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Circular Bioeconomy in the Metropolitan Area of Barcelona: Policy Recommendations to Optimize Biowaste Management

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Abstract: Municipal biowaste management is at the core of the transition towards a circular bioeconomy in the EU. However, most urban systems are still far from being aligned with these principles. This paper addresses the case of the Metropolitan Area of Barcelona. The current system of biowaste management is compared with a more sustainable alternative scenario. Regulatory and non-regulatory drivers and barriers for the transition from the current state to the alternative scenario are identified and later transformed into policy recommendations using a multi-stakeholder approach. This paper focuses on the separate collection of biowaste and the production of biomethane. Increasing the quantity and quality of separate biowaste collection is a prerequisite for the market-relevant production of biogas from anaerobic digestion that can be converted into biomethane. The results show that more efficient collection systems such as door-to-door or smart bins together with tax incentives such as the pay-as-you-throw principle are key to increasing the amount of collected biowaste, while targeted communication combined with controls and penalties are key to minimizing impurities. In addition to financial incentives for the construction of new anaerobic digestion plants, financial incentive systems are also required for the biomethane sector to ensure competitiveness with fossil fuels.

Keywords: circular bioeconomy; separate biowaste collection; biogas; biomethane; biowaste valorization; drivers and barriers; policy recommendations

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1. Introduction

About 113.8 Mt of municipal biowaste per year is generated in Europe (EU27+), of which about 60 Mt is food waste [1]. Over the past two decades, European Union (EU) policy-makers have given high priority to incentives and directives aimed at reducing the amount of biowaste and improving the separate biowaste collection, treatment, and valorization. The most significant ones are the European Union (EU) Waste Framework Directive [2], the European Commission (EC) Circular Economy Action Plan [3], and the European Commission (EC) Bioeconomy strategy [4] and its Action Plan [5]—a core part of the European Green Deal [6]. Even if the 'umbrella' concepts green economy, circular economy, and bioeconomy are based on different operational strategies, they are united by the common ideal of linking economic, ecological, and social issues. In particular, the resource-focused bioeconomy and circular economy concepts are strongly connected, but there is much potential to make bio-based and bio-ecological strategies more circular [7]. While a circular economy aims at increasing the resource efficiency of processes and the use of recycled materials to reduce material consumption [8], a bioeconomy aims at promoting sustainable production of natural resources from biomass rather than fossil- and mineral-based resources. The biogenic resources (i.e., agriculture, forestry, fisheries, and aquaculture) can, in turn, become feedstock for the economic and industrial sectors to produce: (1) food and feed, (2) fibers, (3) chemical and materials that later will be transformed into bio-based products, and (4) bioenergy and biofuels substituting fossil feedstock [4]. As far as the risk of a linear bioeconomy is concerned (competition of land uses, damage to soils, energy demand, fertilizer consumption, etc.), the bioeconomy offers many promising alternatives for replacing fossil fuel products and services, but it also has many limitations. Circular economy and bioeconomy are, therefore, complementary concepts that can reinforce each other. A circular bioeconomy (CBE) unites the main strengths of both concepts and focuses on reducing the use of petrochemicals, mitigating climate change, reducing dependence on natural resource imports, and boosting local economies [9].

Secondary biomass, i.e., biowaste, organic by-products and residues, plays a key role in CBE strategies. As a priority of the EU waste hierarchy [2], waste generation—including food waste as a major part of municipal biowaste—should be reduced. In the case of unavoidable organic waste and residues, it can be considered as a resource that can be reused, recovered, or recycled. The EU Biorefinery Forecast to 2030 [10] supports the EU Bioeconomy Action Plan [5] to promote the development and use of new resource-efficient and sustainable biorefineries in Europe. Biorefining can be broadly defined as the processing of biomass into a range of marketable bio-based products, such as food and feed, chemicals and materials, and bioenergy, through thermochemical, physicochemical, and biochemical processes [11]. With bioproducts and bio-based value chains as the central pathways to a resource-efficient circular economy, this "valorization and value chains" approach encompasses a complex web of processes and actors that lead to socio-economic growth, environmental benefits, and technological progress [12].

This paper shows an excerpt of the results of the BBI-JU H2020 project BIOCIRCULARCITIES (BCC). BCC concentrates on the CBE potential in cities and, therefore, rethinking selected infrastructure systems and supply chains, unlocking the potential of unexploited bio-based waste. BCC investigates the development of economically and environmentally sustainable organic waste valorization models in three pilot territories, each covering different bio-based value chains: (i) forestry residues in the Province of Pazardzhik, Bulgaria; (ii) agro-industrial biowaste (coffee silverskin) in the Metropolitan City of Naples, Italy; and (iii) municipal biowaste in the Metropolitan Area of Barcelona, Spain.

For each of the pilot territories, BCC explored current organic waste management models hand in hand with local stakeholders in order to define an alternative scenario in line with the CBE principles [13]. Both the current situation and the alternative scenarios were compared using life cycle assessment (LCA) and life cycle costing (LCC) to ensure that the proposed alternative scenarios are environmentally friendly, economically feasible, and improve the current management systems [14,15]. In parallel, a multi-actor approach (i.e., including stakeholders and external experts) was carried out for identifying legal, technical, economic, environmental, and social drivers and barriers to a shift from the current to the alternative scenarios [16]. Finally, policy recommendations to promote that shift were formulated [17]. In this publication, we focus on the holistic process needed to identify drivers and barriers and provide policy recommendations to implement a more sustainable municipal biowaste management in the Metropolitan Area of Barcelona (MAB) case study.

The MAB case study aims at improving the quantity and quality of separately collected biowaste to be treated in an anaerobic digestion (AD) plant and subsequently increasing biogas production to be upgraded into biomethane. Biomethane was chosen as the end product of the value chain studied because it offers the possibility to diversify energy sources and reduce dependence on imported natural gas [18]. It also has great potential to help decarbonize the energy sector and can, therefore, play a crucial role in reducing greenhouse gas (GHG) emissions and contribute to the Paris Agreement [19]. When derived from waste sources, using biomethane can result in a net reduction in carbon dioxide (CO_2) emissions [20].

This paper addresses two main research questions: (1) What are the current drivers and barriers—based on the current legal framework and stakeholder feedback—for the successful implementation of a circular economy focusing on separate collection improvement and biogas/biomethane production in the MAB., and (2) what policy recommendations can support the implementation of the proposed alternative value chain in the MAB in line with the bioeconomy principles.

The article is structured into six sections. Section 1 contextualizes the research and provides background. Section 2 presents the materials and methods of the research. Section 3 shows the results in terms of main drivers and barriers for the implementation of a scenario in which municipal biowaste management is improved all along the value chain, focusing on separate collection and biomethane production. Section 4 discusses drivers, barriers, and its transformation into policy recommendations. Section 5 discusses the results. Section 5 concludes the findings and provides directions for future research.

2. Materials and Methods

The detection of regulatory and non-regulatory drivers and barriers to shift from the current to the alternative scenario and the provision of policy recommendations to achieve this transition have been structured in a comprehensive process combining research desk and multi-actor (MA) involvement. The entire process is structured in two main groups of tasks, both including MA engagement (Figure 1). The first set of tasks is related to the technical definition and quantification of the current municipal biowaste management scenario at the different stages (e.g., biowaste generation, collection, treatment, etc.). In addition, this first part of the comprehensive process includes activities related to the design of an alternative management scenario aligned with CBE principles that is environmentally sound according to LCA [21] and economically feasible according to LCC [22].

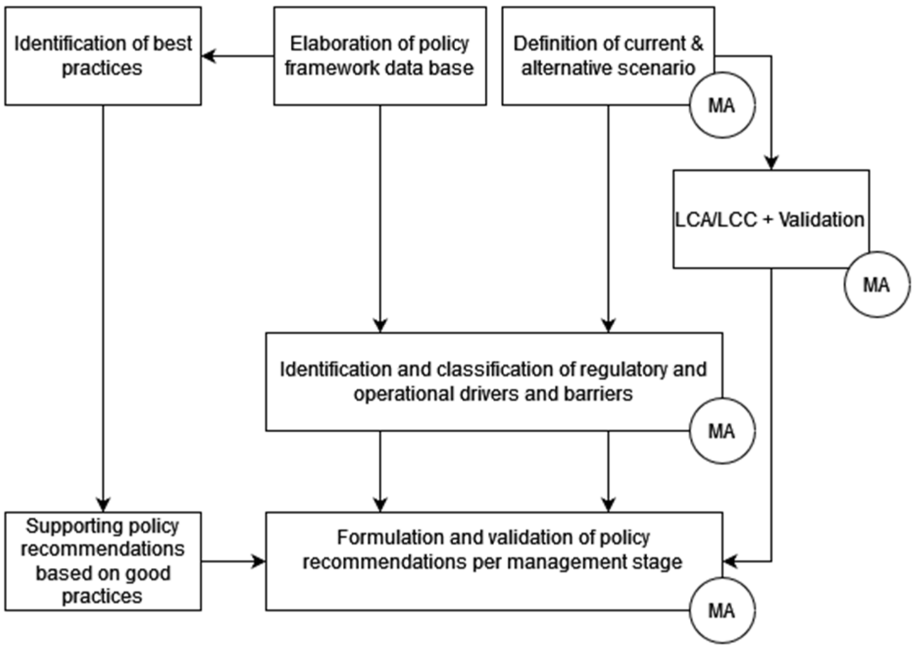

Figure 1. Schematic representation of the methodological steps of the comprehensive process to identify drivers, barriers, and policy recommendations combing research desk and multi-actor (MA) involvement. MA indicates the specific steps where the multi-actor approach was applied, involving local stakeholders and external experts. Source: Own elaboration.

The second group is related to the proper identification of drivers and barriers and formulation of policy recommendations. Drivers and barriers were, in turn, mapped in a two-step exercise: (1) gathering and analyzing information from a research desk analysis and then (2) collecting and elaborating data from stakeholder participation. First, the drivers and barriers, arising from the legal framework, were identified on the basis of an expert analysis of the most important policy framework documents at EU, national, regional, and local level. During this step, international good practices (GPs), related to the selected MAB pilot area, were compiled to later support policy recommendations. Secondly, the drivers and barriers were identified in dedicated meetings with local stakeholders and external international experts not associated with the BCC consortium. Departing from the drivers and barriers identified, a set of policy recommendations were developed and, where possible, illustrated with best practices found in the previous step. Each of the methodological steps are further elaborated in the following sections.

2.1. Multi-Actor Involvement

Building a shared vision of the current municipal biowaste management system, validating alternative scenarios, co-creating common understanding of drivers and barriers, and formulating relevant policy recommendations, requires stakeholders' involvement, for which an MA approach according to the Quadruple Helix Model was set up. The Quadruple Helix Model is an efficient way of fostering cooperation in research and development between four major actors in the innovation system: science, policy, industry, and society [23]. The real added value of involving multiple actors in the decision-making process is to develop "sound and fair" policies by incorporating "useful" (relevant and sound) information into the governance process and by increasing the transparency and quality of the evaluation and decision-making process, taking into account the individual interests of the different social actors involved [24].

Stakeholder involvement took place, on the one hand, through four bi-annual Local Living Labs on-site and online in the language of the MAB (Catalan), attended by relevant local stakeholders related to the municipal biowaste management value chain. In addition, each local Living Lab was followed by an online advisory board meeting and an on-site or online peer review session (both in English) with international experts.

The external project stakeholders involved in the MAB pilot site were:

1. Local stakeholders: 19 stakeholders including local waste management authorities, other local authorities, academic and research institutions, and private companies involved in municipal biowaste management. These stakeholders helped to (i) validate the information related to the state of the art of the current biowaste management scenario, (ii) select the most realistic and sustainable alternative scenario, (iii) identify the related existing drivers and challenges in the current biowaste management system and for the implementation of the alternative scenario, and (iv) give feedback on policy recommendations for a successful implementation of the alternative scenario.
2. International external experts: 18 external experts were selected to provide input after each round of Living Labs. For these tasks, experts from academic and research institutions, research clusters, environmental consultancy companies and engineering companies were selected. Their contribution was key to validate and support internal decision-making and preliminary results, as well as to answer the specific technical questions prepared by the consortium.

2.2. Research Desk Analysis: Elaboration of the Policy Framework Database, Identification of GPs, and Identification of Regulatory Drivers and Barriers to the MAB Alternative Scenario

A database including the most relevant documents regarding the EU policy framework was compiled addressing the EU level plus the national, regional, and local level in the MAB. Departing from the initial database including 95 documents, a first relevance analysis was carried out from which a shorter list of references (47 documents) was filtered for an in depth analysis to extract regulatory drivers and barriers to the implementation of CBE alternative scenario, including 23 documents at the EU level, 12 at the national level (Spain), 10 at the regional level (Catalonia), and 2 at the local level (MAB).

Later, these documents were systematically analyzed to map relevant passages including explicit legal drivers and barriers that might foster or hinder the implementation of alternative scenarios to the current biowaste management value chains. In this paper, “drivers” are defined as all factors that favor the implementation of the CBE and, therefore, the alternative scenario in a bio-based value chain, whereas “barriers” are factors that hinder its implementation. Drivers and barriers were classified into 6 categories according to the scope they were referred to:

- **Legal/Administrative (L/A):** EU-wide, national, regional, and local legislation and its implementation, e.g., through binding targets, administrative penalties for non-compliance, etc.
- **Technical (Tec):** Technological innovations, best available techniques (BAT), available infrastructure and equipment, waste quality requirements, etc.
- **Economic (Ec):** Capacity for investment in innovation, BAT and new product chains, profitability threshold, market situation of raw materials and bio-based products, economic incentives such as tax reductions, waste charges/fees and subsidies.
- **Environment/Health (E/H):** Greenhouse gas emissions, possible other impacts on environment and health.
- **Social (Soc):** Public acceptance of new biowaste collection systems and bio-based products, awareness raising campaigns on biowaste separate collection or biowaste-based products.
- **Stakeholder involvement (SI):** Involvement of various stakeholders from science, industry, politics, citizens, and NGOs in decision-making processes; interdisciplinary exchange via stakeholder platforms.

The identified GPs related to CBE belong to different databases [25]. The very first criterion for selecting the GPs was to focus on actions related to the specific pilot areas. First, existing GPs in Spain and Catalonia to be transferred to the MAB pilot were screened in the “Ministry for the Ecological Transition and Demographic Challenge” (MITERD) platform, the Catalan “Residus Municipals” (municipal waste) platform, and in the “Som gent de profit” (a Catalan platform devoted to prevention of food wastage). In addition, at the European level, the “European Circular Economy Stakeholder Platform” and the “Municipal Waste Europe” platform were considered. During the first local Living Lab, together with the local partners, the main GPs were selected for the three project pilot areas and new ones were proposed. Further proposals came from international experts during the third peer review session. For the MAB pilot, the most important criterion for the selection of GPs was their focus on the optimization of the quality and quantity of biowaste to be used in biocircular biorefinery processes.

2.3. Status Quo Analysis of the Current Municipal Biowaste Management in the Metropolitan Area of Barcelona

The MAB is a territorial entity located in Catalonia, in the province of Barcelona in northeastern Spain (Figure 2). The MAB comprised 36 municipalities with 3.3 million inhabitants in 2021 [26], including the city of Barcelona, which means that 43% of Catalonia’s population lives in less than 2% of the region’s area, ranking MAB as the eighth most populated metropolitan area in the EU. This implies a very high population density, settled predominantly in urban areas interspersed with agricultural and Mediterranean forests and mountain areas. The MAB accounts for 52% of Catalonia’s GDP.

The definition and quantification of the current municipal biowaste management scenario was developed with data provided by the local authority of the MAB pilot area. The MAB pilot area has a total of four waste treatment plants called “Ecoparcs” and two industrial composting plants where biowaste separately collected in the MAB is sent. Ecoparc 2 (Montcada i Reixac) was selected as pilot study because it treats significant amounts of municipal biowaste separately collected in the MAB, and also because the upgrading of biogas to biomethane could be implemented in the short-term.

Figure 2. Location of the BCC pilot study area: the Metropolitan Area of Barcelona in the region of Catalonia in north-eastern Spain (highlighted in red). Source: Own elaboration.

Municipal waste management in the MAB is carried out so that five main waste streams are collected from both households and commercial facilities. The main collection system comprises the separate collection of glass packaging, lightweight packaging, paper and cardboard, food biowaste (kitchen organic waste), and garden waste. Along with residual waste, in general, these streams are collected through open street bins. In addition, bulky waste is collected separately by request, and there is a network of "deixalleries" (recycling centers) where other waste streams are collected separately (e.g., WEEE, mineral oils, etc.). Furthermore, specific separate collection services are provided to commercial activities (e.g., for paper and cardboard).

According to the Spanish regulatory framework, municipal waste collection and treatment are mandatory services to be provided by local authorities [27]. These services can be provided either individually (i.e., each municipality establishes its own collection and treatment services and facilities) or in coordination with other municipalities. In general, in Spain and in Catalonia, the most frequent municipal waste management configuration entails the provision of waste collection services by each municipality while treatment is provided by a local supra-municipal entity, so treatment infrastructures are shared to create economies of scale and minimize treatment and disposal costs.

In 2021 (year of current scenario), separately collected municipal biowaste and green waste represented 13.5% (199,628 t) of the total municipal solid waste (MSW) generation in the MAB (1,478,128 t). The total amount of generated biowaste was estimated to be 431,310 t, meaning that currently, only 46% of the total potential are separately collected. There are three main sources of separately collected biowaste in the MAB. First, kitchen and garden waste (small size green waste) from households and small businesses which is normally disposed of in open 2200-litre street containers and collected by municipal waste collection services. Second, biowaste generated at commercial and industrial premises and collected separately. The third municipal biowaste stream is green waste from municipal park operations. In total, 74% of the total separately collected biowaste was household biowaste and it includes 15% of impurities.

In 2021, Ecoparc 2 received around 43% (85,640 t) of the separately collected biowaste in the MAB: 77,244 t from municipal biowaste plus 8396 t from commercial or industrial sources for treatment. No green waste from municipal park operations is sent to Ecoparc 2. Figure 3 shows the current management system for separately collected biowaste sent to Ecoparc 2.

The treatment steps include the pretreatment biowaste to remove non-organic materials (impurities). After pretreatment, the biowaste entered AD. The products of AD include biogas and digestate (solid + liquid). Digestate is treated as follows: the liquid digestate is sent to wastewater treatment where some of the solid digestate is incinerated and some is sent to other specific treatments/uses. The biogas produced is converted into electricity by means of a combined heat and power (CHP), of which 60% is fed into the national electricity grid, whereas the rest (40%) is consumed by the AD plant. A part of the solid digestate obtained from AD becomes compost.

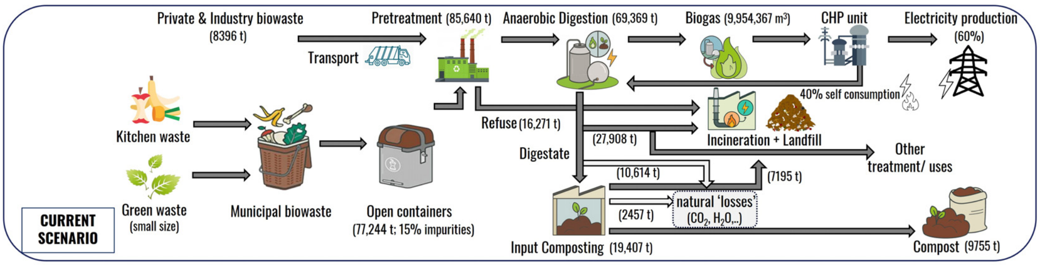

Figure 3. Scheme of the current municipal biowaste management system in the Ecoparc 2 (Current scenario). Source: Own elaboration based on data provided by the MAB local authority and data from DECISIVE database [28].

2.4. Assessment of the Alternative Scenario for Municipal Biowaste in the MAB

The alternative scenario was designed along with representatives from the local authorities Àrea Metropolitana de Barcelona (AMB) and Barcelona Regional (BR), plus several other stakeholders involved in the management of the municipal biowaste treatment plant "Ecoparc 2" [13] and proved to be more sustainable and more economically advantageous than the current situation [14,15]. Local actors suggested to consider a more feasible, realistic, and short-term (timeframe of five years from 2021) alternative scenario instead of hypothesizing innovative technologies. This was mainly due to the scaling up limitations of prototype processes that, while they may have been more innovative, would have been difficult to actualize.

The alternative scenario entails improvements in the three main stages of the value chain including biowaste prevention, separate collection of biowaste, and biowaste treatment: (i) the introduction of prevention measures to reduce 5% of the current amount of biowaste; (ii) a change in the separate collection of biowaste from open street containers to door-to-door (DtD) collection and/or smart bins to increase the quality and quantity of separately collected biowaste; and (iii) the upgrading of the biogas produced from AD into biomethane to be injected into the local gas grid or to be used as biofuel. Mass and energy flows in the alternative scenario are shown in Figure 4. The biowaste reduction (5% of total input biowaste to Ecoparc 2) due to prevention measures and the increase in separately collected biowaste (30% of total input biowaste) were first discussed and then validated with local stakeholders. The combination of these targets will result in a higher quality of source-separated biowaste (less contamination), which in turn will result in higher quality compost, higher biogas production, and a reduction in waste destined for landfill or incineration within the short time horizon of five years.

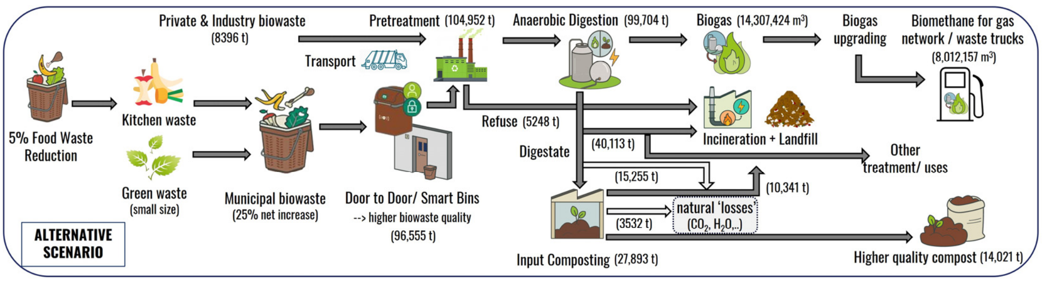

Figure 4. Scheme of the alternative biowaste management scenario in the Ecoparc 2 (Alternative Scenario). Source: Own elaboration based on data provided by the MAB local authority and data from DECISIVE database [28].

In contrast to the current situation, higher volumes of biogas would have been obtained and purified into biomethane by a mix of the most common technologies, namely amino washing, membrane technique, pressure swing adsorption in addition to biomethane production from synthetic gas by fluidized or fixed bed technology. A production of 8,012,157 m^3 of biomethane was estimated. For the alternative scenario, it was calculated that the entire biogas production is upgraded into biomethane. Electricity and heat requirements of the AD plant are assumed to be drawn from the national grid. For the calculation of the biomethane upgrading, a methane (CH_4) content of 56% in the biogas after AD is assumed. In total, 40,113 t of the digestate are treated as follows: the liquid digestate is sent to wastewater treatment, some of the solid digestate is incinerated, and some is sent to other specific treatments/uses. In addition, 14,021 t of high-quality compost is produced. The refuse from the composting process is incinerated or disposed of in landfills.

Once the definition of this scenario was agreed upon with the stakeholders [13], LCA and LCC analyses were performed to assess whether the alternative scenario was technically and economically feasible and environmentally desirable (i.e., that the alternative scenario performs better than the current scenario) [14,15].

2.5. Multi-Actor Identification of Operational (Non-Regulatory) Drivers and Barriers

Departing from the analysis of the regulatory drivers and barriers and having defined the alternative scenario, further operational (non-regulatory) drivers and barriers were identified, analyzed, and classified along with local stakeholders and international external experts in a dedicated participatory session.

Operational drivers and barriers were identified using the same definitions and classified under the same categories utilized in Section 2.2.

2.6. Multi-Actor Formulation of Policy Recommendations

The last step was the formulation of policy recommendations. Policy recommendations were related either to improving the potential enclosed in drivers or overcoming the barriers for the shift from the current to the alternative scenario. Where possible, policy recommendations were accompanied by GPs illustrating the proposal.

The initial formulation of policy recommendations was then independently revised and validated by the local stakeholders and international external experts to produce an improved version of the recommendations.

3. Results

This section includes the results from the identification of drivers and barriers plus the derived policy recommendations for a shift from the current to the alternative scenario. We focus on the two key stages of the value chain, namely the separate collection of municipal biowaste and the optimization of municipal biowaste treatment to maximize biomethane production and high-quality compost. For more details on identified drivers and barriers, please see the Supplementary Materials.

3.1. Drivers and Barriers to Improving the Separate Collection of Municipal Biowaste

According to the identified drivers and barriers, increasing the separate collection of municipal waste relies on a policy mix comprising the implementation of more efficient municipal biowaste separate collection schemes (i.e., DtD and smart bins) and financial incentives, including unit-based pricing (e.g., pay-as-you-throw, PAYT).

Regarding the implementation of high efficiency collection systems, the regulatory framework is well aligned at all administrative levels in terms of supporting the implementation of DtD and smart bin systems. The legislation explicitly includes the mandatory implementation of the separate collection of biowaste and the priority of high efficiency collection systems. However, based on previous experience in Catalonia, where the separate collection of biowaste has been intensely promoted during the last two decades, it is uncommon that high efficiency collection systems are implemented unless it is supported by a broader kit of policy instruments and dedicated funding.

Stakeholders agreed on the relevance of the regulatory drivers in creating a favorable context for the implementation of high efficiency collection systems and pointed out several additional barriers. Public acceptance cannot be taken for granted, and the lack of public support is a relevant barrier, particularly when new collection systems are accompanied by an increase in waste charges. Previous experiences with the inconveniences of DtD collection systems during summer (e.g., hygiene-related issues) may also be seen as a barrier. Related to smart bins, the data processing and specialized skills required to run these models can be seen as a barrier to its implementation. Issues related to privacy and personal data protection were also raised. Also, high efficiency collection systems can be resource intensive when it comes to monitoring, and particularly when applying fines and sanctions. Also, the lack of environmental impact analyses comparing current and a more efficient biowaste collection system might hinder its implementation. Finally, large tourism flows in the MAB are a barrier to the implementation of high efficiency collection systems requiring user identification.

Landfill and incineration taxes are seen as drivers to improve the separate collection of biowaste. Catalonia has applied these taxes since 2004 and has regularly increased the tax rates to reinforce the incentive to separate collection. The tax rates applied in Catalonia, so far lower than in other European countries though significantly higher than in the rest of the Spanish regions, will soon be closer to European benchmarks, therefore exerting a more intense effect.

Binding targets related to separate collection rates and for increasing quality in terms of reducing impurities from the separate collection of biowaste are another complementary lever since high quality standards entail the implementation of high efficiency collection systems. In the case of the MAB, the lack of ambition of the current impurity targets included in the national regulatory framework can be seen as a barrier for obtaining high-quality compost as well as the fact that when more ambitious targets are set at the local level, no fines or sanctions are foreseen in case of non-accomplishment. Stakeholders pointed out that the fact that improved biowaste collection has a positive effect in terms of GHG emissions can be seen as a driver, since climate policy will support enhanced models for collection of biowaste.

Also related to the quality of biowaste collection, the fact that biowaste will need to be collected in compostable bags might contribute to reduce impurities since plastic bags are one of the main refuse materials found at biowaste treatment plants. In the absence of collection systems involving the individual identification of users, the extent of its implementation is subject to the good will of the users. Also, it should be considered that compostable bags made of bioplastics need to comply with EN 13,423 [29], suitable for industrial, but not necessarily home composting (different abiotic conditions). Furthermore, depending on the sorting process for input and output material, bioplastics in biowaste streams can pose a challenge to biowaste (pre-) treatment plants [30]. There is still a lack of education programs on proper separate collection of bioplastics and waste prevention, as some bioplastics (if littered) can also be a problem for aquatic and terrestrial ecosystems [31]. Furthermore, there is public confusion about the suitability of bioplastics for home composting as there is no common European standard (so far there are national standards such as the French standard NF T 51-800 [32]).

Unit-based pricing charges such a PAYT systems are considered a second pillar of an improved separate collection of biowaste. Furthermore, the regulatory framework set several drivers for a better funding of biowaste collection systems such as making full cost recovery mandatory. On the other hand, PAYT is explicitly recommended at all administrative levels. In practice, the implementation of PAYT and similar systems rely on user identification and, therefore, in the implementation of high efficiency collection systems.

Additionally, stakeholders identified several other social barriers such as the lack of knowledge on correct source separation of biowaste, particularly regarding bioplastics.

3.2. Policy Recommendations to Improving the Separate Collection of Municipal Biowaste

Based on the identified regulatory and non-regulatory drivers and barriers hindering the improvement of separate collection of municipal biowaste, a set of related policy recommendations were produced. First, even if already in place in Catalonia and, therefore, in the MAB, landfill and incineration taxes were acknowledged as a key policy instrument to support the implementation of high efficiency separate collection systems. In the absence of this instrument, the incentives for the implementation of any other instruments would be significantly weaker, as it can be observed in the rest of Spain, where separate collection rates are lower. Plus, the fact that the tax revenue from the landfill and incineration tax has been earmarked to improve waste management has allowed specific funding for separate collection and treatment of biowaste, which has boosted its implementation. Therefore, this lesson learnt can be seen as a policy recommendation and GP.

For landfill and incineration taxes to work as an incentive, tax rates should be set at a level that cost-efficiently contributes to accomplish waste management targets. In this sense, landfill and incineration tax rates in Catalonia were 65.3 €/t and 32.7 €/t in 2023, respectively, and are set to be increased up to 71.6 €/t and 35.8 €/t in 2024. Therefore, supported by the good performance of landfill and incineration taxes, a sustained increase in tax rates is recommended at the regional level after 2024.

A second policy recommendation at the national level was making the introduction of high efficiency collection systems (e.g., DtD, smart bin collection) mandatory in areas where the separate collection of biowaste has not been deployed so far or where results are poor. In parallel, it is recommended that the introduction of more open street container collection systems is prohibited. For those areas where the separate collection of biowaste is already carried out, it is advisable to introduce economic incentives for regional and local authorities for shifting to more efficient collection systems. This measure should be accompanied by appropriate funding and subsidies to ensure that the provisions from the Spanish Law 7/2022, where these systems are required to be prioritized, are made operational.

Two GPs support this recommendation: the cities of Münster (Germany) with a population of 317,713 inh., and Albano Laziale (Italy) with a population of 41,598 inh., introduced DtD collection with biowaste barcode bins more than 20 years ago. Results show that separate collection rates reached 87% and 94%, respectively, in 2019 [33]. There are also local examples from the MAB, in Corbera de Llobregat with 15,210 inhabitants, where biowaste collection rates rocketed from 23 kg/cap/year (impurities; 11.3%) to 84 kg/cap/year (impurities: 2.9%) after the implementation of DtD collection in February 2022.

A third set of recommendations involves regulating the use of PAYT to be mainstreamed as the baseline charging system, regarding municipal waste charges is a third central recommendation. The scope of the application of this measure, given the Spanish legal framework, relies on the national level. Charging systems based on the actual amount of waste generated create incentives for separating biowaste (and other recyclables) at source and reducing the amount of mixed residual waste. In Spain, according to Law 7/2022, local authorities shall introduce a charge or, where appropriate, a fee, which shall be specific, differentiated, and cover all waste management costs by 2025. It also states that waste charges should allow for the introduction of PAYT schemes. When applied together with well-designed collection of different waste fractions (including residual waste, biowaste, and recyclables), and adequately supported by communication campaigns, PAYT has been associated with an increase in the overall separate collection rates [34].

A fourth set of recommendations are related to the use of binding targets. For example, the introduction of binding targets regarding maximum biowaste content in mixed residual waste is requested to incentivize the proper collection and recycling of biowaste. According to Zero Waste Europe, such a cap could be set at 25 kg/cap/year by 2030 and 15 kg/cap/year by 2035. This recommendation was addressed at the EU level, although it could be suitable at the national and regional levels.

A fifth group of recommendations relates to information and awareness-raising. For example, at regional level, it is recommended to introduce sensibilization campaigns to improve the quality of source-separated biowaste. This can be performed with a traditional approach or through KAYT (know-as-you-throw), which means providing individuals with continuous, tailored feedback so they can correct their source separation behavior when necessary [35]. As a GP, the case of Bergamo in 2020 illustrates how KAYT works. The fact that people felt monitored was an incentive to change their behavior. In Bergamo, the concept of a 'neighborhood premium' will also be introduced as a collective economic incentive based on the analysis of bag collection data [36]. In general, the use of awareness raising campaigns about the relevance and technical details about the separate collection of biowaste was adopted as a recommendation to ease the transition towards the implementation of high efficiency collection systems. These campaigns should target citizens but also tourists. Raising awareness in the form of training for workers of the municipal waste collection services was also recommended to ensure sufficient knowledge of aspects related to regulations and targets, practical aspects of management, data collection and reporting, costs, and financing of the service.

A sixth recommendation focuses on large cities and provides them with targeted strategies and incentives for improving separate collection. The MAB contains several large cities and the implementation of high efficiency collection systems in these contexts differ from smaller urban and rural areas. A GP example for a larger city is Milan (Italy) with 1.3 million inhabitants, a density above 7000 inhabitants/km^2, and over 80% of the population living in high-rise buildings. In February 2012, the first step of introducing the separate collection of biowaste was to replace the traditional black bag with a transparent bag for the collection of the mixed residual waste, to facilitate the monitoring of the collection [37]. Then, the municipality introduced DtD collection. The yearly quantity of collected biowaste per capita rose from 28 kg/cap/y in 2011 to 110 kg/cap/y in 2019, almost 6 times higher than the EU average. The quality of separately collected biowaste was very high, with a share of only 4.3% of non-compostable materials in 2019, fully compatible with the subsequent treatment by the Italian Association for Composting and Biogas (CIC). Separate collection of municipal waste in general increased from 35% in 2011 to 63% in 2020, as other waste fractions are also targeted for DtD collection.

In MAB municipalities where DtD is already running, it is recommended to introduce clearly communicated sorting obligations for citizens and enforce the obligation by introducing controls on the separate collection of biowaste and the proportion of organic content in mixed residual waste. Where necessary, it is needed to make use of the corresponding fines for non-compliance (according to PREMET25). DtD collection alone does not necessarily lead to a higher biowaste collection quality and, therefore, support from inspections is needed. In the MAB, controls are carried out by the operator at the time of collecting the bin or container (in the case of commercial collection). In the event of non-compliance with the sorting obligations, the bin or container is left standing, and the non-compliance is reported with a sticker as a notice/warning. If the stickers do not lead to an improvement, an official letter can be sent, which may result in a fine. But so far, few municipalities have issued fines. In the case of smart bin collection, the use of approved and coded bags could be enforced, but this is more complicated and less effective. In the city of Münster, a four-phase "Biowaste bin campaign" ("Aktion Biotonne") was launched in 2017, an information campaign combined with a quality check of the biowaste bins of each household biowaste (DtD collection with barcode identification). If the quality found in the bins does not meet the standards, citizens receive a yellow card with instructions for better sorting. If the problem persists, the biowaste bin is removed and households must put the biowaste exclusively in the mixed residual waste bin, paying the highest annual fee. As a result, impurities decreased from 3.5% in mid-2017 to 1.9% in early-2018, indicating that the information campaign influenced separation behavior [33].

A final recommendation directed at the national level is to make yearly waste composition analyses for separately collected biowaste and mixed waste necessary. Knowing the composition of the separately collected biowaste provides information about the proportion and composition of impurities, and the composition of the mixed residual waste fraction provides information about the remaining recyclables, including organic waste. Both types of sorting analysis are crucial for improving separate (bio)waste collection and communication campaigns for the public. In the GP example of Milan, sorting analyses are carried out every 6 months. Knowing the exact composition of the mixed residual waste also helps to estimate the actual success of separate biowaste collection and biowaste prevention measures. In Milan's case, only 14% of food waste remains in the mixed residual waste [38].

3.3. Drivers and Barriers to Enhancing the Production of Biogas to Be Upgraded into Biomethane

In the MAB pilot area, biomethane obtained from AD of municipal biowaste is another key point of optimization towards increased circularity of the system. The drivers for enhancing the quality and quantity of separate collection go hand in hand with the drivers for increasing the number and capacity of AD plants and hence the production and use of biogas and biomethane. A clear environmental driver for biomethane is the reduction of GHG emissions through replacing fossil natural gas with biomethane.

Large-scale expansion also requires planning security for long-term investments, i.e., a stable regulatory framework, medium- to long-term security for subsidies, and support from local institutions. In Spain, as a main driver for the promotion of biogas and biomethane generation, the competent authorities shall promote the use of biogas from AD for energy purposes, for direct use in the plants themselves, as transport fuel, as feedstock for industrial processes and for injection into the natural gas grid in the form of biomethane, where technically and economically feasible [27]. At the EU level, various directives and national regulations support the development of renewable energy, including biomethane. A strong national driving force are, in part, the more ambitious targets than at the EU level, e.g., a 42% share of renewable energy in final energy consumption by 2030 [39] compared to the EU target of 32% renewable energy by 2030 [40].

An enhanced uptake of renewable hydrogen, biogas, and biomethane by industry is seen as a key contributor to the RePowerEU plan's objectives of diversifying gas supply and reducing the EU's dependence on Russian fossil fuels, while at the same time decreasing dependence on fluctuating natural gas prices and tackling the climate crisis [41]. In 2022, the European Commission published a Staff working document [18] which aims to increase biomethane production to 35 billion cubic meters (bcm) per year by 2030 and set the stage for further increasing the potential by 2050. This document contains several possible actions to unlock the potential of biogas and biomethane across all EU countries and explicitly promotes the use of secondary feedstock (crop residues, manure, organic waste), while discouraging the use of food and feed for biomethane production. The promoted multi-stakeholder involvement on defining the biomethane is a clear driver for local authorities to establish a specific framework for collaboration with the academic community and industry sector. In response to the REPowerEU Action Plan, the Spanish Biogas Roadmap was introduced in 2022 [42], setting a minimum biogas target of 10.41 TWh (1.07 bcm) per year by 2030. In addition, a biomethane target was introduced where, in 2030, at least 1% (0.39 bcm) of total gas consumption of the natural gas grid (2021: 377,157 GWh = 38.61 bcm) should be biomethane [43] However, in 2022, only 2% of total gas consumption in Spain was biogas [44]. As a barrier, both targets are rather unambitious and not in line with the RePowerEU target of 35 bcm for the EU by 2030 [18]. The Spanish biomethane production potential is estimated to be up to 20 bcm/y in 2050 [45], which would place Spain only behind France and Germany with 22 bcm/y, respectively [44]. A driver for the use of biomethane in the transport sector is the third Clean Mobility Package, published in May 2018, which includes the first ever CO_2 emission standards for heavy-duty vehicles. The focus on tailpipe emissions does not allow fair competition between the different clean mobility solutions [46].

Currently, there is insufficient infrastructure to produce biogas from biowaste from the food and agricultural sectors, and its conversion into biomethane. As a further barrier, Spain's gas grid infrastructure needs adjustments to accept biomethane after purification and investments for a network expansion, especially in remote areas. Not all AD plants (limited in number in Spain anyway) are located near a connection point for feeding biomethane into the local gas grid so far, so they currently only have the option of producing compressed natural gas (CNG). Another important point is that ensuring the quality of natural gas in the distribution networks is crucial both for the functioning of the system and for the safety of end consumers. A technical obstacle to the use of biomethane is that a certain degree of purity and quality is required for injection into the natural gas grid or for use in vehicles [47]. Achieving this standard consistently can be a technical challenge. Even though RED II can be seen as a driver for fostering the integration of biomethane into European gas grids and its cross-border trade by promoting joint projects and shared efforts [40], specific natural gas quality requirements, including methane content, may vary from among EU Member States, creating a fragmented market and making trade difficult.

The administrative burden for the construction of new biogas and biomethane plants was identified as another obstacle. When it comes to biogas production, a major barrier is that the number of Spanish biogas plants (146 [42] and 81 planned plants [48]) is significantly lower compared to other countries such as Germany (>10,000 plants in 2020) [49], France (1700 plants in 2022) [50], and Italy (approx. 2000 plants in 2020) [51], even though Spain is a country with such an important agri-food sector and hence potentially usable biowaste resources for AD. A lack of biogas plants also means that there are few biomethane upgrading plants. In October 2021, there were 1023 biomethane production plants in Europe, with Germany showing the highest energy production (>80,000 GWh [44]). Spain currently has only five operational biomethane production plants, reaching 95 GWh in 2020 (0.01 bcm [45]). The initial capital cost for the improvement of existing AD plants and the construction of new AD plants and biogas upgrading technologies is also a significant barrier. For the construction of new AD facilities, capacity building is needed in the municipalities to speed up the approval process, as human and financial resources are currently insufficient.

To enable an increase in biomethane production, investments in research and development of innovative technologies for the sustainable production of biogas and biomethane are required. In order to facilitate new investments in biogas and biomethane, the European Commission also offers extended access to grants and loans from existing EU funds, such as the Common Agricultural Policy Rural Development Funds, Structural and Cohesion Funds, National Resilience, and Recovery Plans, Horizon Europe, Innovation and Modernisation Funds, LIFE funds, and other national funds, as well as access to funds for innovative production and use of biomethane and biogas projects. Nevertheless, there is a lack of awareness of these grants as well as administrative challenges in applying for them, especially for SMEs and small municipalities.

Subsidy and support mechanisms, as well as a regulatory and fiscal frameworks that regulate the various applications of biogas, are fundamental driving forces. Without subsidies or a strong economic incentive, the cost of producing biomethane can be higher than that of natural gas or other energy sources. To attract investors, the business model for biomethane production needs to be guaranteed. Without a real and stable biomethane market, this is complicated.

The general public's increasing awareness and concern about climate change and environmental issues drive demand for cleaner, renewable energy sources, including biomethane. As a major driver of increasing the public awareness and facilitating the trading and recognition of biomethane in the energy market, in 2023, Spain established a Guarantee of Origin (GoO) system for renewable energy as a means to certify the renewable nature of 1 MWh of gas while listing the specifics of its production, i.e., when and where it was produced, the type of production facility, and energy source, etc. [52]. This trade mechanism is managed by the National Commission of Markets and Competition (CNMC) and is in line with European directives that encourage Member States to establish such certification mechanisms to promote transparency and consumer confidence in renewable energy.

3.4. Policy Recommendations to Introduce and Increase the Production of Biomethane

So far, there are no specific targets for biomethane production at local and regional levels, which is why the focus is on the EU and national context. For Spain, main policy recommendations include the introduction of a higher minimum biogas target (at least 5 bcm by 2030) and biomethane target (at least 5% of the total gas consumed) linked to the target for new plants to be built into the Spanish Biogas Roadmap [42].

At the EU level, the biomethane quality requirements for gas grid injection vary between Member States [47]. At the national level, technical support for the safe injection of biomethane into the gas grid, the expansion of the existing gas network, as well as the connection of decentralized generation plants with consumption centers over large distances (for example, dispersed settlements as specified at the EU level [18]) should be provided. At the national level, the reduction of the current delay in permitting procedures for new AD plants should be incentivized by increasing the capacity in municipalities responsible for issuing permits. In addition, GPs such as the establishment of one-stop shops for biomethane-related permits should be streamlined and a maximum processing time according to the EU biomethane targets [18] set. In addition, the upscaling of research pilot plants to an industrial scale should be facilitated.

At the EU and national levels, a 'well-to-wheel' approach should be emphasized, i.e., taking into account the whole fuel chain including extraction, production, transport, and use of the fuel or electricity [53], which would allow for a more realistic comparison of the different options, as proposed by the European Biogas Association (EBA) and Natural and bioGas Vehicle Association (NGVA), Europe [54]. Currently, Italy has the most methane refueling stations; 25% of all refueling stations in the EU [55]. A "well-to-wheel" study conducted in Denmark demonstrated that the use of compressed and liquefied natural gas results in a reduction of GHG emissions by 15–27% per kilometer driven compared to conventional fuels in both transport applications and for all vehicle classes. The effect is particularly large, 81–211%, when compressed and liquefied renewable natural gas is used alternatively. The outcomes depend on the type and source of feedstock used, the vehicle engine, the assumed methane leakage and slip, and the allocated energy and environmental credits for digestate in each pathway [56]. At the EU level, there is a target of 14% renewables in the transport sector by 2030 [40]. In 2021, the share of renewable energy in the Spanish transport sector was around 9% of the EU average compared to Sweden with 30.4% [57].

At the national level, it is crucial to introduce financial incentives for bioenergy compared to fossil energy through measures such as a minimum purchase price or incentive tariffs for biomethane with a duration of 15 years (e.g., as enshrined in Italian national law [58]). Another option is negative incentives for the use of fossil energy (e.g., tax increases). At the EU level, an incentive mechanism based on the assessment of the carbon footprint would also be conceivable, i.e., the lower the carbon footprint [CO_2 g/MJ], the higher the price/incentive should be for this product/energy source (instead of having a flat incentive rate). The carbon footprint assessment should be performed according to the International Sustainability and Carbon Certification (ISCC) [59]. An exclusive dedication of the landfill/incineration taxes for the improvement of the current biowaste management including the construction of new AD facilities is recommended.

At the EU level, Public Private Partnerships (PPP) for bio-based industries, e.g., the Circular Bio-based Europe Joint Undertaking (CBE JU) [60], should be strengthened. In addition, the Spanish participation in the Biomethane Industrial Partnership [61] should be encouraged. The implementation of innovative technologies for the sustainable production of biogas and biomethane based on the gasification of biogenic waste as specified at the EU level [18] needs support at the national level. Advances in purification technologies, like pressure swing adsorption or membrane technologies [47], have made it more efficient and economical to upgrade biogas to biomethane suitable for grid injection or vehicular use. Ongoing research and development also include technologies such as "biomethanation", which is converting the CO_2 fraction from the biogas into CH_4 together with added hydrogen (H_2) using excess electricity, producing the same amount of biomethane as the amount of biogas used [62]. However, this technology is dependent on the price of hydrogen. The use of a power-to-gas technology, i.e., converting the surplus electricity from solar or wind energy into hydrogen and convert this hydrogen (together with CO_2) into biomethane [63], might be a possibility and should be examined in the specific local context. In general, the dissemination/utilization of research results needs to be facilitated, e.g., from the SEMPRE-BIO project [64], in which three different technologies for the production of biomethane with three different raw materials are being tested, or from the LIFE INFUSION project [65], in which biogas, nutrients, and treated water are obtained from landfill leachate and liquid digestate from organic municipal waste.

National awareness campaigns on the recently introduced Guarantee of Origin (GoO) system, which consists of demonstrating to an end customer that a certain percentage or amount of energy has been generated from renewable sources [52], are recommended to facilitate the introduction of biomethane in the market and increase its demand.

4. Discussion

The key role of municipal biowaste as feedstock in CBE strategies has been underlined in this work. The availability of biowaste as a raw material is, nevertheless, closely linked to measures to improve the quality and quantity of separately collected municipal biowaste [66]. The current European collection rates of biowaste compared to their total generation (average 34%) show that separate collection is still in its infancy. Therefore, the implementation of biowaste (especially food waste) collection policies and practices is a must in order to increase overall recycling rates in the near future [1]. High efficiency separate collection systems are the basic building blocks for the successful implementation of other measures in the rest of the value chain, i.e., implementing the technology required for biomethane upgrading is pointless unless high efficiency collection systems are in place in advance. Plus, these systems do not produce sufficient shifts in citizen's behavior and should be accompanied by a mix of other instruments including economic incentives [34] and communication campaigns. Open street bins are obsolete when it comes to achieving significant collection rates, because these systems do not allow for user identification (e.g., such as DtD or smart bin collection) and, therefore, the range of incentives applicable and its effectiveness is limited.

The point about the effectiveness of high efficiency collection systems and related incentives as compared to street open bins was already well known by all stakeholders and policy-makers during the local Living Labs. Furthermore, there is enough scientific and practical evidence and knowledge about its effectiveness from decades ago, including case studies from Catalonia [67–69]. However, a still pending barrier that prevents further changes from being implemented is related to governance and the fact that 'command-and-control' measures require political leadership and consensus along with public funding.

Securing high quality biowaste supply is crucial for biomethane projects. Indeed, large-scale biomethane production, especially if based on energy crops, may raise concerns about land use change, biodiversity loss, and competition with food crops [70,71]. While Spain has abundant agricultural residues, there can be competition for these feedstocks for other purposes such as composting, animal bedding, or as raw materials for other industries [72]. For these reasons, a focus on municipal biowaste as a consistent and economical feedstock for biomethane plants is even more important.

In addition to a continuous higher quality and quantity of biowaste, new AD plants are also required to produce biomethane from biogas. The construction of new AD plants, the possible capacity increase of the existing ones or the adaptation of the existing Mechanical Biological Treatment (MBT) to AD treating only source-separated biowaste, require a stable regulatory framework that ensures viability and security, particularly in terms of energy production, so that it is competitive with traditional fossil fuels [73]. As far as financial support for the construction of new AD plants is concerned, it should be noted that the effectiveness of state subsidies also depends on the size of the plant. A case study in southern Spain illustrates that plants of 150 m^3/h (medium scale) are profitable if 10% of the investment is subsidized, while smaller plants do not reach profitability even if 50% of the investment is subsidized [74]. What also should be considered is the usage of BAT in order to maximize the methane yield, to save energy, and to minimize environmental impacts [66,75].

Using biomethane derived from the AD of source-separated biowaste in gas networks could support the decarbonization of the energy sector and the transition to circular economy models and more sustainable cities, reduce energy dependency, and generate new employment opportunities and markets [76,77]. To foster the growth of the biomethane sector in the MAB, the current barriers need to be addressed through a combination of regulatory support, technological advancements, public awareness campaigns, and economic incentives. Even though "Ruta de Biogas" [42] is an important document, Spain is still lacking comprehensive and supportive regulatory framework tailored for biomethane production, injection, and usage. Targeted policy measures and incentives to support and establish a stable medium and long-term biomethane market in Spain and in countries with similar characteristics are needed [73].

Biomethane has also the potential to replace natural gas as a sustainable vehicle fuel, but governmental support is needed [78]. The reduced external costs of biomethane-powered vehicles compared to petrol-powered vehicles could serve as a basis for policy decisions to encourage the growth of biomethane use in the transport sector, leading to a reduction in GHG emissions [79]. Incentivizing the local production of biomethane supports the potential transition to a more sustainable waste transport system in the MAB, using biomethane instead of natural gas as a fuel for the waste collection fleet and hence reducing GHG emissions. In addition, the substitution of fossil fertilizers with high-quality compost could further contribute to decarbonization, lower consumption of raw materials, and less pollution [80].

Overall, the economic factors that can have the greatest impact on the chain's performance are waste disposal fees, the selling price of biomethane, and economic incentives for biomethane producers. However, it is important to rebalance the economic and environmental performance [81]. Among market-based instruments, feed-in support schemes and quota obligations for biomethane are the most important drivers in Europe. To allow the biomethane sector to compete with fossil fuels, policy should focus on reducing existing support mechanisms for electricity producers on the one hand and subsidizing biomethane production on the other. Tax policies aimed at increasing the price of competing fossil fuels would bring additional benefits [82].

The allocation of subsidies is seen as an essential prerequisite for promoting the biomethane transport sector. Subsidies should be combined with other policy measures, supporting a significant change in infrastructure, involving the provision of compressed natural gas (bio-CNG) refueling stations and biomethane-powered vehicles [83]. In the beginning (as with other successful renewable energy schemes) greater incentives would be needed to get the industry off the ground, but these subsidies could be phased out over time [76]. Member States have adopted national policy frameworks to foster alternative fuels in the EU, setting individual targets for the period 2020–2030, leading to a possible fragmentation of alternative fuel infrastructure [84], which needs to be harmonized in the near future. At the EU level, carbon footprint-based incentives for biomethane (avoided carbon footprint) should be linked to the emission commitments of industry or other sectors, i.e., those subject to the EU Emissions Trading System for GHG (EU ETS [85]).

5. Conclusions

In summary, in the course of this study, the two main research questions could be answered: The main drivers and barriers for the implementation of the selected alternative value chain in line with CBE principles were identified, i.e., 34 drivers and 18 barriers detected in the policy framework through desk research and 14 drivers, and 19 barriers determined through stakeholder engagement. The drivers and barriers, together with examples of GPs, were validated by relevant stakeholders and translated into a set of policy recommendations.

Policies to improve the performance of a local biowaste management system should recognize the central role of different stakeholders, whose site-specific knowledge must play a key role in decision-making. Therefore, the identified policy recommendations can accelerate the transition towards a more circular biowaste management in the MAB. To our knowledge, this is the first comprehensive, multi-actor study in Spain that co-creates knowledge about the drivers, barriers, and policy recommendations to improve the quantity and quality of source-separated biowaste, with the aim of promoting biogas production from AD and upgrading it into biomethane.

These results are relevant to European/international audiences given (1) the recently introduced obligation for all European cities to separate biowaste through biowaste collection systems (in Spain: with priority for DtD or smart containers as analyzed in the alternative scenario); and (2) the commitment of EU countries to be in line with the new RePowerEU plan and the need to increase the biomethane production.

Despite the local focus of the analysis, the list of policy recommendations can be used as a starting point to be tailored to the context of other EU cities, of which most are still far from complying with CBE principles as they struggle to reconcile legislation, waste management, circular economy, and bioeconomy.

Further research should be conducted in other urban areas and regions in Spain and beyond, where the circular bioeconomy potential of municipal biowaste has not yet been fully exploited.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16031208/s1; General Information about anaerobic digestion and biomethane; Table on regulatory drivers and barriers to improving the separate collection of municipal biowaste and production and use of biomethane in the MAB; Table on non-regulatory drivers and barriers based on the feedback from stakeholders' involvement (MA approach) to improving the separate collection of municipal biowaste and production and use of biomethane in the MAB. Refs [86–101] are citied in Supplementary Materials.

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