sustainability

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Multi-Criteria Decision Analysis to Evaluate Sustainability and Circularity in Agricultural Waste Management

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Abstract: Agriculture is a major contributor to global anthropogenic emissions, such as waste production and greenhouse gases. In order to reduce these negative impacts, a circular economy should be applied to agriculture waste management. Processes for evaluating treatment and valorization options are fundamental to the implementation of long-term, economically viable, ecologically sound, and socially acceptable policies and practices. In this field, multi-criteria decision analysis methods (MCDAs) can offer a holistic perspective on the decision-making processes. This study deeply explores this area of research by conducting an extensive and critical review of the studies that have used MCDA approaches to support agricultural waste management. The aim is to better understand how MCDA methods have been applied (in an integrated manner or as complementary approaches) and how stakeholders have been involved. The research conducted underlines how MCDAs are now widely used to support decision-making in this area, as well as being increasingly applied in multi-methodologies. This study is part of an ongoing Next-Generation-EU-integrated, large-scale, multi-disciplinary research program, The National Research Centre for Agricultural Technologies.

Keywords: MCDA; waste management; circularity

Citation: Lombardi, P.; Todella, E. Multi-Criteria Decision Analysis to Evaluate Sustainability and Circularity in Agricultural Waste Management. *Sustainability* **2023**, *15*, 14878. https://doi.org/10.3390/su152014878

Academic Editor: Grigorios L. Kyriakopoulos

Received: 4 September 2023
Revised: 28 September 2023
Accepted: 11 October 2023
Published: 14 October 2023

1. Introduction

In the context of the European Green Deal [1] and the United Nations 2030 Agenda [2] implementation, the agricultural sector plays a crucial role in preserving natural capital and achieving climate neutrality by 2050. In particular, the Farm to Fork strategy, as an operational tool to implement the European Green Deal, underlines the need to tackle climate change, protect the environment, and preserve biodiversity. Also, looking at European farmers and all operators in the food value chain as key to managing the transition, the strategy aims to strengthen their efforts in setting up the full circularity of food and agricultural systems.

Operating in the agricultural sector without over-exploiting natural resources is among the current global challenges, and solutions should be sustainable in the long term.

Agriculture emerges as a major contributor to global anthropogenic emissions, such as waste production and greenhouse gases [3,4], requiring a transition from a linear to a circular approach as a prerequisite for efficient reuse through the recycling of agricultural waste [4–6]. In this context, it is necessary to alleviate the environmental and climatic pressure on agricultural production, in particular by investigating the possibility of valorizing the considerable amount of waste that is produced [7–9] as a concrete contribution to the European climate change targets. It is possible to reduce these negative impacts by considering and evaluating the potential for the valorization of these raw materials, e.g., through energy production, nutrient extraction, the production of biomaterials, and other processes [9,10]. The need to move from an approach aimed at the maximum productivity of the land, crops, and means of production to limit environmental damage and the ecological footprint of agriculture [11] makes it necessary to measure the different types of impacts—not only environmental, but also economic, social, and cultural—that different agricultural systems have in order to modify them to minimize damage to the environment [12,13].

Accordingly, interest has progressively grown in assessing the sustainability of agricultural production systems with respect to the recovery and treatment of resources to maintain and improve their sustainability [14,15]. Processes for evaluating treatment and valorization options are fundamental to the implementation of long-term, economically viable, ecologically sound, and socially acceptable policies and practices [14], informing and supporting related decision-making processes. Measuring the sustainability of agricultural systems involves observing multiple, often interconnected, and potentially conflicting aspects, so methods are needed to integrate and keep in balance the different dimensions of sustainability [14,16,17]. The many facets and characteristics of farming systems also imply difficulty in collecting precise and quantitative data, which are not always available and can be expensive to obtain [11,17]. Indeed, multi-dimensional assessments, based on the identification of environmental, economic, and social impacts, contribute to supporting informed decisions and defining efficient policies [1], in line with the objectives of the Green Deal. Accordingly, the rationale of this study is related to which approaches and methodologies can properly deal with these issues, considering such multi-dimensionality able to both characterize and represent the complexity of agricultural systems.

Complex contexts such as agriculture have, therefore, progressively become more and more the subject and field of experimentation of multi-criteria decision analysis methods (MCDAs) [18–20], allowing a holistic perspective on decision-making processes [11,21] and the determination and consideration at the same time as several evaluation criteria relating to multiple—and potentially conflicting—objectives, interests, and actors [18–20].

This study aims to explore the abovementioned area of research by conducting a critical review of the studies that have included MCDA approaches in supporting agricultural waste management. More specifically, this study aims to highlight (i) which MCDAs have been implemented in the process and whether they have been integrated or complemented in multi-methodologies, (ii) which technologies have been applied, and (iii) whether and how stakeholders have been involved.

This study is part of an ongoing, integrated, large-scale, multi-disciplinary research program in the context of the Next Generation EU recovery project (i.e., the National Recovery and Resilience Plan [22]), named AGRITECH—The National Research Centre for Agricultural Technologies [23,24]). This project has been established among 47 partners—both public subjects, such as universities and research institutes, and private actors, such as research organizations and companies [23]. The declared aim is "to adequately address in a truly multidisciplinary context the multifaceted problems associated with sustainable agriculture", integrating research on technologies to advance in the sustainable, ecological, and digital transition and assessment methods that are able to direct research to increase the competitiveness of agri-food supply chains [24]. Such a program aims to implement cutting-edge technologies and to foster the digitalization and de-carbonization of the green transition of agriculture, working on nine different thematic areas, namely spokes. In particular, this study is related to Spoke 8, on "New models of circular economy in agriculture through waste valorization and recycling", focusing on: (i) obtaining from organic wastes high-value products with biological properties and technological potential; (ii) promoting sustainable agro-energy production via waste valorization through biological and thermochemical approaches; and (iii) producing biofertilizers to support soil fertility and mitigate climate change; the specific aim is to advance knowledge with respect to the multi-dimensional evaluation and assessment of new circular technologies in agriculture.

Indeed, given the high expectations for a circular future, the conscious adoption of more sustainable practices in agricultural waste management is related to the crucial responsibility that this sector can have in producing negative externalities [21] related to the process itself. In this sense, MCDA methodologies allow the attribution of different weights to different aspects and dimensions of sustainability, enabling the taking into account of different stakeholders' perspectives and, consequently, informing and instructing the decision-making process [18–20] for improved agricultural waste management [7–9]. Such methodologies allow the consideration of multi-dimensional requirements [21] in order to assess technologies and provide solutions applicable to real decision-making contexts.

In doing so, this research advances the knowledge in the field by enlarging the sustainability and/or circularity assessment through consolidated methods—such as Life Cycle Thinking (LCT) tools—with the possibility of combining quantitative and qualitative evaluations on different environmental, social, and economic data and criteria.

After this introduction, the paper is organized into five parts. Section 2 recalls the topic of agricultural waste management sustainability and the circular economy. Then, an overview of MCDA approaches is provided, and the research methodology of the literature review is discussed. In Section 3, the results of the critical review are provided, and a discussion on the fields of application of MCDAs in agricultural waste management is conducted in Section 4. Finally, in Section 5, the limits and future developments of MCDA methods are analyzed, and conclusions are drawn.

2. Methods

2.1. Sustainable and Circular Agricultural Waste Management: A Conceptual Framework

The choice to valorize agricultural waste, recognizing its potential, can be facilitated using circular economy methods [25,26], recycling it, finding new uses, and reducing its production [9]. A circular approach aims to consider waste as a resource [27], thus balancing economic expansion with the pursuit of a minimal environmental impact [27,28]. The concept has received increasing attention in political and research agendas [29] with particular reference to primary production—e.g., agriculture, fisheries, and forestry—and the valorization of raw materials as a substantial contribution to the achievement of EU objectives [1]. Focusing on the context of circular agriculture [4,30], waste consists mainly of organic matter and by-products [31] that can be reintroduced into production chains through higher-value production [27,29,32]—e.g., not only energy, water, and nutrients but also innovative materials—thus balancing production and environmental conservation [4].

For the purposes of agricultural waste management and valorization, a number of alternative technologies are currently available for the exploitation of organic waste [7,13,17,29,33]—including composting, anaerobic digestion, pyrolysis, etc.—which can then be converted into bioenergy or other bio-based products. Given the variety of possible organic waste, as well as conversion technologies, it is important to have a complex perspective on how these can contribute to sustainable development, in particular by being able to model and evaluate their effectiveness in managing resources [4,34]. The performance of such treatment and conversion systems must, therefore, be evaluated in terms of potential environmental performance, but not only in this context [7], examining each technological solution in detail from the point of view of inputs, treatment methods, and outputs to support decisions on environmental consequences and further considerations related to the broader issue of sustainability [9,29]. In order to determine the performance of different alternatives, it is, therefore, necessary to make comparisons between technologies according to several possible criteria relevant to evaluations [35].

2.2. Multi-Criteria Approaches to the Sustainability Assessment of Agricultural Systems

Precisely because of this complexity in the evaluation and selection of treatment and conversion technologies, agricultural waste management can be considered a multidimensional problem characterized by several potentially conflicting criteria, multiple possible scales and perspectives of observation, and several aspects of uncertainty [14,17]. Methodologies related to the Life Cycle Thinking (LCT) family, of which Life Cycle Assessment (LCA) [36] is part, are widely and commonly used in this field. LCA, for the assessment of environmental performance and impacts at all stages of the life cycle of the system under observation, is a systematic and structured process established in agricultural waste management [7,14,35]. Recently, however, research has emerged that is oriented towards the selection of evaluation criteria that are not only representative from an environmental point of view but also capable of ensuring that additional aspects, such as economic viability and social development related to agricultural sustainability, are taken into account and measured [14]. This research focuses on the application of MCDAs to agricultural waste management, allowing a holistic perspective on decision-making processes [11,21] and the determination and consideration at the same time as several and various evaluation criteria.

MCDAs [18–20] allow several criteria to be considered simultaneously with respect to a complex decision problem, usually by the decision-makers or stakeholders involved in the process itself, to help decision-makers select the appropriate solution to achieve specific objectives. The results of such approaches provide comparative assessments of alternatives through operational advice or recommendations for future action. The choice with respect to the method to be used is strictly dependent on the specific problem to be addressed, the aim to be reached, and users' needs. The choice to use one method over another is not arbitrary but depends on the specific problem and users' needs [19]. In particular, MCDAs have progressively assumed a central role in supporting sustainable decisions [20,37,38], gaining wide acceptance with respect to their combination with other instruments, such as the aforementioned LCA, ecological footprints, and environmental indicators [29]. Specifically, the Analytic Hierarchy Process (AHP) [39] emerged in various studies related to waste management systems, mainly depending on the LCA method's environmental scores [11,40]. MCDAs enable all pillars of sustainability to be covered [15,29,35] and, at the same time, to consider the relationships between different aspects, whereby maximizing one benefit may, for example, lead to the reduction of another [9]. Moreover, by integrating participants' preferences with clear measures [41], they allow an understanding of the inputs that lead to a particular outcome to be incorporated into the process.

Since MCDA approaches are innumerable, the analysis developed in this study will support the identification of the best method to support decision-making in agricultural waste management.

2.3. The Adopted Literature Review Methodology

The literature review methodology adopted in this study can be briefly summarized in the following steps:

- A first phase of a "literature search" allowed the identification of relevant articles in the chosen field of research through database searches, according to certain criteria linked to the type of source;
- A second phase of "selection and screening" made it possible to circumscribe the identified literature to a specific reference period;
- A third phase of "abstract selection" led to the evaluation of papers of potential relevance for research by reading the abstracts;
- The last phase was the actual "literature review" phase, in which the reading of the selected papers aimed to answer the research question on the application of MCDAs to agricultural waste management to address the abovementioned aim of the research.

In the "literature search" step, the Scopus database was identified to scan the scientific literature published up to August 2023. The search was conducted by means of specific search terms in the "article title", "abstract", and "keywords" fields and through the following formulation: "agricultural waste management" and "MCA" or "multicriteria analysis" or "multi-criteria analysis" or "MCDA" or "multicriteria decision analysis" or "multi-criteria decision analysis" or "AHP" or "analytic hierarchy process" or "ANP" or "analytic network process". The formulation had been proposed to include the AHP method [39], highlighted in several studies as the most combined with LCA specifically, and the ANP method [42], as a more general form, used in the multi-criteria decision contexts of the previous one. The search was undertaken with both the reported wording and the specific, separate wording for each term to triangulate the results with a total of 88 references. Also, this selection of papers was filtered by considering the following criteria: (i) English-language papers and (ii) article and review papers as types of products.

In the "selection and screening" phase, the review was organized according to a time frame of 2014–today. The result of this phase was the selection and identification of 74 references, which were then organized into an Excel file.

In the "abstract selection" phase, the abstracts of all references were read in order to select and identify the studies pertaining to the research question concerning the use of MCDAs for agricultural waste management. First, preliminary screening was pursued, excluding titles that did not concern MCDAs (e.g., sometimes with similar acronyms). Then, the basic selection criterion to be met concerned research relevance so that an MCDA was at least mentioned and applied. The result of this phase was the identification and selection of 58 references to be further investigated by means of a full reading and literature review.

The last phase, the "literature review", consisted of a selection of the papers in which an MCDA had been applied to select alternative technologies in agricultural waste management or in which an MCDA application provided relevant key performance indicators (KPIs) for the research question. Accordingly, some papers were considered off-topic, e.g., when related to an MCDA application to select the sites for such conversion plants or to identify and prioritize risks related to the supply chain. Also, the first in-depth research was restricted to more recent articles—the time frame identified was 2020–today—in order to focus on the most recent debate in the field. Some earlier and previously selected papers were nevertheless examined in depth if they were considered definitely relevant to the evaluation of alternative technologies. The result of this phase was the selection of 14 references with the aim of gathering information on existing approaches to supporting decision-making processes related to agricultural waste management.

The results of the last two phases—"abstract selection" and "literature reviews"—will be expanded upon in the next section.

3. Results

3.1. Applied MCDAs and Multi-Methodologies

The 58 papers analyzed in the "abstract selection" phase were related to the application of different 15 methods, specifically the Analytic Hierarchy Process (AHP) [39], the Analytic Network Process (ANP) [42], the Combined Compromise Solution (COCOSO) [43], the Complex Proportional Assessment (COPRAS) [44], the Elimination et Choix Traduisant la Realité (ELECTRE) [45], Gray Relational Analysis (GRA) [46], Multi-Attribute Value Theory (MAVT) [47], the Multi-Criteria Generic Evaluation Sustainable Approach (MCGESA) [48], the Modified Fuzzy Social Choice (MFSC) [49], the Multicriteria Integer Linear Programming Problem (MILP) [50], Potentially All Pairwise Rankings of all Possible Alternatives (PAPRIKA) [51], the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [52], Stepwise Weight Assessment Ratio Analysis (SWARA) [53], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [54], and the Visekriterijumska Optimizacija i Kompromisno Resenje (VIKOR) [55]. Also, the weighted sum method and other unspecified MCDAs had been applied.

Table 1 illustrates the papers in which the methods had been applied and whether they were combined in multi-methodologies. The most applied was the AHP method, with 29 applications (e.g., ten as single uses, two as a fuzzy AHP, five in combination with GIS only, and five in combination with LCA). Also, ELECTRE, TOPSIS, and the weighted sum method were used three times each. It can be also noted that, in the majority of cases (31 papers), the MCDA had been applied in a multi-methodological framework.

Table 1. MCDAs applied in the selected literature.

MCDA Used	Multi-Methodology	References
AHP	-	[4,56–64]
	Business Model Canvas	[9]
	GIS	[65–69]
	GIS + Simple Multi-Attribute Rating Technique (SMART)	[41]
	GIS + priority scale	[70]
	Entropy method	[71]
	F-TOPSIS	[72]
	Index of geoaccumulation (Igeo)	[73]
	LCA	[7,11,14,40,74]
	Uncertainty Measurement Evaluation (UME)	[75]
Fuzzy AHP	-	[76]
	Remote sensing + GIS	[77]
ANP	-	[78]
	PESTEL analysis + Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA)	[79]
Fuzzy ANP	-	[80]
COCOSO	Integrated Determination of Objective Criteria Weights (IDOCRIW)	[81]
COPRAS	Intuitionistic fuzzy sets (IFSs) + SWARA	[17]
ELECTRE	-	[82,83]
	CBA	[29]
GRA	-	[84]
MAVT	-	[85,86]
MCGESA	-	[48]
MFSC	-	[49]
MILP	-	[87]
	GIS	[88]
PAPRIKA	-	[15]
PROMETHEE	GAIA analysis	[89]
SWARA	-	[43]
TOPSIS	-	[90]
	LCA	[91]
	System Dynamics Model (SDM) + cost-benefit-risk tradeoff analysis	[92]
VIKOR	-	[93]
Weighted sum method	-	[13,31,94]
Unspecified MCDA	-	[95]
	Artificial Neural Network (ANN) + GIS	[96]
	Pearson correlation coefficients + Montecarlo analysis	[35]
	Strategic Environmental Assessment (SEA) + GIS	[27]

3.2. *Assessed Technologies of Agricultural Waste Management*

Among the 14 papers identified in the "literature review" phase, seven were applications in which an MCDA was used to select and prioritize different alternative technologies, five were applications in which an MCDA was used elsewhere in the process, and two articles were reviews, which were used in this paper to frame the discussion of the results in the next section.

Table 2 reports a synthesis of the 12 analyzed studies in terms of resource inputs, technologies experimented with, and valorization outputs.

Table 2. The technologies assessed in the reviewed literature.

ID.	References	Method(s)	Focus of the Study			Geographical Context	Scale of the Study
			Input	Technology	Output		
1	[15]	PAPRIKA	Water	WWTP	Water	Island of Phuket	Regional
2	[9]	AHP + business model canvas	Agricultural waste	Thermal treatment	Biochar + energy + biofertilizer	Island of Sri Lanka	Regional
3	[17]	COPRAS + IFSs + SWARA	Agricultural waste	Unspecified	Biofuel + biogas	India	Farm, plant
4	[13]	Weighted sum method	Manure + water	Anaerobic digestion + composting + incineration + nutrient extraction + pyrolysis + source separation	Biochar + biofertilizer + biofuel + biogas + digestate + fertilizer	Three watersheds in the Baltic Sea	Local
5	[14]	AHP + LCA	Agricultural waste	Composting + pyrolysis	Compost + biochar	Island of Aegina	Regional
6	[7]	AHP + LCA	Manure	Anaerobic lagoon + bio/thermochemical + anaerobic digestion	Biofertilizer + biogas + compost + digestate + fertilizer	Island of Cyprus	Farm, plant
7	[62]	AHP	Water	Composting + storage + thermal treatment	Compost + energy + storage	Northern Croatia	Regional
8	[27]	Unspecified MCDA + SEA + GIS	Agricultural waste	Thermal treatment + composting + storage	Energy + biomaterial + compost + fertilizer	Vineyard, Serbia	Farm, plant
9	[35]	Unspecified MCDA + Pearson correlation coefficients + Montecarlo analysis	Agricultural waste + manure + water	Composting + WWTP + thermal treatment	Biofertilizer + water + energy	Eight wineries, Italy	Farm, plant
10	[31]	Weighted sum method	Agricultural product	Bio/thermochemical	Biomaterial	United Kingdom	Regional
11	[29]	ELECTRE + CBA	Agricultural waste + manure	Anaerobic digestion	Biofuel + biofertilizer + digestate	Serres Region, Greece	Regional
12	[4]	AHP	Agricultural product	Anaerobic digestion	Biogas + biofertilizer	China	Regional

Sustainable resource management implies, indeed, not only reflecting on reducing inputs, on the one hand, but also improving system outputs, as well as evaluating and assessing the impacts of different valorization technologies in the considered system [4,9]. Accordingly, starting from the literature, Figure 1 provides an inventory that includes all the inputs mentioned in the studies (e.g., agricultural waste, manure, water, etc.), the involved technologies (e.g., anaerobic digestion, thermal treatment, composting, etc.), and the obtained outputs (e.g., energy, digestate, fertilizer, etc.). It should be pointed out that the articles in Table 1 and Figure 1 are numbered by identification (ID) from 1 to 12 in order to trace the results shown in the graphs back to their specific articles. Indeed, each article often did not refer to only one input, to only one technology, or to only one output; therefore, the article ID numbers in Figure 1 may be repeated several times in relation. Furthermore, one might see the repetition of a citation of the same article in reference to different parameters when more than one of them was analyzed in the study.

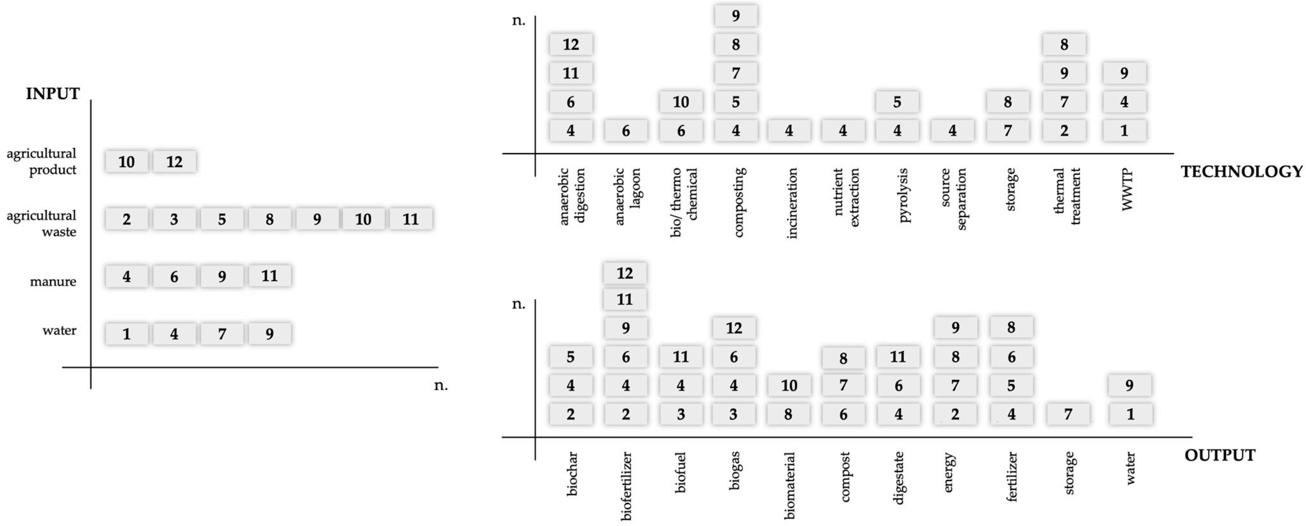

Figure 1. A synthesis of the input, technologies, and outputs that emerged from the literature review.

Most of the studies' inputs were related to different types of agricultural waste [9,14,17,27,29,31,35]. The study by Illankoon et al. [9] investigated the possibilities of valorizing the large quantities of waste and by-products generated by the Sri Lankan rice industry. In particular, the valorization of rice straw and rice husk is treated through thermal processes to produce biochar, electricity and heat, and composting. Mishra et al. [17] reported the selection of an optimal bioenergy production alternative for a plant in India, converting agricultural residues such as oil crops or wet biomass. Six alternatives were evaluated, even if unspecified in terms of technologies, in terms of the production of bioenergy, such as ethanol, biodiesel, and biogas. The research conducted by Bartzas and Komnitsas [14] studied the most sustainable agricultural management practice at the regional level with respect to pistachio production on the island of Aegina, exploring the alternative valorization scenarios of composting and slow pyrolysis for the production of compost and biochar, respectively. Also, the study by Josimović et al. [27] concerned the evaluation of the impacts of different scenarios of agricultural waste reuse in a vineyard in Oplenac, Serbia. Specifically, pruning waste is reutilized via thermal treatment and composting in the production of energy, briquettes, and compost. Furthermore, the storage of waste from the grapes allows the reuse of some components left on the soil as fertilizers. The research proposed by Vlachokostas et al. [29] related not only to agricultural waste (e.g., cheese whey, by-products such as rotten potato pulp, or mill waste) but also to manure valorization in the region of Serres in Greece. Through anaerobic digestion, bioenergy is produced, and other bioproducts, such as biofuel and digestate, are obtained. Another study related to both agricultural waste (e.g., pruning residues) and manure valorization was conducted by D'Ammaro et al. [35]; it also considered the input of water treatment. Indeed, the study investigated the wine sector through eight wineries in Italy, experimenting with technologies such as composting, wastewater treatment, and thermal treatment to obtain organic fertilizers and possible water reuse, electricity, and heat. The reuse of water was also experimented with in Kanchanapiya and Tantisattayakul [15], aiming to assess different options for wastewater recovery technologies in various types of reuse activities on Phuket Island. Both surface water, withdrawn from reservoirs and ponds, and groundwater via wells and seawater are treated through wastewater treatment plants (WWTP) through the alternatives of slow sand filtration and disinfection or slow sand filtration and disinfection, microfiltration, and reverse osmosis. This process allows water to be reused in different sectors, such as agriculture. A study by Dušak et al. [62] also reused wastewater sludge in northern Croatia, at the regional level, through the storage of treated sludge in landfills, composting with an organic fraction of municipal solid waste and livestock waste, usage in agriculture and forestry, and thermal treatment. Such practices allow for storage, the production of compost, and energy recovery for agricultural uses. The reuse of wastewater and manure was also investigated by Koskiaho et al. [13] for the evaluation of different ecotechnologies in three catchment areas in the Baltic Sea. In the first case, manure is treated via composting, anaerobic digestion, and pyrolysis to produce biofertilizer, biogas, digestate, and biochar. In the second case, wastewater is treated via incineration, nutrient extraction, and source separation to produce electricity, heat, biofuel, organic fertilizer, and manure. In the third case, wastewater is treated via nutrient extraction and source separation to produce composted sludge as a fertilizer and biogas. The potential reuse of manure was also reported by Lijó et al. [7], in whose study livestock waste was treated through anaerobic lagoons, biogas plants, and anaerobic digestion to produce organic fertilizer, biogas, digestate, and compost. Finally, two of the papers proposed the reuse of agricultural products. In the work of Bolaji et al. [31], with the aim of identifying the most promising raw materials for the production of sustainable biopolymers from agri-food waste, the residue production from six key crops (namely barley, wheat, maize, soybeans, rice, and sugarcane) in the United Kingdom was investigated. Bio- and thermochemical treatments were proposed, such as chemical pulping, hydrothermal, acidic, and wet oxidation, and the ionic liquid method, to produce natural polymers (e.g., cellulose). As a last example, in the work of Yue et al. [4], grain and straw were treated through anaerobic digestion to produce biogas and biofertilizers in China.

Starting from this overview, it is important to point out that MCDAs allow not only qualitative comparisons and evaluations but also quantitative ones. Approaches to enhancing the value of agricultural waste must be evaluated in terms of their efficiency, the quantity of waste, and so on as the elements on the basis of which a decision on the best waste management technologies can be made. In the examples analyzed, it was common to find the integration of qualitative and quantitative aspects that, precisely due to the peculiarities of MCDAs, were brought back into the same performance evaluation system [18–20]. Accordingly, quantitative environmental aspects such as the electricity consumption of an option [15] or its carbon footprint [15,35,92], or economic aspects, such as total costs as costs for investments, maintenance, and operation [13,31], can be evaluated in the same framework as qualitatively assessed social aspects, such as acceptance [9,13] or risk perception [7].

3.3. Stakeholders' Involvement in MCDA Applications

This part illustrates how stakeholders' involvement was included in the papers which were analyzed. Table 3 synthetizes the principal results of this review according to two aspects: the step of the process and the typology of the involvement. The majority of the studies involved stakeholders in the assessment process before applying MCDAs, using a series of interviews and/or surveys. The aim of these interviews and/or surveys was mainly the identification of criteria and their weighting. Alternatively, an MCDA was used for the evaluation of alternative technologies.

Table 3. An overview of the MCDAs applied and stakeholders' involvement.

ID.	References	Method(s)	MCDA Objective	Stakeholders' Involvement	
				Step of the Process	Type of Involvement
1	[15]	PAPRIKA	Identification of indicators and evaluation of water reuse options	Not involved	Not involved
2	[9]	AHP + Business Model Canvas	Selection among alternative technologies and identification of the best agricultural waste valorization option	Before the MCDA for criteria definition; the MCDA itself for weighting and evaluation	Interviews/surveys
3	[17]	COPRAS + IFSs + SWARA	Selection of the optimal bioenergy production technology alternative	Before the MCDA for criteria definition; the MCDA itself for weighting and evaluation	Interviews/surveys
4	[13]	Weighted sum method	Evaluation of alternative ecotechnologies	The MCDA itself for weighting and evaluation	Participatory workshop
5	[14]	AHP + LCA	Selection of the most sustainable agricultural management practice	Before the MCDA for criteria definition; the MCDA itself for weighting and evaluation	Interviews/surveys
6	[7]	AHP + LCA	Comparison of alternative management options for livestock	The MCDA itself for weighting and evaluation	Surveys
7	[62]	AHP	Evaluation of alternatives for wastewater sludge management	Not specified	Not specified
8	[27]	Unspecified MCDA + SEA + GIS	Determination of a ranking of the impacts of different scenarios	The MCDA itself for weighting and evaluation	Interviews/surveys
9	[35]	Unspecified MCDA + Pearson correlation coefficients + Montecarlo analysis	Investigation of correlations among indicators	Not specified	Not specified
10	[31]	Weighted sum method	Identification of the best feedstocks to produce sustainable biopolymers from agri-food waste	Before the MCDA for criteria definition; the MCDA itself for weighting and evaluation	Interviews/surveys
11	[29]	ELECTRE + CBA	Selection of an optimal site for units of alternative biowaste treatment	The MCDA itself for weighting and evaluation	Participatory workshop
12	[4]	AHP	Allocation of resources under different scenarios towards sustainable, circular agriculture	Not specified	Not specified

For instance, an MCDA was used by Lijó et al. [7], Illankoon et al. [9], Koskiaho et al. [13], Bartzas and Komnitsas [14], Kanchanapiya and Tantisattayakul [15], Mishra et al. [17], and Dušak et al. [62] to evaluate alternative scenarios, technologies, ecotechnologies, and options in general. In terms of the experimental setup of multi-criteria evaluation, the selected methods supported the evaluation in different ways. In the work of Lijó et al. [7], in order to compare the performance of alternative livestock waste management options, the selected technologies were evaluated with a combination of LCA and AHP, which allowed for the integration of social and economic indicators as qualitative and quantitative measures. From a methodological point of view, some environmental indicators defined with LCA were integrated with social and economic indicators through AHP, analyzing the sustainability performance of the whole system. In the research of Illankoon et al. [9], AHP was used to sort between alternative technologies for the valorization of agricultural waste, such as rice straw and rice husks. In this case, after an interview process with experts working in the fields of agricultural waste management, environmental consulting, energy production, local government agencies, the rice industry, and research organizations, ten different criteria (i.e., environmental, social, technological, political, cost, standards and regulations, public health, land use, economic, and cultural) were identified. Alternative technologies were then evaluated according to the AHP approach, involving experts in the decision-making process through both interviews and surveys and both in groups and through individual involvement. Koskiaho et al. [13] involved stakeholders in evaluating alternative ecotechnologies in three river basins. The multi-criteria sustainability analysis was applied to participatory workshops in collaboration with local stakeholders (e.g., farmers, water management and protection authorities, wastewater treatment professionals, etc.). First, sustainability criteria were searched for in the scientific literature on wastewater treatment applications in agriculture. From this list, the criteria deemed appropriate for the scope of the case study sites were selected, and local stakeholders were involved in the weighting process to integrate the performance of each alternative against each criterion. Then, stakeholders assigned weights to the different criteria, first individually and then by dividing into groups, collecting individual weights and calculating group averages. The group averages were then discussed within the entire workshop and, if necessary, modified via consensus. Finally, based on the average of the weights, the weighted sum of the three alternatives was calculated with an overall sustainability score to evaluate them. The study by Bartzas and Komnitsas [14] combined LCA with AHP in a holistic, multi-criteria methodology that was also informed by an environmental risk assessment (ERA) and on-farm surveys. AHP was applied after the identification of 13 sub-criteria based on LCA, ERA, and surveys related to the three pillars of sustainability as the main criteria. After that, AHP itself was applied by combining the judgments received from a group of 12 experts from academia and agriculture and other stakeholders (e.g., municipalities, organizations, and associations). In Kanchanapiya and Tantisattayakul [15], the PAPRIKA method was used to select and identify the best wastewater treatment option. There was no direct involvement by experts here, but the 1000Minds software was used to prioritize each water reuse option on the basis of a four-dimensional scorecard comprising economic, social, health, and environmental aspects. The weighting values of each criterion were, in this case, determined directly by the software with a systematic algorithm to weight them according to the government's budget allocation in the different economic, social, health, and environmental sectors. In the case of Mishra et al. [17], a study with interviews and a literature review was conducted to identify the main evaluation criteria for selecting an optimal alternative bioenergy production technology. Based on the results of the survey, four main dimensions were identified, including environmental, social, economic, and technological dimensions, with 11 related criteria, on the basis of which a self-administered questionnaire was developed to be sent to experts in the field. Each expert, according to his or her expertise, expressed his or her opinion on bioenergy production technologies through questionnaires designed using intuitionistic fuzzy sets (IFS).

Other applications of MCDAs in agricultural waste management were related to the ranking of the impacts of different scenarios [27], the investigation of correlations among indicators [35], the identification of the best feedstocks to produce sustainable biopolymers from agri-food waste [31], the selection of an optimal site for units of alternative biowaste treatment [29], or the allocation of resources under different scenarios towards sustainable, circular agriculture [4]. Almost all papers used an MCDA method in the weighting and evaluation phase, as it is the main feature of these approaches. The most applied MCDA method was certainly AHP; in two cases, this was used in combination with LCA methodologies [7,14] as a source for identifying the environmental indicators to be applied using an MCDA framework.

Analyzing the stakeholders' involvement in terms of the "Step of the process" revealed that four papers involved stakeholders before MCDAs for criteria definition and during the MCDA application itself to weight the criteria and provide evaluations and prioritizations of alternative technologies [9,14,17] or alternative inputs for valorization [31]. In four other studies, stakeholders were involved directly in the MCDA application for weighting and evaluation purposes [7,13,27,29]. In most cases, MCDAs were accompanied by other participative methods, such as interviews or surveys. In two cases, experts were involved through participatory workshops [13,29]. Among these studies, Kanchanapiya and Tantisattayakul [15] did not involve stakeholders; instead, they declared that the use of software and algorithms would avoid subjectivity and biased feedback from participants. Finally, three of the above studies did not specify whether stakeholders and/or experts were actually involved in the applications [4,35,62].

4. Discussion

After presenting the results of the literature review, in this section, a discussion on the major findings is proposed that encompasses both the following: (1) the contribution by an MCDA to agricultural waste management in terms of not only specific methods' features and aims but also the potential for a multi-methodological combination to assess different dimensions of sustainability; and (2) the role and contribution of stakeholders' involvement to achieve greater sustainability and circularity.

More generally, the results illustrated in Section 3 show how, in the field of agricultural waste management, an integrated approach is gradually emerging due to the complexity and multi-disciplinarity of the phenomenon. In other words, MCDA methods allow the consideration of different dimensions of sustainability specifically linked to the circular economy paradigm, making the assessment of alternative solutions for complex systems more effective [40]. The research conducted underlines how MCDAs are now widely used to support decision-making in this area, as well as being increasingly applied in multi-methodologies (see Table 1). In this sense, the advantage of integrating different approaches can be found in the complementarity with respect to different objectives in the process (e.g., LCA can be used for the assessment of environmental and economic aspects but needs MCDA methods to integrate different dimensions, such as social or cultural dimensions). Furthermore, MCDA analysis offers a variety of strategies to evaluate alternative solutions in a practical and straightforward manner, following a systematic process of analyzing them and, thus, not only breaking down complex problems into smaller parts, on the one hand, but also allowing the aggregation of considered aspects—based on defined criteria and sub-criteria—to select the best alternative.

Also, MCDA methods, as the review revealed, are mostly used in combination with other techniques, as they cannot provide objective or definitive answers on their own, and other evaluation methods are also needed to provide reliable impact assessments [11]. AHP emerges as the most applied method, given the simplicity of application, through the support of the available software (Expert Choice) [38].

Among the many methods with which not only AHP—but also many others—is usually combined, there emerges a prevalence of multi-methodology applications with LCA and GIS, which allow the former to integrate and construct combined indicators for a broad and comprehensive analysis and the latter to add the spatial dimension as a decision-making component in an assessment. The conclusion that can be drawn is, therefore, that, in the assessment of the sustainability of agricultural systems, the most common practice is to integrate several methods in order to consider all relevant sustainability aspects better and more effectively. In this way, different criteria can be integrated in a holistic way when analyzing the sustainability performance of a system. Such an approach allows not only the combination and integration of those criteria but also the definition of trade-offs between conflicting sustainability goals and criteria in general terms with respect to the ones that can be identified between different dimensions of sustainability and in particular with respect to the multiple perspectives of different stakeholders involved in the decision-making process. Indeed, taking multiple criteria into account through MCDA techniques allows alternative scenarios to be classified through the aggregation of even conflicting indicators from a perspective that is not only multi-criteria but also multi-stakeholder.

An integrated sustainability and circularity assessment of agricultural systems is a process that usually involves experts and stakeholders in the development of the assessment of either criteria or strategies and technologies. Indeed, the further advantages of the use of MCDA methods precisely include the facilitation of collaboration with different stakeholders [11] through an explication and clarification of environmental, economic, and social issues that are often otherwise considered "incommensurable", as well as the consideration and possibility of aggregating preferences, taking into account multiple objectives and points of view. The studies analyzed mainly involved stakeholders in one or two phases of their evaluations, either in the criteria definition phase before or during the application of the MCDA methods or in the application of the MCDA analysis for the elicitation of preferences and, thus, for the definition of criteria weights, as well as for the final choices. Often, processes are instructed through the preliminary literature [9,17], just as it may also be the case that criteria are identified through scientific publications [13]. More often, the definition of relevant criteria takes place through interviews and/or surveys with experts [9,14,17,31]. Such experts are also involved in weighting processes to integrate the performance of each alternative against each criterion and proceed with an evaluation [7,9,13,14,17,31]. It, thus, emerges how the participation of stakeholders is crucial for providing relevant knowledge to research, as they are privileged witnesses and experts in relevant fields, and for sharing relevant information to actors that learn in this way to interface with the consequences of their decisions explicit in the applied methods. At the same time, when involved as participants in the process of evaluation, they enable the integration of multiple objectives and different interests in the decision-making process, effectively expanding the scope of the social dimension in the applications [11]. Indeed, most of the actors involved through the participatory approaches were experts because of their experience and capability in evaluating and comparing the impacts related to the systems in question.

5. Conclusions

The purpose of this article was to conduct a critical review of the studies that have included MCDA approaches in supporting agricultural waste management. The specific aim was to highlight (i) which MCDAs have been implemented in the process and whether they were integrated or complemented in multi-methodologies, (ii) which technologies have been applied, and (iii) whether and how stakeholders have been involved.

With respect to the first point, we can observe that 15 different MCDA methods were applied in the first 58 analyzed papers (in the "abstract selection" phase). The most used was the AHP method, with 29 applications. Also, ELECTRE, TOPSIS, and the weighted sum method were applied three times each. It can be also noted that, in the majority of cases (31 papers), an MCDA was applied in a multi-methodological framework.

Then, in the sample of the 14 analyzed papers presenting MCDA applications (in the "literature review" phase), most of the studies' inputs were related to different types of agricultural waste even if manure treatment and water reuse also emerged as key inputs for circular agriculture. Several technologies were applied, in particular anaerobic digestion, composting, and thermal treatment emerged as the most used. The outputs were mostly related to biofertilizers, biogas, energy, and fertilizers.

The majority of the studies involved stakeholders in the assessment process because often, before applying an MCDA, a series of interviews and/or surveys are conducted with selected stakeholders, which can serve both in the identification of criteria and possibly in the weighing of criteria. Furthermore, the MCDA is alternatively used for criteria weighing and criteria evaluation or for the evaluation of alternative technologies. The most applied MCDA method was AHP, in two cases combined with LCA. In most cases, MCDAs were accompanied by other participative methods, such as interviews or surveys, and only in two cases were experts involved through participatory workshops.

The use of MCDA methods, thus, emerges as progressively expanding in the area of sustainability and circularity assessment in agriculture. In particular, the use of AHP, in combination with LCA, appears to be the most widely used method in applications while satisfying the consideration of many different criteria and ease of use. Nevertheless, the literature analyzed did not always clarify in detail how to involve experts; nor did it provide extracts from the proposed interviews and surveys.

In this sense, a future development of the research will be to test AHP in a multi-methodology with LCA to assess the integrated sustainability of innovative technologies in the context of the AGRITECH project. According to this initial classification and review of the existing and currently applied methodologies, it will be necessary to define relevant sustainability indicators according to both the literature and the direct involvement of relevant actors. The ultimate goal is the evaluation and prioritization of agricultural waste management technologies according to a multidimensional approach that is repeatable and expendable in different application contexts.

Author Contributions: Conceptualization, P.L. and E.T.; investigation, P.L. and E.T.; methodology, P.L. and E.T.; validation, P.L. and E.T.; writing—original draft, P.L. and E.T.; writing—review and editing, P.L. and E.T. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out within the "National Research Centre for Agricultural Technologies—AGRITECH" and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—Avviso n. 3138 del 16/12/2021, Codice Programma CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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