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Review

The Potential Contribution of Decentralized Anaerobic Digestion towards Urban Biowaste Recovery Systems: A Scoping Review

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Abstract: The potential contribution of decentralized approaches in implementing biowaste recovery systems has attracted interest in urban policy making and scientific research. Although the scientific literature on the topic is rapidly increasing, it is still limited and scattered. A comprehensive overview of current scientific knowledge is thus needed to support future research on decentralized options for biowaste recovery systems. Anaerobic digestion (AD) is a mature biowaste treatment technology that recovers energy and nutrients, and can close urban resource loops. Through a scoping literature review, this paper investigated decentralized AD and its potential contribution in implementing urban biowaste recovery systems. We identified opportunities and challenges for planning of decentralized AD, and concluded that these mainly concern: (a) digestate management; (b) the potential for local circularity with product valorization in outlets such as urban agriculture; and (c) the development and application of decision support tools. The findings highlighted the need to enhance scientific evidence on the impact of decentralized AD in different urban contexts. Results from published studies were highly context-specific, making it difficult to draw general conclusions. This study can support the transition to integrated planning of AD and wider urban biowaste recovery systems. Such planning must include a comprehensive analysis of configuration approaches.

Keywords: local circularity; decentralized biowaste management; circular economy; resource recovery; anaerobic digestion

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1. Introduction

Solid waste management is a pressing sustainability challenge for modern cities. Global and urban populations constantly grow, as does the amount of municipal solid waste (MSW) generated, with cities being accountable for approximately 70% of global waste [1]. In 2050, global waste is expected to reach 3.4 billion tonnes, a 70% increase compared to 2016 [2]. MSW is defined as the waste generated in municipalities, mainly composed of organic biodegradable waste, paper and cardboard, plastic, metal, and glass [2]. The growing MSW amount is largely attributed to the dominant linear model of global production and consumption that operates under a 'take-make-use-dispose' approach. This model is unsustainable, as resources are discarded after use and their value is lost [3,4]. The circular economy (CE) has gained increasing attention as a means to rethink overall resource management: it aims to preserve the value of products, materials and resources for as long as possible and minimize waste generation [5]. There are significant opportunities to transition from linear to circular resource management and apply CE as a transition strategy to sustainable low- and zero-carbon societies [6–8].

According to the 'waste hierarchy' framework, waste prevention should be the top priority of strategies towards sustainable resource management. Nonetheless, resource recovery is also an indispensable component of the hierarchy as a strategy to manage unavoidable waste [9–11]. The terms 'waste recovery' or 'resource recovery' describe any process that uses waste as input to replace resources (e.g., extraction of virgin resources) that would be used otherwise [12,13]. Resource recovery captures value in the system that would otherwise be lost. In this context, the establishment of effective resource recovery systems is essential, and has attracted increasing scientific and public interest [3].

1.1. Urban Biowaste Recovery: A Largely Untapped Potential

Biowaste has a crucial role in the implementation of resource recovery and wider sustainability transitions through CE [8,14]. 'Biowaste' was here considered as the organic fraction of municipal solid waste (OFMSW): food and kitchen waste from households and institutional and commercial (including restaurants and food markets) buildings, and comparable waste from food processing plants, as well as green waste from parks, yards, and green spaces [15]. It usually constitutes the largest fraction of municipal solid waste [2]. In this paper, 'biowaste recovery' refers to resource recovery from biowaste streams. Biowaste recovery systems can contribute to the development of a circular bioeconomy: an economy in which biowaste and other bioresources are used in bioenergy and biorefinery systems to generate high-value biobased products, such as biofuels for energy services and nutrient-rich biofertilizers [13,16].

Nevertheless, biowaste still remains a largely untapped resource globally. In most urban areas, it is still collected while mixed with other MSW types and disposed in landfills and open dumps [2,17]. The current global status of biowaste management highlights the shortcomings of the linear economic model and the largely unexploited potential to close resource loops through biowaste recovery [18]. The authors of [19] conducted a scoping review on circular organic waste management. Among key future research directions, they suggested to explore different pathways for biowaste recovery, with focus on assessing the value added through energy and nutrient recovery [19].

1.2. Anaerobic Digestion (AD): A Pathway for Biowaste Recovery

Four main types of technologies can treat biowaste: (a) direct use (e.g., direct combustion); (b) biochemical treatment (e.g., fermentation and anaerobic digestion); (c) physicochemical treatment (e.g., transesterification); and (d) thermochemical treatment (e.g., gasification) [20]. Figure 1 shows that some treatment technologies recover bioenergy among their products—the so-called "waste-to-energy" (WtE) technologies. WtE options address two global challenges simultaneously: the growing amount of waste, as well as the increasing energy demand, providing a clean energy alternative to replace fossil fuel use. They contribute to 'cleaning' and diversifying the energy mix and reducing reliance on external energy imports towards resilient energy systems [21]. In addition, some WtE technologies provide opportunities to recover nutrients and close loops in bioresource management [22].

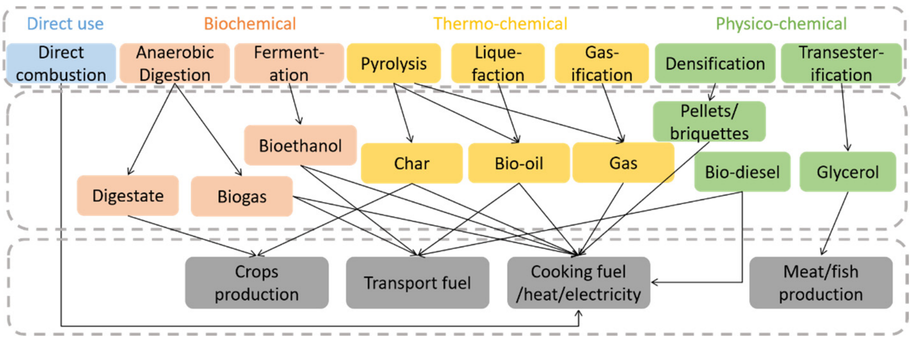

Figure 1. WtE pathways for biowaste treatment. Adapted from [20].

Among available WtE technologies, anaerobic digestion (AD) is an established technology: there are various AD options with a high technology-readiness level that are commercially available and applied [23]. AD is a biochemical process that decomposes organic matter in the absence of oxygen. It can treat biowaste and other biomass feedstocks such as agricultural residues, livestock manure, wastewater and fecal sludge, industrial waste, and energy crops [8,24]. The products of the process are biogas (a renewable energy source) and digestate, which contains organic matter and nutrients such as nitrogen, phosphorus, and potassium (N,P,K) [25]. Biogas can be used as cooking fuel or converted to heat and electricity through combined heat and power (CHP) engines. It can also be upgraded to biomethane to use as vehicle fuel or to inject into natural gas grids [26]. Through biogas combustion, AD systems avoid methane emissions compared to other conventional biowaste management options such as landfilling. In turn, digestate can be further processed to use as fertilizer, soil amendment, or livestock bedding [20]. Another emerging option is digestate use in 'digeponics', a type of hydroponics in which digestate-based products are used as substrate to grow plants [27]. Overall, AD has a multifunctional character [28], and can contribute to sustainable and circular resource management towards energy and food security, waste management, and sanitation [29,30]. The authors of [31] considered AD '*not as an energy technology but as a technology that addresses challenges across multiple resource domains*'. This multifunctional character requires an integrated approach for AD planning: in this study, the term 'integrated' refers to the assessment of direct or indirect interlinkages across scales, systems, and sectors.

Figure 2 depicts the AD process chain in the urban biowaste recovery context. As shown, the process chain comprises three key stages: the substrate chain, AD treatment, and the product chain. At the substrate chain stage, various urban sources generate biowaste. Urban biowaste is collected and transported for treatment. Pretreatment can enhance substrate quality. Then, the substrate undergoes treatment (i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis) through a suitable AD technology. Biogas and digestate products can undergo post-treatment, depending on the intended product use (e.g., biogas upgrade to biomethane and use as transport fuel). Finally, the end products are stored and distributed for valorization at suitable outlets [32].

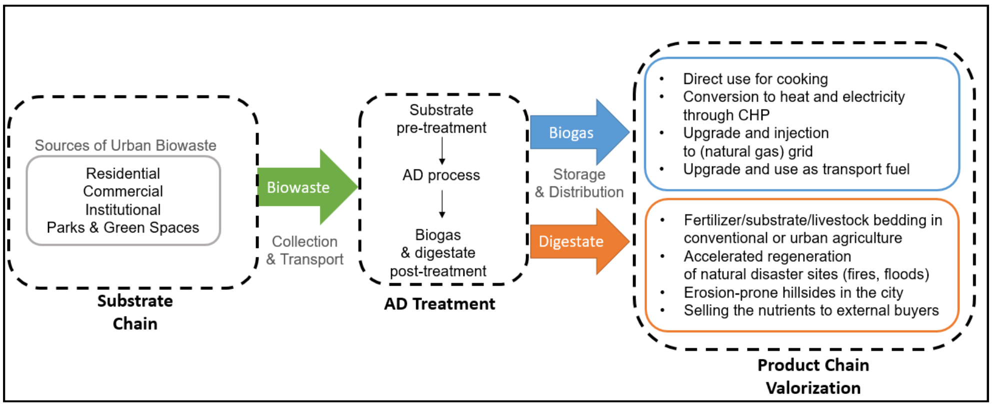

Figure 2. Process chain of anaerobic digestion for urban biowaste recovery. Based on [32,33].

Despite the potential benefits, AD implementation for urban biowaste recovery is still low compared to its full potential at the global level [34,35]. According the International Energy Agency (IEA), actual biogas production amounted to 35 million tonnes of oil equivalent (Mtoe) in 2018. This represents roughly 6% of the full biogas potential (i.e., 570 Mtoe) using available feedstocks. Realizing the full potential could supply approximately 20% of the world's current gas demand [36]. The feedstocks leading to this estimate included crop residues, livestock manure, MSW, and wastewater. MSW represents roughly 20% of the global biogas potential (i.e., 112 Mtoe). Therefore, increasing AD implementation can significantly contribute to achieving the biowaste recovery potential. Further research on the implementation of urban AD systems, as well as related opportunities and challenges, can support decision making. In this paper, the terms 'urban AD systems' and 'urban AD' refer to AD systems that treat urban biowaste as primary feedstock.

1.3. Centralized and Decentralized Approaches for Integrated Biowaste Management Systems

Modern cities have mainly followed centralized approaches to organize waste management, as well as other resource management systems such as for energy and water [37]. Drivers of centralized approaches include economies of scale and transport costs [38]. However, the rapidly growing global waste generation pushes for renewal and expansion of relevant infrastructure; e.g., disposal and treatment facilities, waste collection fleets, etc. This infrastructure demand puts increasing pressure on centralized waste management systems and can trigger sustainability challenges [39]. For example, collection fleets must travel larger distances to treatment and disposal facilities, using larger amounts of vehicle fuels (economic cost) and thus increasing transport-related greenhouse gas (GHG) emissions (environmental cost) [18]. MSW collection and transport require up to 40% of municipal revenues for cities in developing countries [40]. In this context, decentralized systems are an alternative to shape waste management systems, and have attracted interest by practitioners, policy makers, and the scientific community [41].

Considering relevant scientific literature, the authors of [42] applied bivariate analysis on different types of energy technologies and found various potential benefits of decentralized, small-scale technologies (e.g., faster diffusion, opportunities to escape lock-in) to facilitate decarbonization. In the bioenergy context, the authors of [43] reviewed international case studies and identified opportunities and challenges for the implementation of decentralized bioenergy systems. They mapped interlinkages across the three sustainability pillars (economic, social, and environmental), and highlighted market viability as a major challenge. To support product establishment in the market, the authors emphasized opportunities to integrate bioenergy production with other sectors to develop closed-loop systems. However, the authors of [43] did not consider urban biowaste among the feedstock types addressed (forestry and agricultural residues, livestock manure).

The implementation of urban AD has followed a pattern similar to many waste management systems, as most operating urban AD systems globally are centralized [44]. It has been suggested that partial decentralization of biowaste management can better support the transition from linear to circular systems, and shift perspective from 'waste' management to a wider resource management approach [45]. Nevertheless, the authors of [37] characterized the current scientific literature on technologies for decentralized biowaste treatment '*fragmented and incomplete*'. To begin filling this gap, they classified and compared decentralized options for urban biowaste treatment (including AD) through extended material flow analysis (EMFA). Their analysis focused on techno-economic aspects of decentralized options and did not investigate system level planning. Through an interview-based stakeholder analysis, the authors of [41] identified institutional drivers and barriers towards the implementation of decentralized biowaste management systems. However, to the authors' knowledge, there was currently no systematic and comprehensive review to provide an overview of decentralized AD at the system level addressing questions such as: What is the current scientific knowledge on key planning aspects for decentralized AD at system level? What are the opportunities and challenges for planning of decentralized AD? What is the potential contribution of decentralized AD towards the implementation of urban biowaste recovery systems? Moreover, relevant studies have rarely provided explicit definitions of centralized and decentralized management systems.

1.4. Paper Objective and Outline

Through a scoping literature review, this study aimed to provide a comprehensive overview of current scientific knowledge on decentralized AD. It focused on its potential contribution towards the implementation of urban biowaste recovery systems. Such systematic assessment of scientific knowledge related to decentralized AD is currently not available in the literature. The synthesis led to key opportunities and challenges of decentralized AD planning. These can guide future decision making and scientific research on planning of decentralized AD and urban biowaste recovery systems.

The rest of the paper is organized as follows: Section 2 outlines the research design. Section 3 synthesizes current knowledge on decentralized AD for urban biowaste recovery based on the scientific literature. Section 3.1 presents definitions of centralized and decentralized approaches. Through a literature classification, Section 3.2 discusses key planning aspects of decentralized AD systems for urban biowaste recovery. Section 4 further investigates emerging research themes that can guide the implementation of decentralized AD. Section 5 summarizes key messages through the lens of opportunities and challenges for future development of decentralized urban AD. Finally, Section 6 draws the study conclusions.

2. Research Design

A study must follow a transparent and systematic process to employ a literature review as a robust research method [46]. This study conducted a scoping review with the aim to analyze emerging evidence and research gaps on the topic, as well as investigate how research is conducted [47]. It was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard [48], an established approach to guide scoping and systematic reviews.

The literature review process followed these steps: (1) using a search string to identify relevant scientific studies through two scientific databases; (2) screening these studies based on a series of eligibility criteria; and (3) conducting a qualitative synthesis. The qualitative synthesis exposed key opportunities and challenges of decentralized AD through: (a) provision of definitions of centralized and decentralized approaches; (b) classification of current knowledge on decentralized AD; and (c) identification of emerging themes that can support future research. Figure 3 visualises the review process (data related to the review material are also provided in Tables S1–S5 of the Supplementary Material).

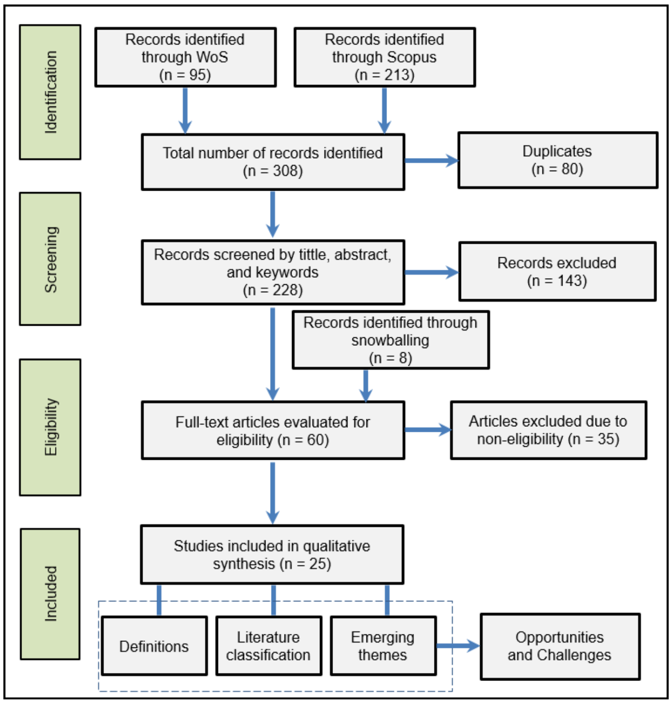

Figure 3. The literature review process, based on [48].

2.1. The Literature Collection Process

The following search string was used (using Boolean operators and truncation) to identify relevant literature in the scientific databases 'Scopus' and 'Web of Science' (WoS):

("anaerobic digestion" OR "biogas" OR "digestate" OR "nutrient") AND ("decentrali*" OR "small" OR "micro" OR "centrali*" OR "large") AND ("urban" OR "city" OR "cities") AND ("biowaste" OR "organic waste" OR "organic solid waste" OR "organic fraction of municipal solid waste" OR "food waste" OR "food and garden waste")*

The search string was applied in a search based on title, abstract, and keywords. The search was limited to peer-reviewed journal publications in English, in the time range of 2010 to July 2021. It was assumed that current literature reflected and incorporated all major scientific knowledge from studies published before 2010. Duplicate results from the two databases were removed.

2.2. Eligibility Criteria to Screen the Review Material

To screen the remaining (unique) documents, a series of eligibility criteria were set (see Table 1). In the first screening round, the eligibility criteria were applied by reading the title, abstract, and keywords of each document. In the second screening round, each document was read in full to determine eligibility based on the same criteria. Several papers were excluded based on the second criterion: while they addressed AD for urban biowaste, they often focused on AD at the plant scale and technical/operational aspects of the AD process. In addition, 'snowball sampling' [49] was also applied: some studies identified through database search cited or were cited by papers relevant to the review criteria (screening stage, see Figure 3). A final list of 25 records (20 original research articles and 5 review articles) was compiled to conduct qualitative synthesis. Twenty additional references from the wider scientific literature were cited to provide background to the analysis, where appropriate (e.g., [50]).

Table 1. Eligibility criteria and relation to classification parameters.

	Eligibility Criteria for Paper Screening (Methodology)	Relevant Classification Categories (Analysis)
1	Does the paper consider urban biowaste (and subcategories) as the primary feedstock for anaerobic digestion?	• Feedstocks • Geographic scope of analysis • Embeddedness in the urban environment
2	Does the paper address decentralized approaches, or compare or combine AD configuration approaches?	• Configuration approach
3	Does the paper address aspects of AD planning at the system level (as a pathway for urban biowaste recovery) beyond the plant/project level?	• Selection of treatment technologies • Implementation aspects • Methodological tools • Circular (bio)economy

The selected eligibility criteria were based on (necessary) assumptions and could have been subject to bias, despite all efforts for objectivity. Nevertheless, the research design was reported fully, and it can be replicated or modified by other researchers for future research (see Supplementary Material).

2.3. Qualitative Synthesis

The qualitative synthesis was based on literature classification and thematic analysis [51,52]. The literature classification approach was informed by [7,19]. Eight classification categories were formed based on thematic analysis of the literature and the eligibility criteria. Table 1 shows how the classification categories (analyzed in Section 3.2) related to the eligibility criteria. The literature classification provided an initial organization of the review material and set the ground for further thematic analysis. Thematic analysis is a research method that aims to identify, analyze, and report patterns (themes) within data [53]. It was used to synthesize the review material.

3. Current Scientific Knowledge on Decentralized AD for Urban Biowaste Recovery

The literature review findings are presented in two sections aiming to discuss: definitions of centralized and decentralized systems (Section 3.1) and highlight key planning aspects of decentralized urban AD (Section 3.2).

3.1. Definitions of Centralized and Decentralized AD Systems

To explore centralized and decentralized AD approaches, the authors first examined how they are defined in the papers reviewed. Table S6 (see Supplementary Material) summarizes definitions/descriptions of centralized and decentralized approaches used in the 25 papers reviewed. The findings showed that definitions of 'centralized' and 'decentralized' treatment and 'large-scale' and 'small-scale' facilities could largely vary depending on the system boundaries and contextual characteristics of each study.

In most cases, the authors did not provide explicit definitions of centralized and decentralized AD systems. Several studies described decentralized systems as: (a) consisting of small-scale plants and (b) located close to the waste source, compared to centralized approaches. For example, according to [54], decentralized systems consist of small-scale AD plants that are approximately *'75 m^2 (15 m $\times$ 5 m) to accommodate all the equipment and the required space around'*. In contrast, the authors of [37] describe decentralized treatment systems as: *'A class of treatments that encompasses relatively small facilities capable to metabolize less than approx. 10 tonnes biowaste/year'*.

In turn, there is discrepancy in definitions of 'large-scale' and 'small-scale'. The papers reviewed used different parameters to define small-scale AD (see Table S6 in Supplementary material). Some studies used digester volume to distinguish small- and large-scale systems (e.g., [55]), while others referred to treatment capacity (e.g., [56]), biogas production (e.g., [33]), or installed capacity (e.g., [57]). Even when two studies used the same parameter to describe scale, the ranges set could largely vary. For example, in a local context with large feedstock (e.g., biowaste) availability, the threshold for 'small-scale' could be set higher compared to a geographic area with lower feedstock availability. The large variety of definitions highlighted that planning of AD systems requires integrated approaches based on contextual characteristics of the geographic area of implementation [58].

For this study, 'decentralized systems' consisted of relatively small-scale facilities usually located at short distance from waste sources and end users. In contrast, 'centralized systems' consisted of (usually fewer) large-scale facilities located at larger distance from the city. Based on the review material, one example of centralized AD was an urban biowaste large-scale facility 130 km from the city of Brussels that treats food waste with capacity of 50,000 tonnes/year [17]. One example of decentralized AD was a system of 170 small-scale AD sites to treat urban biowaste in the Lyon metropolitan area, each located at a maximum distance of 5 km from waste sources and with capacity of less than 61 tonnes/year [54].

3.2. Key Planning Aspects of Decentralized AD for Urban Biowaste Recovery

To analyze the scientific knowledge on planning of decentralized AD for urban biowaste recovery, the review material was classified under eight categories. In the Supplementary Material, Table S7 lists the eight categories and their subcategories. Table S8 shows the paper classification. Key findings from this analysis are discussed below, and were organized according to the eligibility criteria for paper selection (see Table 1).

3.2.1. Urban Biowaste as Primary Feedstock for AD

The authors screened for papers that focused on urban biowaste as exclusive AD feedstock or together with other feedstocks. This criterion included papers that focused on urban biowaste subcategories, such as food waste. The papers were classified while considering the feedstock types they addressed, their geographic scope of analysis, and whether/how they addressed AD embeddedness in the urban environment.

Feedstocks

AD can treat a wide range of biomass feedstocks. Even with focus on one bioresource category (here urban biowaste), AD feedstock characteristics may largely vary from one study to another, depending on various aspects. Firstly, biowaste must be separated from other MSW fractions as early as possible in the AD process chain. Early sorting and collection maximize feedstock quality, which in turn largely determines treatment efficiency and the quality of the final AD products [41]. The transition to separate biowaste sorting and collection has been addressed by other studies (e.g., [59,60]) and is beyond the scope of this paper. At times, biowaste subcategories (food and green waste) were collected and treated combined or separately. For example, four papers focused on food waste as key AD feedstock, while [17] found that combined collection of food and green waste, separated from other waste fractions, was the most efficient collection approach for their Brussels case study. The suitable feedstock, as well as the suitable mode of separation and collection, were context-specific for each recovery project, depending on several characteristics of the city studied. For example, the authors of [61] studied the biogas performance of urban feedstocks collected through different methods (e.g., mixed collection and mechanical separation, separation at source, and hand sorting), and highlighted that urban characteristics such as morphology (e.g., urban density and size of the streets) largely influenced waste generation, the sorting and collection methods, and thus treatment efficiency. Moreover, biowaste can undergo pretreatment (see Figure 2) to enhance treatment efficiency; e.g., processing through a chopper mill and feeding to the digester through pumps [62]. Biowaste can be codigested with other substrates such as sewage sludge: five reviewed papers addressed codigestion. In the review material, 13 papers focused on urban biowaste as main AD feedstock, which is also termed 'organic fraction of municipal solid waste (OFMSW)' or 'food and green waste'. Three other papers considered the wider waste management system (including nonorganic MSW) and addressed biowaste treatment among other waste categories. The classification of feedstocks showed that the scientific literature has addressed several feedstock options in the decentralized context. Feedstock characteristics are highly influenced by several context-specific factors that must be assessed in AD planning (e.g., optimization and sustainability assessment).

Geographic Scope of Analysis

System boundaries can largely vary in terms of how studies approach the 'urban' scale of analysis: a paper may study urban biowaste recovery at the municipal, metropolitan or even regional level. For example, the authors of [63] compared aspects of environmental and economic performance of different treatment systems between municipal districts in the metropolitan region of Porto, Portugal. The authors of [64] developed a DST for AD planning at regional/county level, while those of [38] applied a multilevel analysis considering the deployment of biowaste recovery systems at the national, district, and organizational level. The study in [56] focused on a small community (land area: 80 km^2, 17,000 inhabitants, 550 kg waste per capita per year).

Moreover, it was observed that most papers reviewed mainly analyzed case studies in developed regions. This tendency reflected the geographic distribution of implemented decentralized AD projects, which were also found mainly in developed countries. While decentralized AD projects in developing contexts have also been addressed by the scientific literature and implemented in practice, these were mainly found in rural areas, and often focused on other feedstock types such as livestock manure (e.g., [65,66]).

Embeddedness in the Urban Environment

Accounting for potential interactions between AD systems and their geographical space of implementation is essential to achieve integrated planning. The study in [67] indicated that the embeddedness process differs between the rural and urban context, depending on the socioeconomic structures in each context. Moreover, decentralized urban

AD presents opportunities to locate treatment plants within the urban environment, in contrast to centralized facilities, usually located in city outskirts. In such cases, AD systems must be embedded within city boundaries, in harmony with the urban environment [68]. Essential questions to address include: Where will AD facilities be located? How do they affect pre-existing urban elements (e.g., other types of infrastructure)? The authors of [18] indicated that, in the shift from centralized to more decentralized, AD systems can be embedded at various urban levels: an AD plant may target biowaste at the building, district, or municipal level. It is thus essential to address different embeddedness levels. Including [18], 18 papers addressed different levels of AD embeddedness in the urban environment, either implicitly or explicitly. For example, the authors of [55] focused on embeddedness at the building level, and [45] at the municipal level. Some papers referred to more than one level of embeddedness. For example, the authors of [62] addressed embeddedness at the building level (community café) as well as district level. In their London case study, households close to the plant provided the AD feedstock. The biogas produced was used for the plant's energy needs (heat and electricity), but also by a nearby community café (cooking fuel). Finally, nine papers considered the potential for urban AD embeddedness through synergies with UA. The reasoning for such an integration was to use recovery products in UA, thus developing local circularity. This potential integration is further analyzed in Section 4.

3.2.2. Configuration Approaches for AD Planning

AD systems can be based on centralized, decentralized, or combined approaches that mix centralized and decentralized configurations. The system's configuration can largely influence the quality of AD products [41] and the wider sustainability impact of the system. In the review material, 11 papers focused only on decentralized approaches for AD planning. One study focused on centralized approaches. One study addressed AD planning without referring to a specific configuration approach. Finally, 12 studies compared different configuration scenarios and combined approaches to enhance the performance of biowaste recovery systems. These studies emphasized that the effect of different system configurations of AD and wider urban biowaste recovery systems has been marginally addressed. Moreover, several studies highlighted potential opportunities of implementing decentralized urban AD. However, the description of such opportunities was rarely supported by relevant scientific evidence. The findings showed that quantitative and qualitative assessments of opportunities, as well as related challenges (as part of sustainability assessment), are limited. Future research is essential to further analyze and integrate system configurations into planning of AD and wider urban biowaste recovery systems. Sections 4 and 5 further address pathways to enhance knowledge of decentralized urban AD.

3.2.3. Other System Level Aspects for AD Planning

This paper addresses decentralized AD at the system level as opposed to the plant level. Plant-level studies refer to those that focus on individual AD facilities, mainly addressing technical/operational and technoeconomic aspects of the AD process itself. In contrast, the screening aimed for system-level studies that focused on networks of AD facilities to treat a city's biowaste or a fraction of it. Papers were classified considering treatment technologies that can be combined with AD to develop biowaste recovery systems. Other classification categories were 'methodological tools' and 'implementation aspects', because system-level analyses need to address various implementation aspects and can use a wide range of methods. Moreover, the sustainability context under which AD was addressed was also classified, with focus on the contexts of circular economy and bioeconomy.

Selection of Treatment Technologies

The treatment technologies addressed in each paper were also classified. While this review focused on AD, several technologies for biowaste treatment exist (see Figure 1).

Sixteen papers reviewed focused only on AD as an option for biowaste recovery. Nine papers compared and combined AD with other treatment technologies to select suitable technology combinations in different contexts. For example, the authors of [63] assessed the economic and environmental costs of different technology scenarios (landfilling with gas recovery, centralized incineration, centralized AD, and centralized and decentralized composting) using life-cycle assessment (LCA) and spatial analysis. Their results showed trade-offs occurring in each scenario (e.g., local composting had low economic costs, but high environmental costs compared to AD), and that system design must be guided by urban characteristics (e.g., local composting is suitable for remote, less dense neighbourhoods). Moreover, the authors of [38] assessed scenarios of partially and completely decentralized configurations of AD and gasification. Both AD and gasification scenarios led to sustainability benefits. The gasification scenario had the highest economic (e.g., revenues from upgrading biogas to fuel), environmental (e.g., GHG emission savings), and social (e.g., job creation) benefits. However, gasification options are still less advanced than AD at the technical and commercial level [38]. The findings above showed the complexity of identifying suitable technologies and configurations as part of planning biowaste recovery systems. Moreover, planning such aspects must reflect the case study's specific local context. Therefore, additional case study research investigating different scenarios can better inform scientific knowledge and decision making regarding AD and biowaste recovery systems. Furthermore, the findings of [38] highlighted AD as a low-hanging fruit: a conventional technology ready to implement while other novel technologies for high-value bioproducts are further developed.

Implementation Aspects

The need for integrated planning across the three sustainability pillars has been highlighted in the wider literature for resource recovery systems [69]. The reviewed studies addressed various AD implementation aspects. The level of analytical detail, system boundaries, methodological tools (see next section), and metrics used largely varied across studies. Some papers did not provide in-depth analyses, but instead merely provided preliminary descriptions of implementation aspects. For example, while 12 papers addressed environmental aspects of AD implementation in their analysis, only 4 examined environmental performance comprehensively through LCA approaches. Other studies followed less-comprehensive approaches to assess environmental performance. For example, the authors of [64] estimated expected CO_2 emissions based on distance of biowaste collection and transportation. The study of environmental performance is further addressed in Section 4.2.

Twenty papers included technical aspects (e.g., digester sizing) to assess implementation. Sixteen papers considered economic (e.g., capital and operational costs), twelve considered environmental (e.g., associated GHG emissions), and nine addressed social (e.g., plant acceptance) aspects. Moreover, seven papers addressed institutional aspects for AD implementation. For example, the authors of [38] assessed (national) policy frameworks to identify challenges of the current waste management system, for the case of the United Kingdom. The authors of [70] mentioned that policy interventions such as grant incentives can impact AD uptake significantly. Spatiotemporal aspects are also crucial to consider for AD planning [71,72]. Seven papers addressed spatial dimensions, while only two papers addressed both spatial and temporal aspects. The study in [64] used spatial analysis to develop an agent-based model (ABM), and included the temporal rate of implementation (slow, mid, or aggressive) as a parameter to design AD planning scenarios. The authors of [18] used spatial analysis and considered a range of time periods (over 1, 10, and 15 years) to estimate AD implementation over space and time. Overall, comprehensive assessment of all relevant implementation aspects can enhance the level of detail and accuracy of AD planning.

Methodological Tools

Integrated AD planning requires support from adequate methodological tools. The classification shows that the reviewed studies applied a wide range of methodological approaches, from material flow analysis (MFA) (four papers) to multilevel perspective (MLP) [45] and visual analytics [64]. Most studies applied mixed research methods, and as mentioned for 'Implementation aspects', analytical depth largely varied. For example, most papers employed some form of literature review as part of their studies: an overview of current knowledge and research gaps for research motivation. Five papers employed literature review as their main methodological tool, but only [57] followed a systematic process. The other papers applied more ad hoc approaches in using a literature review as a key research method, although some supported their review findings with interviews with experts. None of these papers provided a systematic and comprehensive analysis of urban AD planning through decentralized approaches. Notable methodological approaches that can support further research towards integrated planning of AD and wider biowaste recovery systems are discussed further in Section 4.

Circular Economy and Bioeconomy

The role of AD as part of a circular economy and circular bioeconomy is also crucial to consider as an aspect of integrated planning. In the review material, only three papers addressed urban AD explicitly in the context of circular bioeconomy. Namely, the authors of [17] mentioned the study of bio-based materials deriving from AD as a future research step. The authors of [57] reviewed digestate valorization options, including advanced technologies, to support the development of biorefinery systems. The authors of [41] identified institutional factors that enabled or constrained implementation of decentralized biowaste management systems in the context of the circular bioeconomy. Therefore, potential interlinkages between urban AD and other stages in cascading biomass use were beyond the scope of these studies and have not been researched explicitly. However, there are several options to cascade biomass use (e.g., production of chemicals through advanced biorefineries), beyond energy and nutrient recovery through AD biogas and digestate. It is thus crucial to integrate AD in the wider context of circular bioeconomy comparing it to other options. Moreover, 16 papers contextualised their contribution within circular economy, while 6 papers referred to a wider sustainability context.

4. Emerging Research Themes on Decentralized AD towards Integrated Planning of Urban Biowaste Recovery

Decentralized AD can enable local circularity or '*local valorization loops*' by minimizing distances along stages of the value chain [54]. Contrary to centralized approaches, in decentralized systems, waste is treated closer to the source and end users, and thus recovery products can find local end uses, adding value to the urban environment. Figure 4 provides an example in which decentralized AD contributes to a local valorization loop: biowaste is collected from sources such as households and UA and treated through decentralized AD. Biogas produced can be used by the households; e.g., as cooking fuel, and digestate as fertilizer in UA.

The potential for local circularity must be assessed to plan such localized systems (feedstock sources, treatment methods, product outlets, and end uses). In this context, assessing the relation between resource supply and demand is crucial. Here, 'supply' refers to AD products and 'demand' to the resource requirements of potential product outlets locally. The authors of [63,73] used the term '*urban sinks*' to describe local product outlets and '*local sink capacity*' when referring to the potential to use recovery products locally. They highlighted that scientific knowledge is limited concerning local sink capacity and the performance of decentralized treatment systems under large-scale deployment.

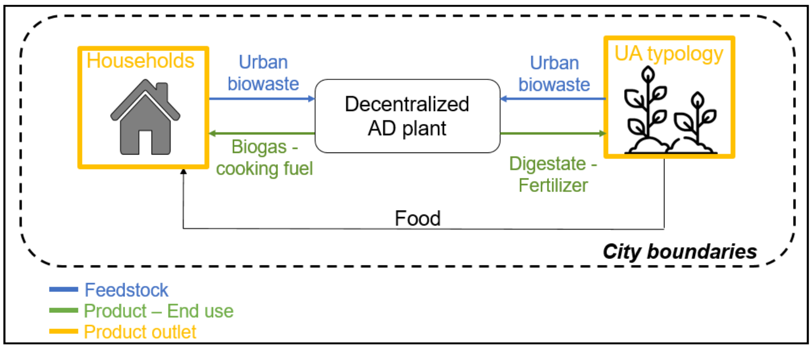

Figure 4. Example of a simplified 'local valorization loop' (own graph). Icons used were designed by Freepik (https://www.freepik.com, accessed on 2 July 2021).

Building on Section 3, this section identifies emerging research themes on decentralized AD with focus on integrated planning of urban biowaste recovery systems. The findings showed that all reviewed papers addressed biowaste recovery through local valorization loops either explicitly or implicitly. The emerging research themes identified were: (a) spatial analysis; (b) life cycle analyses of environmental performance; (c) decision support tools (DSTs) and frameworks; (d) nexus approaches; and (e) UA as an entry point for embeddedness in the urban environment. Most papers touched upon more than one of these themes (see Table S9 in the Supplementary Material). For example, the authors of [64] developed a DST for AD planning (c), largely based on spatial analysis (a), while it also adopted a nexus approach (d) for sustainability assessment. Each theme is further discussed below.

4.1. Spatial Analysis

The integration of spatial dimensions in planning of resource systems has received significant scientific interest [50]. This interest is reflected in the decentralized AD context. Spatial analysis combines methods of mathematical optimization and geographic information systems (GIS) to determine the spatial organization of AD systems. It informs decisions to achieve balance between supply and demand considering quantity, quality, and availability of biowaste feedstock, treatment facilities, product outlets, and their spatial distribution. For example, the authors of [54] presented a spatial optimization model to support the design of decentralized urban AD systems. For the case of Lyon, they found sufficient digestate potential to complement nutrient demand in periurban agriculture (PUA). For biogas, they assumed conversion through CHP, but did not provide further analysis; e.g., comparison to local electricity and heating demands. Moreover, their model focused on minimization of payload distances, while assessment of other aspects (e.g., environmental, social) was proposed for future work. Using spatial optimization, the authors of [73] explored the energy impact of upscaling UA and the potential to cover UA's energy and nutrient demand through biowaste recovery via AD, composting, and insect rearing. For the cases of Lyon and Glasgow, they found that digestate supply far exceeded UA's nutrient demand. Additional urban outlets would be required to use digestate surplus locally. Biogas use through CHP could cover only part of UA's energy demand (heat and electricity). On the other hand, they found that waste valorization contributed to reducing UA's carbon footprint (−7.9% for Glasgow, −12.6 for Lyon compared to upscaled UA scenarios without waste valorization in UA). The study in [63] applied spatial analysis to compare the environmental performance of municipal districts, as well as their sink capacity and related logistics (see Section 4.2); the authors of [18,64] also applied spatial analysis to develop DSTs (see Section 4.3).

Findings of spatial analysis supported that decentralized AD could contribute to local circularity with positive sustainability impact. Spatial methods assessed local sink capacity and informed decisions to match digestate supply with local fertilizer demand and plan for surplus management while considering sustainability implications [73]. Biogas management presented fewer technical challenges than digestate management. Current spatial methods also highlight the complexity of AD planning that integrates decentralized approaches. It is essential to further study UA and other urban outlets for product valorization. Local data are essential, but may be difficult to obtain due to lack of access and/or documentation. Future research can further develop/refine spatial methods to address different configuration approaches.

4.2. Life Cycle Analyses of Environmental Performance

The environmental performance of decentralized AD systems remains largely unclear. As mentioned in Section 3.2, few studies have examined environmental performance comprehensively through LCA. The authors in [56] conducted LCA for biowaste treatment scenarios for a small Italian community. They considered three impact categories: global warming potential (GWP); acidification, eutrophication, and ozone depletion; and photochemical ozone creation. Decentralized AD with digestate composting was the best-performing scenario for all impact categories. However, they also highlighted that AD environmental performance was largely dependent on local digestate use. The system's emissions may increase significantly if digestate requires transport for treatment and use elsewhere, largely due to transport-related GHG emissions. The authors of [17] conducted an LCA of centralized and more localized biowaste recovery systems and found that, under certain conditions, treatment systems located closer to the city performed better while considering the endpoint categories: human health, ecosystem damages, and availability of resources. The local AD scenario had the best environmental performance in their Brussels case study. The scenario referred to a large-scale plant (capacity: 50,000 tonnes/year) due to lack of local data for small-scale AD. It was located within the metropolitan area, compared to other scenarios, with a centralized AD facility located 130 km outside Brussels. Only their composting scenario included local small-scale facilities, which performed well in terms of resource use, but had lower overall environmental performance compared to local AD. The authors addressed the lack of other decentralized scenarios as a study limitation; they highlighted the need to expand research to assess the variety of decentralized biowaste treatment scenarios. The authors of [63] assessed economic and environmental metrics (annualized treatment cost and GWP) of centralized and decentralized treatment scenarios, while also considering spatial parameters such as urban sink capacity and related logistics (allocation of compost bins and urban farms as product outlets) across municipal districts of the Porto metropolitan area, applying LCA and spatial analysis. Local composting had the lowest economic costs and centralized AD the lowest environmental costs. They also found that additional urban farms would increase local sink capacity, but marginally reduce economic treatment costs (range of 0.5–2.5%). Environmental savings largely varied across the municipalities considered (range of 0.1–39.9%). The authors of [63] highlighted that their results largely varied due to the influence of context-specific factors such as urban density (see also Section 3.2.1), the energy sources of the electricity grid, and the potential for local digestate use. Finally, the authors of [74] conducted LCA while addressing not only AD configurations, but also various end uses for each configuration assessed. For the case of Singapore, they found that all AD scenarios performed better than incineration. Considering 17 impact categories, centralized AD for transport fuel and decentralized AD for cooking fuel were the scenarios with the highest environmental savings, with the latter performing best in terms of GWP and fossil fuel depletion.

Similar to studies of spatial analysis, studies with a focus on environmental performance highlighted the importance and challenges of assessing local sink capacity and digestate management. Further research can enhance knowledge on environmental implications of decentralized applying comprehensive methodological approaches, such as LCA and studying a variety of decentralized scenarios. Current findings highlighted AD's context-specific nature, and hence the need to conduct environmental-impact assessments that integrate local characteristics.

4.3. Decision-Support Tools and Frameworks (DSTs)

As described above, spatial analysis and LCA of environmental performance are valuable methodological tools to support AD planning. However, planning decisions such as the selection of suitable configurations also require more overarching decision support tools and frameworks (DSTs) [74]. DSTs are often based on multicriteria decision analysis (MCDA), which aims to address all relevant AD implementation aspects (see Section 3.2) while considering the three sustainability pillars and context-specific characteristics. DSTs that apply MCDA can thus support decision making towards integrated AD planning.

Methods such as spatial analysis and LCA can be part of such overarching DSTs. For example, the authors of [18] used spatial optimization as well as LCA data as part of their DST to estimate GWP. Their DST used modeling of MSW distribution, optimization of the management system (with focus on cost optimization), and a multicriteria framework for sustainability assessment. Their findings showed that, compared to the conventional MSW scenario (incineration), the combined centralized/decentralized AD system could double electricity profits through biogas, reduce capacity land fragmentation by 75% (thus enhancing land use) and GWP by 19%, operational expenses up to 50%, and the required transport fleet up to 15%. The authors recommended future research on the effect of different planning priorities (e.g., prioritizing GWP performance over economic costs) to assess centralized and decentralized approaches. The authors of [38] developed the Systems Thinking Approach to Resource Recovery (STARR) framework based on the case of the United Kingdom. It included a review of national waste management policy and a multilevel system analysis, which applied MFA to measure the potential recovery at the national, community, and organizational (supermarket) level. At the community level, the authors developed three scenarios for biogas and digestate production, and conducted sustainability assessment that included economic, environmental, and social parameters and indicators (see also Section 3.2). The authors of [64] developed an ABM to support AD planning and decision making at the regional/county level. The model considered the effect of policy decisions regarding AD configuration (centralized, uniform, or decentralized) and temporal rate of adoption (slow, mid, or aggressive). It also addressed potential implications in the water–energy–food (WEF) nexus through consideration of environmental, social, economic, and spatial parameters.

The three studies presenting DSTs highlighted the need to further develop indicators to assess circularity, sustainability, and associated nexus interlinkages. Further application of DSTs in different geographic contexts can enhance relevant scientific knowledge. Moreover, current DSTs have not built upon one another. Each adopted a different perspective towards AD planning and the consideration of configuration approaches. The development of commonly agreed DSTs could organize and enhance future AD research and planning, while always accounting for contextual characteristics.

4.4. Nexus Approaches

Nexus approaches address interlinkages between resource systems across sectors and scales and aim to identify and manage relevant trade-offs and synergies [75]. In recent years, they have gained increasing scientific interest as tools to support research for sustainable development (e.g., [76,77]). In the AD context, the authors of [31] characterized nexus approaches as valuable tools to address AD's multifunctional character towards integrated resource management. The multisectoral and multiscalar nature of nexus approaches can also be useful in the development of MCDA tools (see Section 4.3).

Only two papers we reviewed addressed urban AD through a nexus approach, both focusing on the WEF nexus. The authors of [73] referred to the WEF nexus in the context of integrating biowaste valorization with UA. However, they only assessed WEF material and energy flows, and did not conduct comprehensive nexus assessment to address nexus interlinkages explicitly (for a description of the concept of 'nexus assessment', see [78]). The study in [64] developed a DST for AD planning, which addressed WEF nexus implications (e.g., fresh water consumed) as part of a sustainability assessment. Their findings showed that each AD strategy could involve several trade-offs, such as between GHG emissions and social acceptance: decentralized scenarios often require short transport distances that minimize associated GHG emissions; however, the proximity of treatment plants to populated areas is associated with low social acceptance. In return, centralized systems can have a lower 'visual impact', since they are located far from populated areas. Nevertheless, larger transport distances can lead to higher GHG emissions, compared to decentralized approaches. These findings highlighted the value of nexus approaches in identifying potential trade-offs and synergies. Nexus approaches can be further applied in the study of decentralized AD. For example, the authors of [64] encouraged further research on nexus metrics in the urban AD context to increase analytical detail, and thus address complexity of measuring nexus interlinkages. Moreover, among the scales addressed through nexus approaches, the urban scale is essential to consider in the context of AD for urban biowaste treatment and embedding AD in the urban environment.

4.5. UA as Entry Point for AD Implementation

AD implementation and its embeddedness in the urban environment can be approached through various entry points (see also Section 3.2.1). Among such entry points, several studies have focused on synergies between AD and UA. In recent years, urban agriculture (UA) has been advocated as a potential contributor to urban sustainability. Scientific literature has explored potential UA benefits ranging across various dimensions such as food security, ecosystem services, social cohesion, and others (e.g., [79,80]). In the CE context, UA can contribute to sustainable urban metabolism, with outputs from one process serving as inputs for another [81,82].

To realize potential benefits, UA must be 'upscaled': UA growing practices need to expand in available land areas (ranging from ground-based land plots to building rooftops). While upscaling, UA's resource requirements increase and must be assessed and managed sustainably. However, the authors of [81] highlighted resource requirements of both current and upscaled systems as largely unexplored. The authors of [83] found scientific knowledge insufficient to reach definite conclusions on UA's expected sustainability impact. They also provided an overview of waste valorization pathways to enhance UA's resource efficiency and explore WEF nexus interlinkages. UA can utilize recovery products from urban waste streams (biowaste but also wastewater, waste heat, and CO_2) to cover its resource requirements such as water for irrigation, nutrients, and energy in the forms of heating and electricity (in the case of advanced UA practices such as greenhouses) [73,83]. The potential for synergies between biowaste management and UA has long been mentioned (e.g., [81,84–86]) but few studies have actually assessed aspects of this potential. The study in [80] addressed the potential for nutrient circularity among opportunities and challenges for UA's future development. The authors of [62] conducted a technoeconomic assessment of a pilot AD plant located in a greenhouse in a park in London, UK. The authors reported challenges to balance supply and demand for digestate: in terms of identifying suitable outlets, but also in promoting digestate to consumers; digestate management at the small scale remains highly unregulated, and there is limited scientific evidence on safety to use in UA (in terms of digestate quality and potential toxic effects). Using the same pilot project as [62], the authors of [87] studied the feasibility of digestate use in cities. They also applied actor network theory (ANT) to assess stakeholder views on digestate management. They identified technical feasibility of onsite treatment and its economic viability as main challenges for implementation. The study in [54] assessed digestate use in PUA through short-distance AD systems, and found significant potential for digestate valorization. Case study findings from Lyon and Glasgow supported that biowaste recovery could reduce UA's carbon footprint [73] (as described in Section 4.1). However, even in upscaled UA scenarios, it is unlikely that UA alone can valorize recovery products fully. To achieve integrated resource management, it is important to explore UA further, as well as other urban outlets for biowaste valorization [63].

In summary, the scientific literature supported that upscaling UA can contribute to sustainable urban metabolism and other potential benefits significantly. Upscaling also requires sustainable management of UA's increasing resource requirements, which can be potentially met using urban waste streams. However, the review findings highlighted that few studies have quantified UA's resource demand and the potential for waste valorization to supply them. Current findings showed that it can be challenging to match supply and demand of resources locally. Future research must explore UA along with other urban outlets that can enable sustainable local valorization loops. Nexus approaches can also assist in identifying interlinkages between UA and AD in the urban context.

5. Opportunities and Challenges of Decentralized AD Approaches

The study of definitions, key planning aspects (Section 3), and emerging research themes (Section 4) led to the identification of key opportunities and challenges that can guide future development of decentralized AD, in terms of scientific research and decision making. Table S10 (see Supplementary Material) presents these opportunities and challenges, and also shows the key papers used to identify them.

In summary, all papers addressed the potential of decentralized approaches to develop local circularity, either implicitly or explicitly. To achieve this potential, it is essential to identify urban outlets to support the development of local valorization loops. Local resource supply needs to match the demand and the sustainability impact of local valorization loops must be assessed. UA and PUA have received attention as potential urban outlets: they need to be further explored in combination with other potential urban outlets. Preliminary findings showed that under certain scenarios, decentralized or combined (combinations of centralized and decentralized) configurations have better environmental performance than centralized options. However, such results are highly context-specific. A treatment system that integrates decentralized AD characteristics and is successful for one city may not work for another, and the results are largely dependent on local characteristics. Moreover, there are several remaining challenges related to digestate post-treatment and valorization. Offsite digestate management may increase the system's environmental impact, largely due to transport-related GHG emissions.

The context-specific results highlighted the need to ground AD planning in integrated approaches based on local characteristics. There is need for further case study research in different urban contexts. Even then, results must be extrapolated with caution. Several current themes can support further research on decentralized AD. Notably, DSTs that apply MCDA approaches and consider characteristics of different system configurations can contribute towards integrated AD planning. The inclusion and development of spatial methods can enhance planning accuracy. Nevertheless, context-specific assessments require local data that are often undocumented or unavailable. Further development of indicators to measure circularity, sustainability impact, and associated nexus interlinkages is also needed. Such indicators can be used in DSTs and contribute to integrated AD planning. AD embeddedness in the urban environment has many aspects that remain unexplored, such as product end uses, relevant stakeholders, market structure, and policy measures in different contexts.

6. Conclusions

Practitioners, policy makers, and the scientific community have shown increasing interest in the potential contribution of decentralized approaches in the context of implementing urban biowaste recovery systems. Through a scoping review, this paper provided a comprehensive overview of current scientific knowledge on decentralized AD approaches for urban biowaste recovery systems. The findings showed that there is limited scientific evidence on the impact of decentralized configuration approaches on resource circularity and sustainability in different urban contexts. However, five emerging research themes were identified: (a) spatial analysis; (b) LCA of environmental performance; (c) DSTs and frameworks; (d) nexus approaches; and (e) UA as an entry point for embeddedness in the urban environment. Opportunities and challenges for planning of decentralized AD exist, which mainly concern: (a) digestate management; (b) the potential for local circularity with product valorization in outlets such as UA; and (c) the development and application of DSTs to support integrated planning. Through the opportunities, challenges, and emerging themes addressed, this study can guide future research and decision making towards integrated planning of AD and biowaste recovery systems in cities. The findings highlighted the comprehensive analysis of configuration approaches as an essential component towards integrated planning. Local conditions and context should also be considered in the development of integrated planning to harness the full potential of biowaste recovery systems.

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Abbreviations

ABM	Agent-based model
AD	Anaerobic digestion
ANT	Actor network theory
CE	Circular economy
CHP	Combined heat and power
DST	Decision-support tools
EMFA	Extended material flow analysis
GHG	Greenhouse gas
GIS	Geographic information systems
GWP	Global warming potential
IEA	International Energy Agency
LCA	Life cycle assessment
MCDA	Multicriteria decision analysis
MFA	Material flow analysis
MSW	Municipal solid waste
Mtoe	Million tons of oil equivalent
N, P, K	Nitrogen, phosphorus, potassium
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
OFMSW	Organic fraction of municipal solid waste
PUA	Periurban agriculture
STARR	Systems Thinking Approach to Resource Recovery (framework)
WEF	Water–energy–food (nexus)
WoS	Web of Science
WtE	Waste-to-energy
UA	Urban agriculture

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