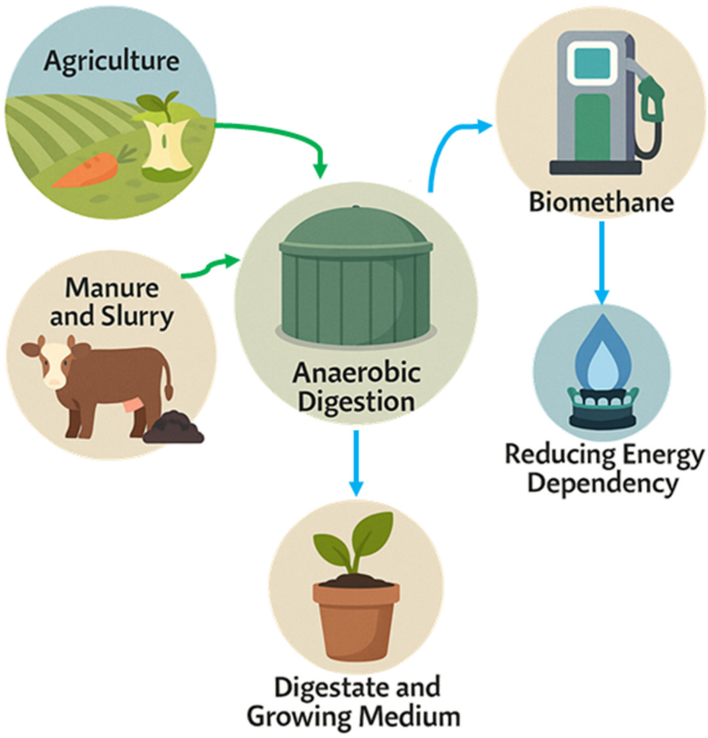

Figure 4. Circular bioeconomy model based on anaerobic digestion: valorisation of biowaste for energy, agriculture, and sustainability.

8. Challenges and Future Perspectives for Biomethane Development in the Mediterranean Circular Bioeconomy

Despite the clear environmental and socio-economic benefits associated with biomethane production, several technical, economic, and social challenges continue to limit its widespread adoption across the Mediterranean region. From a technical perspective, one of the primary constraints lies in the heterogeneity and seasonality of available feedstocks. Agro-industrial residues such as olive pomace and wastewater, citrus peel, grape marc, and livestock manure are highly variable in their composition. These feedstocks often exhibit fluctuations in moisture content, contain inhibitory compounds such as phenolics and limonene, and possess recalcitrant lignocellulosic fractions. Such characteristics necessitate the application of appropriate pre-treatment technologies to improve substrate hydrolysis and microbial accessibility, ensuring stable and efficient anaerobic digestion (AD) processes [22,23]. Moreover, sustaining a resilient and active microbial community capable of adapting to these variations and to fluctuating environmental conditions remains an essential research priority, particularly for decentralised and small-scale digesters operating in rural and island territories [67,70].

Infrastructure limitations further constrain the scalability of biomethane projects. Many peri-urban and remote Mediterranean areas lack sufficient gas upgrading facilities and grid injection points, limiting the capacity to valorise biogas as high-purity biomethane suitable for energy networks or transport applications. Addressing these gaps will require substantial investments in upgrading technologies and energy infrastructure.

Economic barriers also present significant hurdles. The development of AD plants, particularly those equipped with biomethane upgrading units, involves substantial capital investment. In addition, operational costs—including energy consumption, digestate handling, and system maintenance—are considerable, especially for small and medium-sized enterprises. While several Mediterranean countries have introduced supportive policies, such as Italy's Biometano Decree and Spain's Recovery, Transformation and Resilience Plan, the absence of a harmonised regulatory framework across the Mediterranean basin creates policy fragmentation. This disjointed policy environment discourages cross-border investment and impedes the development of a cohesive Mediterranean biomethane market [29]. Furthermore, the lack of long-term feed-in tariffs or stable biomethane pricing mechanisms creates financial uncertainty for project developers and investors, undermining market stability.

Social acceptance also represents a critical challenge. Public awareness of biomethane's role in sustainable energy and agricultural systems remains limited, and the use of digestate as a fertiliser in food-producing sectors faces moderate acceptance. Concerns persist regarding odour emissions, land application practices, and the proximity of AD plants to residential areas [71]. Overcoming these social barriers will require targeted stakeholder engagement strategies, transparent communication, and educational campaigns aimed at increasing public understanding and trust. The development of cooperative business models and multifunctional farm-based biomethane systems may also enhance community participation and foster socio-environmental acceptance.

Looking forward, the advancement of the Mediterranean biomethane sector will require coordinated multi-actor innovation strategies. Research priorities include optimising co-digestion practices by leveraging locally abundant and seasonal feedstocks, engineering microbial consortia with thermotolerant and inhibitor-resistant strains, and developing real-time process monitoring systems using Internet of Things (IoT) technologies and artificial intelligence-based diagnostics [30,31]. The deployment of modular and mobile AD plants represents a promising approach for off-grid or seasonal production systems, particularly suited to the fragmented agricultural landscapes of the Mediterranean.

Further integration of AD plants with on-site renewable electricity sources, such as solar photovoltaic (PV) systems, will enhance energy self-sufficiency and reduce carbon footprints. In parallel, the valorisation of digestate into high-value bio-based products—such as compost, biochar, or bioplastics—will contribute to the overall circularity and economic viability of biomethane systems [71–78].

Finally, fostering cross-border collaboration will be essential to harmonise technical standards, facilitate knowledge exchange, and stimulate innovation. International platforms such as PRIMA (Partnership for Research and Innovation in the Mediterranean Area), IEA Bioenergy, and Horizon Europe are pivotal in supporting joint research initiatives, sharing best practices, and building resilient innovation ecosystems for the Mediterranean biomethane sector.

Table 3 summarises the current status of biomethane-related policies, support mechanisms, and regulatory frameworks across five representative Mediterranean countries: Italy, Spain, France, Greece, and Tunisia. This comparative overview highlights the significant institutional and legislative disparities that characterise the region and influence the scale, pace, and efficiency of biomethane sector development.

Table 3. Overview of national policies and regulatory frameworks for biomethane in the Mediterranean region.

Country	Key Policies and Laws	Incentives and Support	Grid Injection Status	National Target (2030)
Italy	Biometano Decree 2018, PNIEC	Feed-in premiums, tax credits, CAP integration	Fully regulated by ARERA	5 billion m^3 biomethane/year
Spain	Climate Law 7/2021, PNIEC	Green gas incentives, infrastructure investment	Partial (pilot-based)	1.5–2 billion m^3/year
France	LTECV, PPE	15-year feed-in contracts, R&D grants	Fully regulated (GRDF)	10% of the gas grid by 2030
Greece	Law 4936/2022, REPowerEU plan	EU Cohesion Funds, pilot support	Not yet regulated	Target not defined
Tunisia	National Biogas Plan (draft), Decree-Law 2020-33	GIZ/EIB technical and financial support	Legal draft under development	~0.3 billion m^3 (draft target)

Italy represents one of the most advanced cases in the Mediterranean context, having established a comprehensive regulatory framework for biomethane. The Biometano Decree, originally introduced in 2018 and revised in 2022, supports the full biomethane value chain from upgrading to grid injection. Incentives include feed-in premiums, capital subsidies, and favourable tariffs, particularly targeting the transport sector. Furthermore, the Italian Regulatory Authority for Energy, Networks, and Environment (ARERA) has implemented detailed technical and safety standards for gas grid injection, positioning Italy among the few Mediterranean countries with an operational and regulated biomethane market. Italy has also set an ambitious national production target of 5 billion cubic meters of biomethane per year by 2030, directly contributing to the goals of the EU Biomethane Industrial Partnership [79].

France also benefits from a robust policy framework. Its Energy Transition for Green Growth Law (LTECV) and the Multi-Year Energy Programme (PPE) provide long-term policy continuity for renewable gas development. Biomethane producers are supported by 15-year guaranteed feed-in tariffs, while the national gas grid operator, GRDF, facilitates biomethane injection with traceability and certification tools. France has set a 2030 target of achieving a 10 percent renewable gas share in its national gas network, reflecting a strong policy commitment to decarbonisation [80].

In contrast, Spain's biomethane sector is still in an emerging phase. While the Climate Change and Energy Transition Law (7/2021) and the Integrated National Energy and Climate Plan (PNIEC) include biomethane in the national decarbonisation strategy, the country's biomethane infrastructure remains limited, with grid injection confined mainly to pilot projects. Current support consists of tax incentives and innovation grants, but the absence of long-term pricing mechanisms for biomethane hinders market certainty. The Institute for Energy Diversification and Saving (IDAE) has proposed a tentative production target of 1.5 to 2 billion cubic meters per year by 2030, although this objective has not yet been formalised into law [81].

Greece is at an even earlier stage of biomethane sector development. The National Climate Law 4936/2022 and EU-backed programmes such as REPowerEU acknowledge the potential of biomethane, but the country lacks a regulatory framework for gas grid injection. Current activities are largely confined to biogas-based electricity production, with no formal biomethane production targets established. Nevertheless, EU Cohesion Funds and Horizon Europe are beginning to support pilot initiatives and capacity-building programmes [82].

Tunisia, although not a member of the European Union, provides a relevant non-EU Mediterranean example. The country has drafted a National Biogas Plan and enacted Decree-Law 2020-33 to promote renewable energy development. Supported by international cooperation initiatives, including technical and financial assistance from the German Agency for International Cooperation (GIZ), the European Investment Bank (EIB), and the European Union, Tunisia has launched pilot agricultural anaerobic digestion projects in livestock and horticultural sectors. However, the legal and technical frameworks for gas grid injection are still under development, and a preliminary biomethane production target of approximately 0.3 billion cubic meters per year is envisioned in the long term.

This comparative analysis reveals clear differences in regulatory maturity, market incentives, and infrastructure accessibility across the Mediterranean region. Countries such as France and Italy demonstrate advanced regulatory environments and operational markets, whereas Greece and Tunisia are still in the foundational phases of policy and technical development. Key gaps persist in the harmonisation of grid injection standards, the availability of long-term feed-in mechanisms, and the definition of binding production targets. This heterogeneity represents both a constraint to regional market integration and an opportunity to prioritise policy harmonisation, capacity building, and cross-border cooperation. Initiatives such as Horizon Europe, PRIMA (Partnership for Research and Innovation in the Mediterranean Area), and the Green Deal Industrial Plan are well positioned to support these integration efforts.

Beyond policy discrepancies, the Mediterranean biomethane sector faces broader structural challenges. One critical barrier is the fragmentation of waste management systems and the lack of a unified circular bioeconomy strategy. In many Mediterranean countries, transitioning from linear waste disposal to multi-waste valorisation models requires not only supportive regulations but also cultural shifts and infrastructure upgrades. The integration of anaerobic digestion into a coherent circular economy approach remains incomplete.

Emerging technologies such as bio-electrochemical systems, which enable the simultaneous production of hydrogen and electricity from organic waste, offer complementary pathways to biomethane production. However, their large-scale deployment in Mediterranean rural contexts is limited by high capital costs and the need for specialised technical expertise. Additionally, the adoption of waste hierarchy-based decision frameworks and the digitalisation of waste valorisation processes, inspired by Industry 4.0 principles, are increasingly seen as key drivers for optimising resource recovery and improving the economic performance of biomethane systems.

Lessons from countries with advanced circular bioeconomies, such as Germany, illustrate that progress in biomethane production depends on systemic reforms that integrate environmental policies, innovation incentives, and market-driven mechanisms. Maximising the value of biowaste in the Mediterranean region will require a shift from waste treatment paradigms to integrated circular economy models, where biomethane functions not only as a renewable energy vector but also as a catalyst for regional economic development.

Looking forward, the future growth of biomethane in the Mediterranean will depend on coordinated efforts to harmonise policies, advance technological innovation, and mobilise regional investment strategies that simultaneously address energy security and ecological sustainability [78–86].

9. Conclusions

Anaerobic digestion (AD) represents a strategic technology at the nexus of sustainable agriculture, climate adaptation, and the circular bioeconomy (CBE), offering regionally tailored solutions to the environmental and energy challenges facing Mediterranean countries. In a context characterised by abundant biowaste streams, declining soil fertility, and persistent dependence on fossil gas imports, AD provides a multifunctional approach capable of converting agricultural and agro-industrial residues into two high-value products: biomethane, a renewable and locally produced energy vector, and digestate, a nutrient-rich amendment that contributes to the restoration of degraded soils and the closure of nutrient cycles.

The dual function of AD in generating renewable energy and regenerating soil health is fully aligned with the foundational principles of the CBE. Its integration into diversified and multifunctional farming systems has the potential to mitigate greenhouse gas emissions, improve soil organic matter content, and enhance water retention capacity—benefits that are particularly critical in Mediterranean regions such as Sicily, Spain, Malta, and Greece, where desertification and land degradation pose growing threats to agricultural sustainability. Moreover, the decentralised deployment of small- and medium-scale biomethane plants in rural and insular areas promotes local energy autonomy, supports rural economic diversification, and strengthens climate-smart infrastructure.

Empirical evidence from case studies in Italy, Spain, Tunisia, and other Mediterranean countries confirms the technical feasibility and socio-economic value of embedding AD systems within existing agricultural and waste management frameworks. These systems enable diverse utilisation pathways, including biomethane grid injection, vehicle biofuel production, on-site combined heat and power generation, and digestate reuse. Collectively, these applications create synergies that extend across the environmental, economic, and agronomic dimensions of Mediterranean rural systems.

Nevertheless, unlocking the full potential of biomethane in the region requires a paradigm shift from linear resource management models to circular bioeconomy approaches. Achieving this transition will depend on coordinated advances in innovation, policy harmonisation, and capacity building. Technological challenges—such as feedstock seasonality, lignocellulosic recalcitrance, and the high costs of biogas upgrading—demand further research into optimised co-digestion strategies, enhanced microbial consortia, and efficient pre-treatment technologies. Simultaneously, the adoption of digital monitoring tools, precision agriculture practices, and IoT-enabled management systems will be essential for improving process control and tailoring digestate application to site-specific soil and crop conditions.

Policy frameworks such as the Renewable Energy Directive III (RED III) and evolving national biogas strategies offer important regulatory momentum. However, scaling up biomethane deployment will require greater policy harmonisation across Mediterranean countries, the establishment of stable long-term investment incentives, and the promotion of stakeholder engagement at multiple governance levels. Social acceptance and knowledge transfer mechanisms, including training and cooperative platforms, will be critical for integrating AD into mainstream agricultural, waste management, and energy policies.

Ultimately, anaerobic digestion is not merely a waste management technology but a cornerstone of low-carbon, resilient, and regenerative Mediterranean agriculture. By positioning AD within a comprehensive circular bioeconomy framework, Mediterranean countries have the opportunity to simultaneously reduce organic waste, enhance food and energy security, mitigate climate risks, and revitalise rural economies. In doing so, they can lead the transition toward an agricultural future that is productive, environmentally sustainable, and socially inclusive.

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