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Review

Integrating Multi-Criteria Techniques in Life-Cycle Tools for the Circular Bioeconomy Transition of Agri-Food Waste Biomass: A Systematic Review

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Abstract: Agri-food waste biomass (AWB) is consolidating as a relevant bioresource for supplying material products and energy in a circular bioeconomy. However, its recovery and sustainable processing present trade-offs that must be understood. The integration of multi-criteria decision analysis (MCDA) into life-cycle assessment (LCA) tools has emerged as a novel way to address this challenge. This paper aims to conduct a systematic literature review to critically synthesize how MCDA has been integrated into LCA in an assessment framework and how helpful it is in AWB's circular bioeconomy transition. The literature shows that the most studied AWBs are rice husk, sugarcane bagasse, and household food waste. These are processed through the technologies of composting, anaerobic digestion, and pyrolysis for applications such as biofuels, bioenergy, and soil amendment. Environmental LCA (E-LCA) is the most widely used LCA tool, while both the analytical hierarchy process (AHP) and the technique for ordering preference by similarity to the ideal solution (TOPSIS) are the most applied techniques for MCDA. The current trend of integrating MCDA into LCA does not fully cover the LCA phases, favoring solely the impact assessment phase and indicating that the other phases are overlooked. The potential and involvement of the stakeholders are partially explored. Although there are holistic sustainability assessments, the social implications are rarely considered. The number of MCDA/LCA studies is expected to increase, assessments at the micro-, meso-, and macro-scales to become more articulated, and the impact of the results to become more aligned with government and company goals.

Keywords: circular economy; sustainable agriculture; multi-criteria decision making; TOPSIS; stakeholders; social LCA; life-cycle costing; bioenergy; biorefinery

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1. Introduction

The circular bioeconomy is an emerging field that is booming in the scholarly and political communities. The most widely accepted definition of circular bioeconomy stems from the intersection of bioeconomy and circular economy [1,2]. The circular bioeconomy focuses on the sustainable and efficient recovery of biomass and biowaste resources in integrated, multi-output production chains, optimizing their value over time and taking the three sustainability pillars into account [3]. The term "circular bioeconomy" appeared around 2015 and has been the focus of many scientific publications since 2016 [1]. The European Commission's 2018 updated bioeconomy strategy emphasized that the "*European Bioeconomy needs to have sustainability and circularity at its heart*" [4]. The circular bioeconomy is envisioned as one of the approaches that will make the greatest contribution to addressing sustainability challenges.

Properly providing biomass-based feedstock is a multipurpose objective of the circular bioeconomy [5]. Agri-food waste biomass (AWB), a type of biomass, is produced and used in large quantities around the world, with the amount increasing more than threefold in the last 50 years [6]. The AWB amounts are inputs for the development of biorefineries and biotechnologies that are part of the circular bioeconomy. Nevertheless, they are affecting the sustainability of the planet by emitting greenhouse gases and causing inefficient water use. AWB management is a widespread issue that poses a challenge for food safety, environmental pollution, and economic stability [7].

Several circular-bioeconomy-based strategies for recovering AWB and producing food in a less-polluting manner have been proposed. While findings with immediate applications of AWB have been abundantly studied, the sustainable implications of the technologies have been questioned [8,9]. Some circular bioeconomy strategies and research consider the circular bioeconomy to be inherently sustainable [10]. Yet, there is emerging evidence that highlights potential obstacles and trade-offs [11,12]. Therefore, a sustainability check should not be overlooked in this research context.

Analyzing the sustainability of AWB management framed in a circular bioeconomy is pivotal for the definition and implementation of economic activities and investments, technological development plans, and policies. This action requires a robust measurement and interpretation of indicators associated with decision-making processes that impact society [13]. To fulfill this purpose, methodological tools that integrate the social, economic, and environmental dimensions as pillars of sustainability are necessary [14].

Environmental life-cycle assessment (E-LCA) is a well-known and widely applied method in AWB [15]. E-LCA is a tool focused on the environmental impacts of a product, service, or process based on the life-cycle perspective [16]. This perspective represents the processes that converge from raw materials to waste management [17]. The E-LCA has been used not only in AWB but also in other economic sectors, translating environmental science into useful knowledge in business and regulatory areas [18,19]. However, the E-LCA by itself does not cover sustainability as a whole [20]. Over time, efforts have been made to broaden the approach to the economic and social spheres, thus developing life-cycle costing (LCC) and social life-cycle analysis (S-LCA). The integration of these three tools later constituted the life-cycle sustainability assessment (LCSA) [21].

Multiple-criteria decision analysis (MCDA) is a recognized approach to complex decision making that has also been applied to AWB management issues [22]. It offers a systematic way for selecting, ordering, assigning, and weighting various indicators via processes that can involve a diverse range of stakeholders [23]. Some of the most popular MCDA techniques are analytical network processing (ANP), analytical hierarchical processing (AHP), technique for order performance by similarity to the ideal solution (TOPSIS), and multi-criteria optimization and compromise solution (VIKOR) [24].

Combining LCA and MCDA as a holistic sustainability assessment framework is a prominent stream of research. Its origins are not recent, but its popularity is growing. The purpose of this synergistic framework is to achieve more complete and conclusive results for decision makers. Research efforts have been reported in renewable energy systems, the automotive industry, and agricultural practices [25–27]. However, what is the current state of the MCDA/LCA framework's application in AWB's circular bioeconomy transition? A synthesis of previous research on this study context in the literature is currently lacking. This paper is an attempt to close this gap by conducting a systematic review on the usefulness and operability of the MCDA/LCA framework in assessing sustainability in the transition to AWB's circular bioeconomy. Trends and intrinsic aspects of biomass, technologies, applications, spatial scales, stakeholder participation, tools, and impact categories used are identified and discussed. Additionally, strengths and weaknesses of the methodological interaction and crucial issues for future work are examined.

The rest of this paper is structured as follows: The second and third sections represent the theoretical background of AWB as well as the rationale for integrating MCDA and LCA. The fourth section is about the methodology used. The fifth section deals with the MCDA/LCA research landscape in AWB evaluation, while the sixth section discusses the synergies and trade-offs of combining the two tools. The seventh section shows possible steps forward to improve the impact of the MCDA/LCA framework. The eighth section provides the conclusions.

2. AWB Characteristics in the Circular Bioeconomy

Biomass is the term used to describe all organic materials that represent an alternative feedstock to crude oil and natural gas. Biomass is used in a variety of applications, including wood-based materials, pulp and paper production, biomass-derived fibers, and biofuels [28]. Biomass sources can be classified as animal waste, municipal waste, forest waste, industrial waste, and AWB (Figure 1A). AWB is divided into two main types: agricultural waste and food-processing waste. Agricultural waste is cropping field waste that remains in the fields as a by-product of post-harvesting activities, whereas food-processing waste is solid or liquid waste from the industrial processing of agricultural products [29].

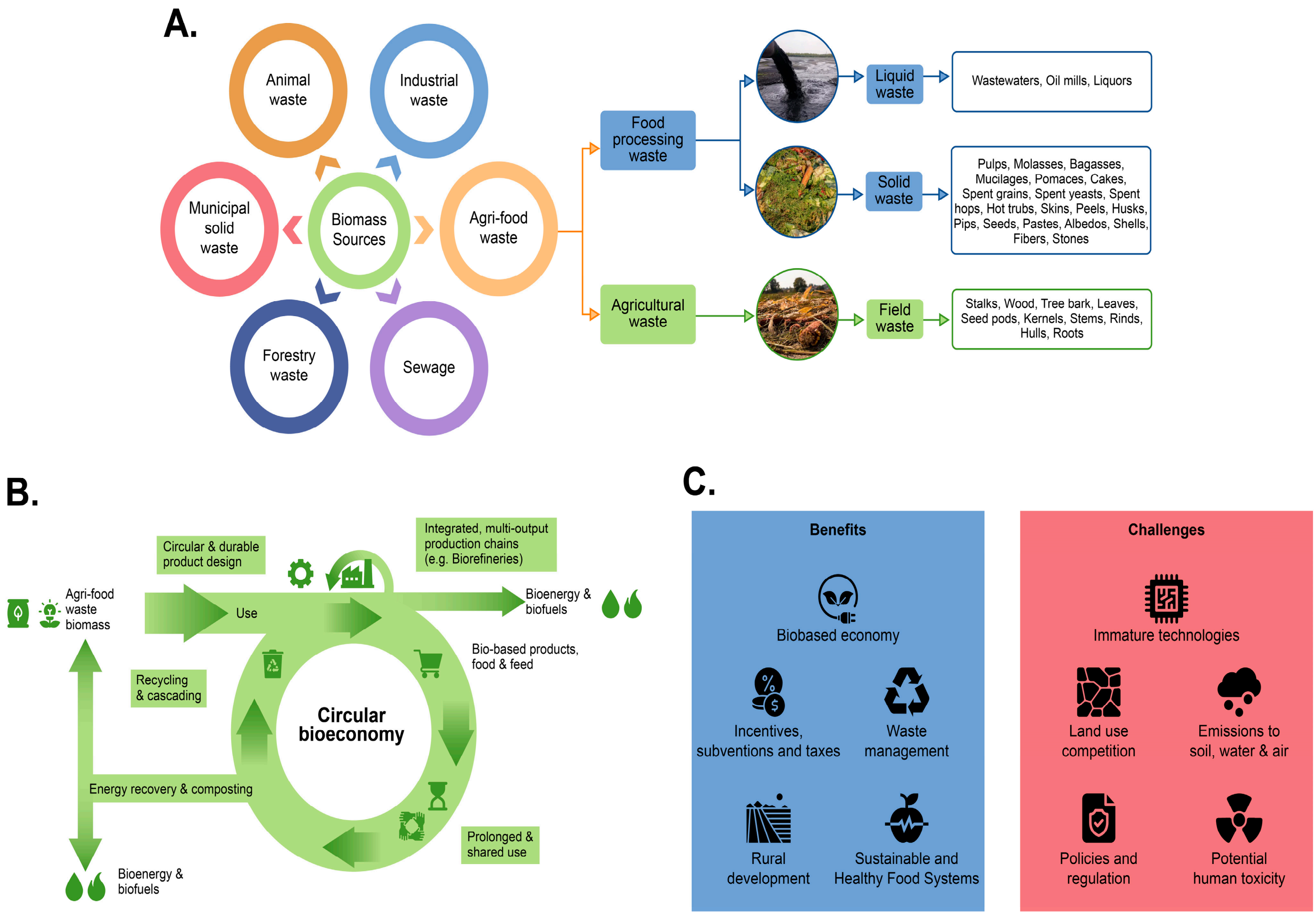

Figure 1. Features of AWB's transition to a circular bioeconomy. Classification of biomass sources and AWB types (**A**). A circular bioeconomy conceptual model for AWB (**B**). Benefits and challenges of AWB development in the circular bioeconomy (**C**). (Own elaboration with modifications from [3,29–32].)

It was estimated that more than 9 billion tons of crops were produced in 2017, with 1.3 billion tons of food wasted [33]. Roughly 1000 tons of food are wasted every minute, and 50% of food is lost at the production stage alone. By 2025, the agri-food sector could generate approximately 44% of global waste. AWB varies greatly between developed and developing countries, not only in quantity but also in location. North America, Oceania, Europe, and East Asia waste the most food in terms of volume [7]. AWB occurs primarily at the consumer level in developed countries, whereas food waste occurs at the production level in developing countries [34]. There are three major stages of AWB: agricultural production (33%), post-harvest and storage (54%), and processing, consumption, and distribution (46%). The primary AWB sources are beverages (26%), fruits and vegetables (14.8%), cereals and seeds (12.9%), and edible oils (3.9%), among others [35].

Accumulation and non-recovery of AWB have a negative impact on sustainability. In the social dimension, food waste is facing world hunger. A quarter of the world's total food waste could be used to feed the hungry. In terms of economics, developed countries waste USD 680 billion in food each year, while developing countries waste USD 310 billion [7]. The environmental impact of AWB is largely ignored. Every year, AWBs emit approximately 3.3 billion tons of carbon dioxide into the atmosphere, or approximately 1000 tons of carbon dioxide per minute [36]. AWBs strain water resources by consuming 250 square kilometers of fresh water; in other words, a quarter of the world's fresh water is wasted. In land use, approximately 1.4 billion hectares of arable land, or the size of the United States, India, and Egypt combined, has been designated for AWB [37].

A circular bioeconomy requires the use of sustainable biomass to ensure that the restoration cycle is completed and continues. As illustrated in Figure 1B, integrated and multi-output production chains can extend the life of biobased production to become a source of biomass and bioenergy [38]. The pillars of the circular bioeconomy are resource efficiency, optimizing the value of biomass over time, and sustainability, which push practitioners toward an energy-efficient and renewable management of AWB [3]. Some of the technologies highlighted in AWB to generate applications in bioenergy, biomaterials for construction, soil amendments, animal feed, and biopolymer production are composting, anaerobic digestion, transesterification, pyrolysis, and gasification [38,39].

AWB's transition to a circular bioeconomy has the potential to deliver several benefits, for example, the consolidation of a biobased economy to produce goods, services, or energy through the promotion of incentives, taxes, and subsidies. Other benefits include improving waste management, promoting rural development, and promoting sustainable and healthy food systems [27,32]. However, several impediments to achieving these benefits remain, such as immature technological development; competition for land use; soil, air, and water pollution; and indirect toxicity to humans. Furthermore, there are no legal guidelines in most countries for the disposal of unrecoverable AWB [27,36] (Figure 1C).

3. The Need to Integrate MCDA into LCA

LCA is based on the collection of inputs and outputs associated with the environmental, economic, and social impacts of a system of products and services throughout its life cycle [17]. LCA results are often difficult to interpret due to trade-offs between the impact category results of the scenarios under consideration [19]. These findings may even contradict one another, making decision making difficult. In response to this issue, two actions have been reported. The first action is to weight and add the LCA results from each impact category to produce a single scoring indicator. The second is to use a small number of impact categories to make interpretation of the results easier. These two decisions are contentious issues among LCA practitioners [40,41].

MCDA is based on mathematical protocols that are applied to inputs in structure analysis and interpretation processes that lead to decision making in numerous fields of knowledge [24]. However, there is a remarkable limitation in how the impact criteria are measured, as decision makers typically use qualitative scales [42]. Although qualitative scales are more practical for social aspects, it has been demonstrated that they are not always an accurate and precise way of representing the environmental and economic performance of the alternatives under consideration [43]. It is critical to achieve sustainability by using structured tools to assess the performance of alternatives in terms of multiple criteria [42].

LCA is composed of four phases, and MCDA generally has three, but their operation follows the same logical sequence (Figure 2). LCA is objective, reproducible, and standardized. MCDA is subjective on many occasions and can capture various perspectives that provide a broader view of the study context [44].

According to the descriptions above, LCA and MCDA are decision support tools that present different approaches [45]. LCA quantifies impact indicators that must be properly interpreted, while MCDA interprets real-world contexts for decision making that must be effectively based on indicators [44]. Furthermore, the two tools have complementary properties. Therefore, LCA and MCDA can be used in tandem.

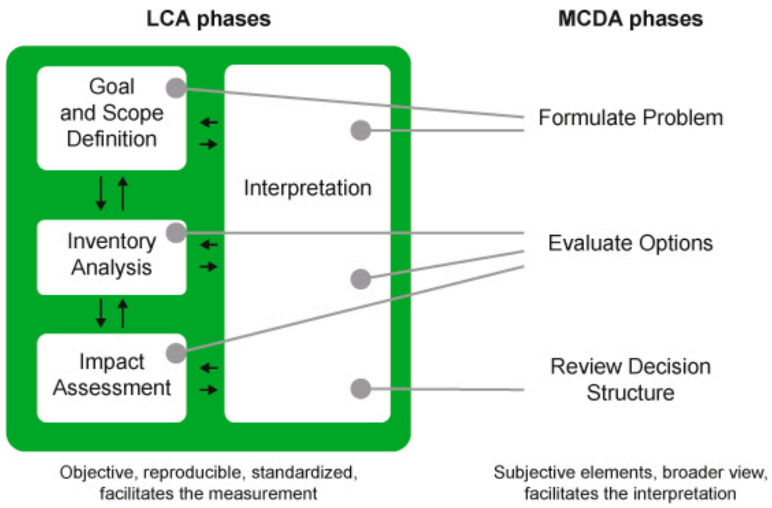

Figure 2. Complementary features between LCA and MCDA—own elaboration with modifications from [44,46].

The first applications of the MCDA/LCA framework emerged between the 1990s and 2000s. The work of Miettinen et al. [47] is an example of this, where they combined the use of E-LCA and the hierarchical analysis of processes (AHP) to weigh the impact categories of industrial beverage packaging systems. Hence, the methodological association of MCDA and LCA has been applied and discussed for more than 25 years.

The joint use of MCDA and LCA can be carried out in two ways: by integrating LCA into MCDA or by integrating MCDA into LCA [40]. The first is for LCA to provide indicators for the MCDA process. The second seeks for the robust interpretation of MCDA to be included in the life-cycle perspective. This review focuses on the second way: integration of MCDA into LCA. It is necessary to mention that the acronym LCA can be used as an umbrella concept encompassing life-cycle-based tools (i.e., E-LCA, S-LCA, LCC, and LCSA, among others), which is used in this paper.

4. Materials and Methods

This review article was structured as a systematic literature review to make the research replicable in other study areas or even updating the findings shown here in the future. The procedures described by Tranfield et al. [48] were adopted as follows:

- Step 1: Identify the opportunity for research.
- Step 2: Define the steps to consolidate the reported literature.
- Step 3: Select the aspects that will be analyzed to extract the information.

The first step, identifying the research opportunity, was already justified in this paper's introduction and background. The relevance of multi-criteria and life-cycle tools for AWB's transition to a circular bioeconomy was emphasized, as was the lack of state-of-the-art on the integration of these two tools in the scholarly literature.

The second step was carried out using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol [49]. This protocol establishes the following four phases: identification, screening, eligibility, and inclusion (Table 1). The identification phase consists of defining the parameters for the literature search in the databases and thus identifying the set of publications. The search required the definition of associated keywords using Boolean operators (" ", OR, AND, *) (Table S1). Keywords were meticulously selected from the reported bibliometric analysis [23,40,50]. The search was not limited to a period to cover the evidence published to date and was carried out in a single day to avoid bias caused by daily database updates. The search query was applied to the SCOPUS and Web of Science databases. These databases have a high incidence of access in research fields and contain peer-reviewed academic publications [51].

Table 1. Phases of the PRISMA protocol applied to obtain the set of publications to be reviewed.

Steps	Criterion	Effect
Identification	Search query Time horizon Search date Database	in Tittle, Abs, Key No limit 9 January 2023 Scopus and ISI Web of Science
	Finding publications by searching databases	Scopus: n = 43 ISI WOS: n = 117
Screening	Inclusion criteria: 1. Research articles	Records included Scopus: n = 41 ISI WOS: n = 109
	2. English publications	Scopus: n = 41 ISI WOS: n = 109
	3. No duplicate publications	Full-text publications consolidated: n = 120
Eligibility	Inclusion criteria: Publications related to the topic (Review of the first reading)	Full-text publications included: n = 40
Included	Review of the second reading, critical reading, and scrutiny	Final sample of reviewed publications: n = 23

The screening phase entailed developing criteria such as the type and language of publications required to conduct the review process as thoroughly as possible. The types of publications included were research articles; non-English publications were excluded. Moreover, duplicate publications between the two databases were eliminated to consolidate a single set of papers. The eligibility phase represented an exhaustive review of the content of the publications to confirm their intrinsic association with the research context. Since the scope of this paper is the integration of MCDA into LCA, only publications that applied both tools in this integration way were considered. In the included phase, the final sample of publications was established as an input for the next step.

The third step involved a critical reading, scrutiny, and detailed synthesis of the publications from two analytical perspectives that define the scope of this review. The first was based on the general characteristics of this field of research, such as biomass type, recovery technologies and applications, stakeholder contribution, spatial scales, and the techniques and indicators implemented (Table S2). The categories of these aspects were based on reported works and were defined iteratively, i.e., the reviews of the publications allowed the categories to be confirmed, added, or reconsidered [52,53]. The second perspective was a more in-depth interpretation that focused on neglected aspects of technique development, synergies and trade-offs in methodological association, and key issues for future sustainability assessments in AWB recovery.

5. Overview of MCDA/LCA Studies in AWB Recovery

MCDA/LCA studies on AWB are a relatively new but increasingly common approach as a sustainability assessment framework. Evidence collected and explored in this review paper covers several sectors (i.e., agri-food, construction, manufacturing, and energy) and geographic contexts (i.e., North America, South America, Europe, West Africa, and Eastern Asia).

5.1. Biomass, Technologies, Applications, and Spatial Scales Used

The MCDA/LCA framework implementation has been useful for a variety of applications involving conversion and processing technologies utilizing different AWBs (Table 2).

The production of biofuels from rapeseed, sugarcane bagasse, rice straw, wheat straw, moringa, maize, and triticale has been the most notable application.

Rapeseed (*Brassica napus*) research has sought to propose feasible scenarios for producing second-generation biofuels. Comparisons of biodiesel chains with different geographic feedstock origins have been conducted [54]. Locally produced feedstocks were chosen over imported feedstocks based on job creation and gross value added [55]. The establishment of environmental impact assessment processes has identified aspects that are affected but are not contemplated in the LCA standard, such as biodiversity [56].

Sugarcane bagasse research has pursued multiple purposes, including investigating value-added product processing routes and selecting feedstock sources. Joglekar et al. [57] studied the influence of six sugarcane bagasse processing routes, highlighting that the first- and second-generation ethanol-based routes with biogas promote both environmental preservation and productivity. Ramesh et al. [58] compared five lignocellulosic biomasses for second-generation bioethanol production and found that vetiver grass favors sustainability, followed by moringa, rice straw, wheat straw, and sugarcane bagasse. *Vetiver zizanioides* is cultivated in many countries, such as India, China, and Brazil, for its essential oil. This grass is drawing attention for exhibiting biorefinery potential, growing in conditions of drought, flood, high temperature, and contaminated soil [59].

Biofuels derived from maize have been used to standardize methodologies for evaluating the sustainability performance of fossil and renewable fuel chains. Ekener et al. [60] developed a life-cycle sustainability assessment methodology by applying value-based sustainability weights. These authors have shown that the maize-based biofuel chain leads to sustainable benefits compared to fossil fuels.

Table 2. Overview of all studies reviewed in terms of applications, recovery, and processing technologies, AWB, and spatial scales.

Applications	Recovery/Processing Technologies	AWB	Spatial Scales	Reference
Biofuel (Transportation)	Pre-treatment, saccharification, fermentation, and purification	Sugarcane bagasse, rice straw, wheat straw, moringa, and vetiver	Nation	[58]
	Extraction and transesterification	Rapeseed (*Brassica napus*)	Supply chain	[54]
	pre-treatment, saccharification, fermentation, and purification	Sugarcane bagasse	Process	[57]
	Extraction and transesterification	Rapeseed (*Brassica napus*) and soybean	Nation	[55]
	Husky process, gasification, pre-treatment with lime, saccharification, co-fermentation, dry milling, extrusion, and pelletizing	Triticale (X *Triticosecale* Wittmack)	Process	[61]
	Mechanical compressing, purifying, and refinement of biodiesel	Rapeseed (*Brassica napus*) and oil palm	Supply chain	[56]
	Pyrolysis, gasification, and methanol synthesis	Rice straw	Supply chain	[62]
	Biofuel production processes	Sugarcane and maize	Supply chain and farm-based	[60]

Table 2. *Cont.*

Applications	Recovery/Processing Technologies	AWB	Spatial Scales	Reference
Bioenergy (Bioelectricity and bioheating)	Collection, incineration, centralized composting, anaerobic digestion, biogas upgrading, and post-composting	Household food waste	City	[63]
	Anaerobic digestion, in-vessel composting, incineration, and landfilling	Household food waste	World regions	[64]
	Anaerobic digestion	A mixture of grape marc and cow manure	World regions	[65]
	Direct-combustion power generation, gasification power generation, and briquette fuel	Urban food waste	Resources	[66]
	Bioenergy systems based mainly on combustion, gasification, and pyrolysis	Lignocellulosic biomass	Resources	[67]
Soil amendments	Fertilizer production	Oil palm	Product and Farm-based	[68]
	Composting	Coffee residue	Farm-based	[69]
	Planting, pre-harvesting, harvesting, straw recovery	Sugarcane straw	Farm-based	[70]
	Anaerobic digestion	Household food waste	City	[41]
Construction biomaterials	Manufacturing, construction, and demolition	Rice husk ash and carbon nanotubes	Product and process	[71]
	Manufacturing processes	Rice husk ash and cotton mill waste	Product and process	[72]
Food waste recovery manufacturing strategy	Extraction and anaerobic digestion	Urban food waste	Process	[73]
Biopolymers	Anaerobic digestion, booster technology, polyhydroxybutyrate technology	Sugarcane straw, sugarcane bagasse, rice straw, rice husk ash	World regions, nation, city	[74]
Biochemicals	Polyphenol extraction methods	Red wine pomace	Process	[75]
Animal feed	Landfilling, incineration, and production process	Urban food waste	Nation	[76]

Triticale (*X Triticosecale Wittmack*) has been cataloged as a preferred non-food energy crop for biorefineries. The advantages of triticale lie in its ability to grow on marginal land and its higher yields compared to cereal crops [77]. These properties have driven decade-long research on triticale-based biorefinery processes from the MCDA/LCA perspective. For example, Liard et al. [61] analyzed the technical, economic, and environmental risks of three triticale-based biorefinery platforms incorporating two technological options. The platforms were ethanol, polylactic acid, and a mixture of thermoplastic starch and polylactic acid, while the technologies were ultrafiltration and cogeneration. These researchers noted that ultrafiltration technology substantially mitigates the environmental effects of the polylactic acid platform.

MCDA/LCA studies with AWB highlight bioenergy generation in terms of bioelectricity and bioheating. Here, the main source has been household food waste. Quantifications of the environmental and socioeconomic impacts of household food waste management in the Amsterdam Metropolitan Area for biogas production have been consolidated [65]. Findings by Wang et al. [66] have pointed out that direct-combustion power generation, gasification power generation, and briquette fuel are recognized as sustainable bioenergy technologies for household food waste. Slorach et al. [64] present a methodology to assess environmental performance in the food–energy–water–health nexus using four treatment options: anaerobic digestion, in-vessel composting, incineration, and landfill. They found that anaerobic digestion is the most environmentally sustainable option with the lowest overall impact on the nexus and that in-vessel composting is the worst option, even though it dominates circular economy waste hierarchies.

The production of biogas and the co-production of polyhydroxyalkanoates and biogas from grape pomace and cow manure have been investigated. Vega et al. [65] determined that the environmental performance of a biorefinery with polyhydroxyalkanoates and biogas co-production is preferable to a biorefinery only producing biogas at the territorial level, both in southern France and the western United States. Lignocellulosic biomass has also been associated with bioelectricity and bioheating. Von Doderer and Kleynhans [67] studied 37 plausible lignocellulosic bioenergy systems based on economic-financial, socioeconomic, and environmental indicators. These researchers indicated that a feller buncher for harvesting, a forwarder for biomass extraction, mobile comminution at the roadside, secondary transport in truck–container–trailer combinations, and an integrated gasification system for conversion to electricity are feasible and sustainable options.

To achieve sustainable production in a circular bioeconomy, bioenergy management faces challenges such as decreasing competition with food production that supports food security, mitigating the environmental impact of crop production, increasing feedstock options, incentivizing the use of AWB, and reducing production costs [78,79]. AWB represents a renewable energy source with a high growth potential for the circular bioeconomy.

Oil palm, coffee residue, and sugarcane straw are AWBs that have aroused research interest as soil amendments. The strategy of converting AWB to organic fertilizer is a common practice that has been applied to oil palm. In that vein, Lim et al. [68] carried out a fertilizer formulation process that incorporated organic and chemical compounds based on sustainability indices. The formulation obtained consisted of 0.96 wt% urea, 1.14 wt% monoammonium phosphate, 0.10 wt% kieserite, and 97.81 wt% palm-based organic fertilizer for oil palm. The circulation of resources that recovers biowaste has also been applied in horticulture systems, with promising results that are making another goal possible: replacing substrates obtained from processes under the perspective of the linear economy [80].

Composting coffee residues was used as a circular practice to propose the LCA4CSA method, which promotes climate-smart agriculture at the farm and cropping system levels. This work quantified the climate change mitigation potential of the use of compost, which ranged between 22% and 41%, by considering operations that occur on and upstream of the farm [69]. They also noted contamination transfers between impact categories such as climate change indicators, acidification, and terrestrial eutrophication. One emerging biotechnological strategy is the combination of AWB and microbial biostimulants to reduce contamination transfer, improve plant growth, reduce fossil fertilizer doses, and mitigate abiotic stress [39,81].

Sugarcane straw has been studied for the economic, social, and environmental impacts caused by manual and mechanical technologies for its recovery, as well as for the planting and harvesting of sugarcane. Cardoso et al. [70] showed that there are clear differences in the sustainable performance of manual and mechanized technologies. Manual technologies encourage job creation but negatively affect internal rates of return, ethanol production costs, and the environmental effect. By contrast, mechanized technologies present lower ethanol production costs, higher internal rates of return, and better environmental impact, confirming that mechanized scenarios are more sustainable.

The MCDA/LCA literature on soil amendments as biofertilizers for agricultural management practices so far is industrially focused for commercialization. However, no studies were found that sought to strengthen the economy of rural areas through the valorization of AWB. An investigation that promoted this social purpose is the one carried out by Juanpera et al. [82]. This work deduced that vermifiltration is a feasible alternative for the post-treatment of digestates from low-tech digesters implemented in small-scale farms. Vermifiltration produces a high-quality biofertilizer, is easy to use, and is implemented with local materials.

Biobased building materials are gaining ground in this research context. The circularity strategy to produce construction biomaterials is to combine virgin materials and materials recovered from AWB. For example, partially replacing the cement in the green concrete mix with rice hull ash nanowaste particles has been shown to be a promising alternative [71]. Its use reduces carbon emissions and requires less energy during the cement manufacturing phase. Cotton mill waste is another AWB used as an input for alternative building materials. Joglekar et al. [72] suggest that bricks based on this waste use fewer natural resources and use moderate conditions in the manufacturing process compared to burnt clay bricks used for masonry. Their study underlines that the serious handling and disposal problems of this waste are converted into an opportunity for green construction.

There are applications in food waste recovery manufacturing strategy, biopolymer production, biochemical synthesis, and animal feed with less dominance. The implementation of the MCDA/LCA framework, combined with the cost–benefit analysis has shed light on optimal strategies for citrus waste management by companies [73]. Strategies identified included the wholesale of imperfect but still edible waste as well as investments in facilities to extract higher-value pectin using a microwave-assisted pectin extraction process. Technological scenarios associated with the production of bioplastics have been evaluated to determine the benefits that they produce at territorial scales [74]. The environmental and economic performance at both laboratory and industrial scales of the extraction of polyphenols from red wine pomace has been crucial for making decisions on process standardization [75]. Lastly, some authors have indicated that using urban food waste as animal feed is environmentally feasible if the safe recovery rate exceeds 48% compared to the use of sanitary landfills and incineration [76].

The reported findings reveal that the macro-, meso-, and micro-scales have been addressed. Most of the case studies have been conducted at the meso-scale (i.e., supply chain and farm base), followed by the micro-scale (i.e., resources, processes, products), and the macro-scale (i.e., national, regional, and world). The integration of studies at the three scales would provide a complete picture of the circular bioeconomy debate in AWB. Following this direction, research can strongly contribute to larger-scale policymaking to foster circular and sustainable production patterns [83].

Three approaches must be promoted to move the circular bioeconomy toward sustainability: sustainability of the bioresource base, sustainability of processes and products, and sustainability of circular processes of material flows [84]. All the research summarized above indicated that the use of the MCDA/LCA framework has been aligned with these three approaches, mainly the second and third, suggesting that it has contributed to the sustainable advancement of the circular bioeconomy. Although the prevailing narrative in the literature is optimistic, there are critical positions on the barriers and limits, even suggesting that "circular" does not necessarily mean "environmentally friendly". The rationale of this statement is associated with the rebound effect, the risk of greenwashing strategies, and the development of new technologies without sufficient knowledge of their consequences [85,86]. These aspects must be addressed on a case-by-case basis to guide the academic community and determine the real benefits.

5.2. Stakeholder Engagement

The role, worldview, and values held by stakeholders strongly influence sustainability motivation and performance [60]. The relevance of communication and cooperation between governments, organizations, and actors are essential elements for decision making on sustainability [87]. The AWB literature associated with the MCDA/LCA framework revealed that stakeholders are not considered in most studies. In fact, less than half of the investigations included them (Figure 3A).

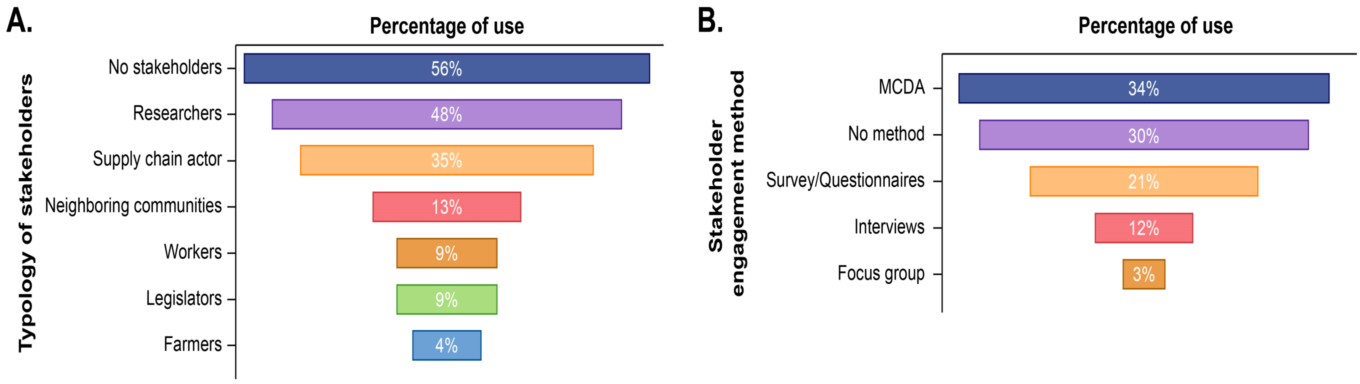

Figure 3. Role of stakeholders in the joint use of MCDA and LCA for AWB's circular bioeconomy transition. (**A**) Typology of stakeholders. (**B**) Stakeholder engagement method—own elaboration.

The stakeholders included in the studies consisted mainly of researchers and supply chain actors. Neighboring communities, workers, legislators, and farmers were less prominent. Some works underline the involvement of researchers for their ability to objectively compare sustainability impacts rather than relying on subjective opinions [57,58]. The frequently observed reason for choosing stakeholders is experience and knowledge. However, few studies have clearly documented a systematic selection of stakeholders, which could affect fully encompassing the multifaceted connotation of AWB management.

The selection of stakeholders may be based on their legitimate participation. Although there are divergent answers on how to define legitimate participation, Kruetli et al. [88] suggest addressing the following two questions: *Does the stakeholder affect or are they affected by the decision?* And *what participatory approach does the stakeholder play?* Brandt et al. [89] contribute to this debate by proposing four degrees of intensity of legitimate stakeholder engagement: information, consultation, collaboration, and empowerment. These grades are distinguished according to the attitudes of the stakeholders toward the evaluation process.

The reviewed studies elicited that various stakeholder engagement methods have been implemented. The popularly used method is to integrate the stakeholders into the development of the MCDA technique, which is performed with face-to-face questionnaires or via email (Figure 3B). Other methods used are interviews, focus groups, and surveys. These methods are carried out when the role of the stakeholders is multifunctional and independent of MCDA, thus contributing to various actions throughout LCA. De Luca et al. [27] suggest that stakeholder engagement methods need to be carefully elucidated as they determine the intensity of stakeholder engagement. Unfortunately, few studies have reflected a comprehensive understanding of the significance of the participatory method for stakeholders.

The literature showed that stakeholders have participated in all four phases of LCA (Figure 4). The impact assessment phase is the most impacted, followed by the inventory analysis phase. The interpretation phase is approached lightly, and the goal and scope definition phases are substantially overlooked.

The most common reason for involving stakeholders is to weigh indicators during the impact assessment phase. This trend, which was noted in AWB's circular bioeconomy transition, has also been seen in research promoting sustainable agriculture and renewable energy technologies [42,43]. The major benefit of this practice is ranking impacts measured by capturing multiple perspectives provided by stakeholders. Consequently, decision making is less complex in the interpretative phase and is based on the real interests of society.

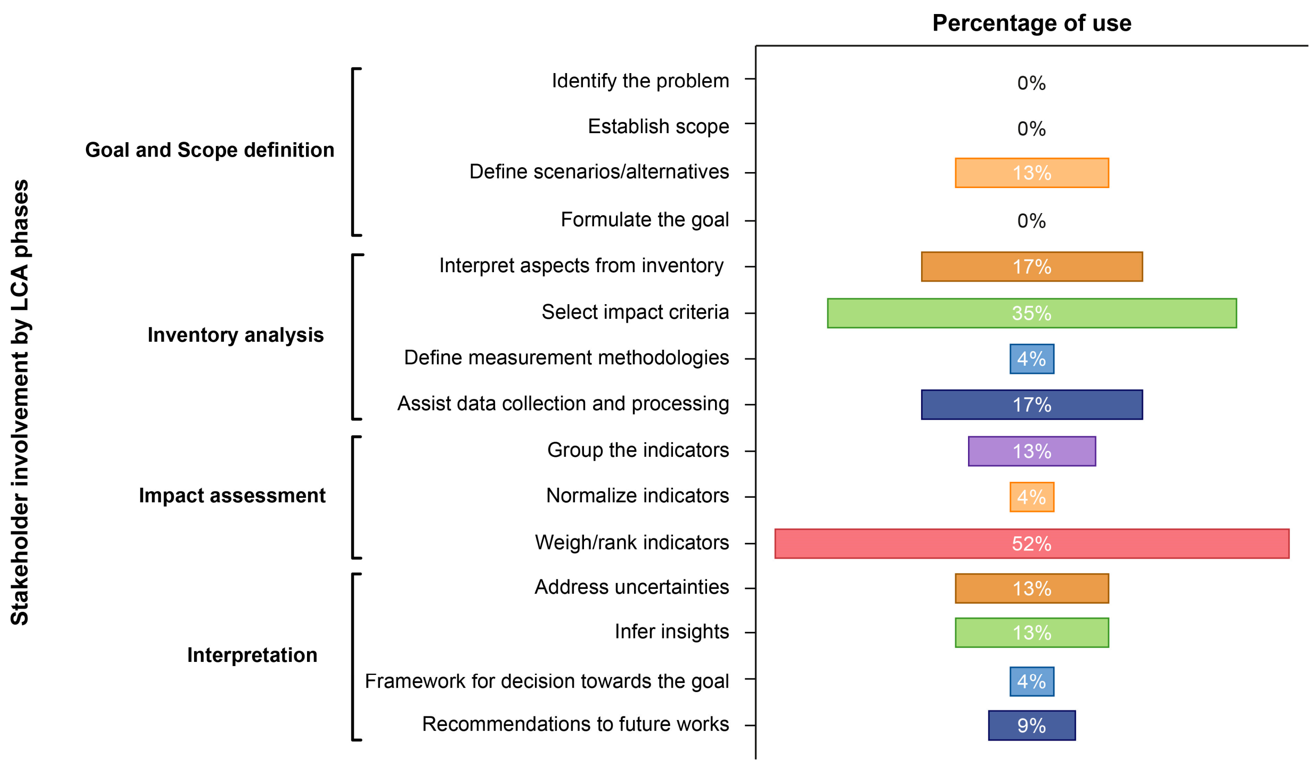

Figure 4. Contribution of stakeholders by LCA phases in the joint use of MCDA and LCA for AWB's circular bioeconomy transition. The percentage of use corresponds to the total number of publications consolidated for this review—own elaboration.

As mentioned above, there are authors of studies that did not involve stakeholders. They argue that the decision makers' analysis is time- and resource-intensive, which may hinder their application in practice [90]. They also expose that it is preferable to use stochastic methods that avoid subjective value judgments about which indicators are most important. Under this approach, different types of weighting, such as equal weights for all criteria evaluated and higher criteria values, and methodologies to define weighting are used [18]. Dias et al. [54] propose an analysis strategy based on stochastic multi-criteria acceptability analysis and variable interdependent parameter analysis to provide an exact limit of how much better each alternative is compared to another, from a perspective of pairwise comparison.

While these studies are methodologically sound, Thokala and Madhavan [91] take a different stance. They claim that the outputs will not be translated into tangible actions because decision makers do not trust them due to their limited or no involvement in the process. Iofrida et al. [92] describe that the consideration of stakeholder values is challenging but should not be a scientific weakness to interpretivism to the point that it is avoided. This review emphasizes that a methodological synergy can be achieved between these two approaches. Scientific validity must be promoted and can strongly support both the reconciliation of different objectives and the resolution of conflicting ambitions in social contexts.

The grouping of indicators is the second action carried out by stakeholders during the impact assessment phase, for which MCDA served as a methodological bridge. The two most common options are grouping by sustainable dimension and grouping by relevance to the identified problem. Both options lead to a decrease in the number of indicators that favor the following actions in LCA; yet, grouping by sustainability dimension has been recommended to encourage balanced approaches to sustainability [45].

Stakeholders have supported the inventory phase. The action preferably carried out by them has been the selection of impact categories. This observation possibly responds to previously reported suggestions to mitigate the bias of the research authors themselves [93]. Stakeholder selection of impact categories reflected alignment with the LCA goal but not the adoption of holistic sustainability perspectives. In line with this observation, Wang et al. [94] suggest using the Sustainable Development Goals as a guide to choose and structure the impact categories.

Stakeholders also perform actions such as interpreting aspects of the inventory and assisting with data collection and processing. While several theoretical frameworks have been proposed at a theoretical level, few works have documented comprehensive data collection with stakeholders. Contrasting studies illustrating the specific benefits of including stakeholders in the establishment of inputs have not been reported, but their influence may promote a more accurate analysis of the study object. Regarding data management, stakeholders have been reported to have contributed to the measurement of semi-quantitative indicators, mainly in the social dimension [76].

Stakeholders have been involved in the interpretation phase to address uncertainties and gain insights. A less considerate action for stakeholders is to propose recommendations for future work. Interestingly, living stakeholder labs have been created to follow up on the implementation of the findings obtained and thus establish a roadmap [63]. Living laboratories, known as living labs, are open innovation ecosystems in real-life settings whose main goal is to solve societal challenges through iterative feedback processes between stakeholders for collective ideation and collaboration [95].

Stakeholders have been weakly linked to the scope and objective definition phase. The sole action carried out by them is the establishment of alternatives and scenarios to be evaluated through the MCDA/LCA framework. Stakeholders have not been considered to identify the problem, establish the scope, and formulate the goal. Huttunen et al. [96] reported that stakeholders can improve the definition of system boundary elements, goal orientation, and the scope of the social dimension in the first phase of LCA. Stakeholders can even be empowered by learning about the consequences of their decisions and actions.

In the scope and objective definition phase, it is key to make sure that the set of stakeholders is comprehensively composed and that they represent all types of stakeholders. It is relevant to consider whether there are any value chain stakeholders who are indirectly dependent on the AWB. Garcia-Garcia et al. [73] exemplify this issue by asking the following question: *if local farmers are collecting waste for use as free animal feed, what would they do if this supply became unavailable?*

Taken together, stakeholder engagement reflected a routine development. The degree of integration of the stakeholders was not at the process level but at the level of the final findings. Their potential and development are partially exploited and detailed in AWB's circular bioeconomy transition when the MCDA/LCA framework is applied. The need for inter- and transdisciplinary approaches that combine, interpret, and communicate scientific and local knowledge is still increasing [97]. The processes of selection and involvement of the stakeholders depend on the study context, but being aware of the different ways of carrying out these processes contributes to the design of more meaningful, effective, and practical processes in the MCDA/LCA framework.

5.3. Techniques Applied

In promoting AWB's circular bioeconomy, the MCDA/LCA framework has shown the integration of various multi-criteria techniques and life-cycle tools. As expected, the E-LCA is the predominant tool in LCA; however, S-LCA and LCSA have rarely been applied, and LCC is not reported (Figure 5A). This pattern has been described in both the standalone implementation of LCA and its combination use with other tools [98–100]. Therefore, it is not due to an incompatibility of LCA and MCDA.

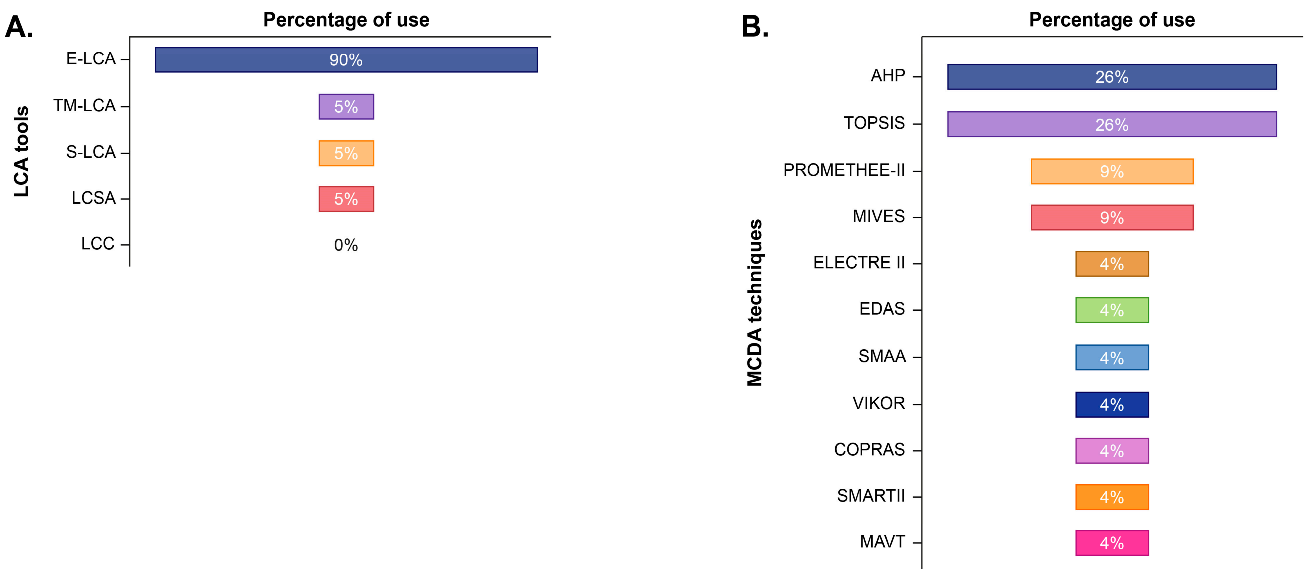

Figure 5. Use of tools in the MCDA/LCA framework for the transition to AWB's circular bioeconomy. (**A**) LCA tools. (**B**) MCDA tools. The frequency of LCSA use was not included in the S-LCA and LCC tools. In other words, the percentage of application of S-LCA and LCC was based on their individual use and was independent of LCSA—own elaboration.

The observed trend is to use the E-LCA and, at the same time, quantify various economic and social parameters independently. The authors do not expose reasons to avoid the implementation of S-LCA and LCC. However, three issues have been identified: (i) The comprehensive sustainable assessment method based on life-cycle theory for AWB circular management is still immature [6]; (ii) the E-LCA, LCC, and S-LCA analyses do not have the same level of maturity [101]; and (iii) there is a lack of harmonization of LCA tools that makes comparative analyses difficult [102].

E-LCA is a method that ISO 14044 standardized in 2006 and is widely used to investigate the environmental impacts of products and processes [16]. LCC is not yet standardized, but it considers all the costs and revenues attributable to cost objects from invention to abandonment [103]. S-LCA is a methodology that has shown a lack of consensus, but it has recently received standardization guidelines [104]. It evaluates the social impacts of stakeholder groups throughout the product life cycle [105].

LCSA can be extremely useful when used in conjunction with MCDA, contributing to a more comprehensive assessment and ensuring that all stakeholder concerns are included in the analyses [44]. Despite these virtues, LCSA is rarely used. Its application has consisted of the three life-cycle tools' results evaluated separately, concluding the fence of sustainability in a comparative way. This LCSA development path is due to the complex synergy of many of the existing methods in LCA tools [106]. As an alternative option to LCSA, triple-bottom-line evaluation has been used. The environmental bottom line has been calculated using LCA, the economic bottom line has been determined using net present value, and the social bottom line has been evaluated using SWOT analysis [76].

A study that is outside the context of this review but that represents a relevant reference for the use of LCSA is the one published by Hildebrandt et al. [107]. They assessed three scenarios involving existing and future wood-based value-added networks in Germany. The framework implemented in this work includes a set of 55 calibrated categories to sustainably monitor regional bioeconomy clusters. According to Visentin et al. [18], future research on LCSA should concentrate on three directions: standardizing analytical methodologies, establishing and measuring indicators, and applying LCSA in case studies. These priorities must be considered in the MCDA/LCA framework.

The territorial metabolism–life-cycle assessment (TM-LCA) framework is booming for circular AWB management. Its use allows for the study of the environmental and economic consequences of AWB management chains on a macro-scale, addressing their complexity, seasonality, and regionality [108]. Interestingly, the joint use of the multi-criteria approach to TM-LCA has been highlighted for the simulation and prediction of the environmental performance of future systems [109]. Its integration further extends the approach with scenario analysis, including regional and seasonal aspects, several product life cycles, and comparing these across a wide range of impact categories simultaneously [110].

The substantially used MCDA tools are AHP, TOPSIS, PROMETHEE-II, and MIVES (Figure 5B). Other tools, less commonly reported, are ELECTRE II, EDAS, SMAA, VIKOR, COPRAS, SMART, and MAVT. This trend indicated that the MCDA techniques used are aligned with two typologies: the theory of multi-attribute value and the prioritization and classification method, where the former is more prevalent. It is noteworthy that some researchers stated that they were using a multi-criteria approach but did not refer to any specific MCDA technique [27,111]. Some researchers describe the pros and cons of MCDA models regarding the system and objective under study to determine the most feasible model [41].

AHP is a hierarchical MCDA with levels of objectives, criteria, possible sub-criteria, and alternatives. This method compares the criteria pairwise to determine a preference ranking [112]. AHP has presented a broad area of application spanning the social, natural, and economic sciences [113,114]. AHP is used in the LCA/MCDA framework to establish the weight and ranking of the categories. The AHP method was applied either individually or in combination with other MCDAs (i.e., AHP + TOPSIS + Entropy and AHP + VIKOR). The most frequent application of AHP in the reviewed literature was to select AWB, the conversion and processing technology, and the supply chain scenario that would lead to the best sustainable beneficial impacts. The benefits of integrating AHP with LCA are that it is a robust, flexible, and well-known method that clearly illustrates the pillars of sustainability, measures the consistency of decision makers' judgments, can be easily combined with other methods, and presents an algorithmic structure that facilitates the communication of results to decision makers [42,115].

The TOPSIS method is based on the idea that the chosen alternative should be the shortest geometric distance from the best solution and the furthest away from the worst solution [116]. It requires little input data and produces results that are both understandable and reliable. TOPSIS's benefits include its simplicity, ability to measure the relative performance of each alternative, and high computational efficiency [117].

PROMETHEE is a method that classifies and selects a finite set of alternative actions between criteria that are often contradictory [118]. MIVES is a tool especially aligned to sustainability that combines features of multi-level requirement aggregation, inclusion of a weighting process, and indicator value utility functions [119]. MCDA technique comparisons have been reported to support appropriate selection based on study context [120,121]. Lastly, a potential strategy is to implement different MCDA techniques to compare the weights obtained and consolidate them into a final ranking of the study alternatives. This alternative provides a broader picture for decision making.

5.4. Impact Categories Assessed

AWB's circular bioeconomy transition has been measured using 57 impact categories spanning six dimensions via the MCDA/LCA association. Environmental categories account for 39% of the total, followed by social categories (26%), economic categories (18%), and technical categories (7%). Both the business strategy and government categories received 5% (Table S3).

In many cases, the impact categories were established without regard for selection criteria. Some studies base their impact criteria on previous studies conducted with similar conditions [57]. In macro-scale studies, selection criteria such as reliability, measurability, and relevance to the territory's situation have been used [122].

Global warming potential is the most measured indicator in the environmental area, to the point that all studies included it (Figure 6). However, few authors measure it in more specific terms, such as sulfur dioxide mitigation, nitrous oxide mitigation, and chemical oxygen demand discharge, to provide a more detailed environmental description. Overall, the findings showed global warming potential decreases through circular strategies, indicating that it is possible to improve the current response to the global climate crisis [123]. Acidification showed a measurement frequency of 65%, while eutrophication showed a frequency of 57%. These three indicators have been vital to studying the implications of circular AWB flows. Contamination transfers from AWB to the system have been found in them [41].

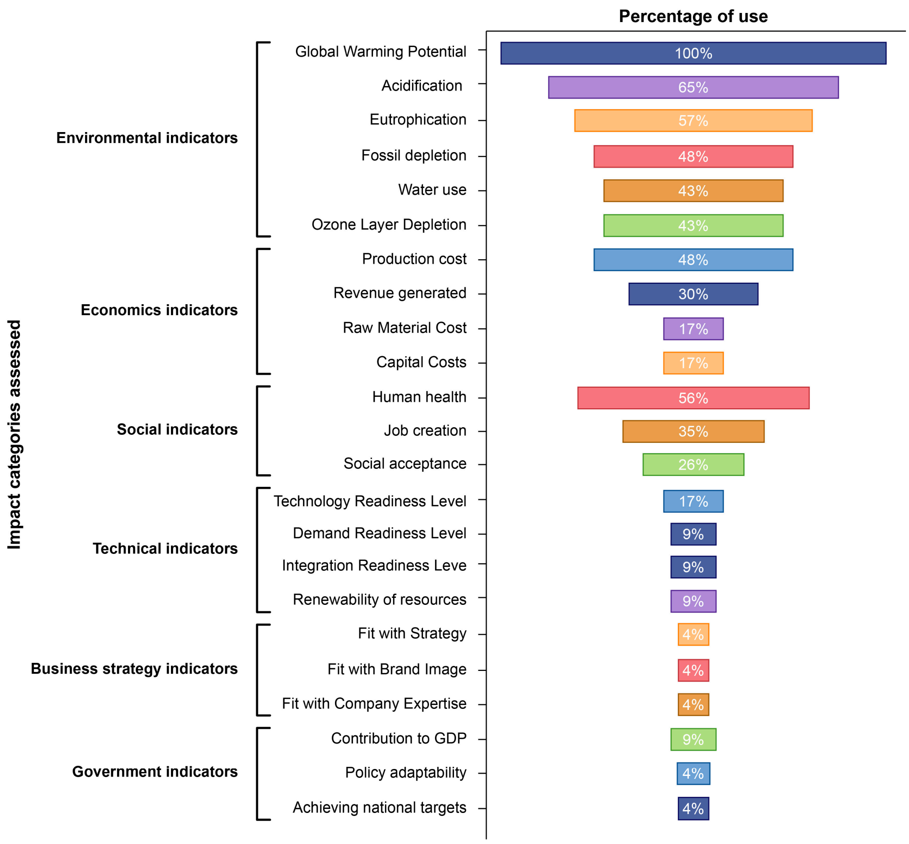

Figure 6. Impact categories most reported in the literature on the use of the MCDA/LCA framework in AWB's circular bioeconomy transition. The other categories are found in Table S3—own elaboration.

Fossil depletion was the fourth most reported indicator, covering 48% of the literature. This is a highly discussed impact category in LCA as it is a problem crossing the economy–environment system boundary [124]. Water use and ozone layer depletion registered 43% each. Moderately frequent environmental indicators in the studies are ecotoxicity potential, land use, photochemical oxidation, and particulate matter. The above impact categories are addressed in nearly every E-LCA. Rarely measured environmental indicators are residual waste, macronutrient (N, P, and K) content recovery, recycled contents, and undesirable substances.

Several authors have mentioned two limitations concerning environmental indicators. The first is that the estimates of LCA impacts were limited to impact categories for which inventory data were available [125]. The second is linked to the inaccurate interpretations that can occur when the databases are not regionalized [126]. In response to these barriers, computational frameworks have been proposed to strengthen the efficiency of data collection in LCA, and government efforts to promote and finance this goal have been highlighted on global agendas [127,128].

Studying the social dimension to measure its feasibility in the circular bioeconomy has always been a challenge [105]. The social indicators outnumber the economic indicators when compared to the total number of indicators; however, there is considerable variation in the number of indicators between studies. Consequently, current studies usually capture indicators of environmental impact, economic indicators, and, on occasion, social indicators.

The most contemplated social indicator is human health, with its presence in more than half of the literature. Previous works have emphasized the relevance of this indicator, which is a long-lasting endeavor of mankind [129]. This category implies the evaluation and comparison of both positive and negative human health impacts along product life cycles [130]. Job creation is included in a third of the publications, and it is an indicator that has received considerable research attention. Methodologies aimed at characterizing the social dimension through the evaluation of potential job creation have been reported [131]. Social acceptance stands out with 26% usage. The focus that has predominated in the categories of social impact is health and socioeconomic repercussions.

The participation of the workforce in each sector, occupational accident levels, education levels, skilled labor, safety, odor generation, noise creation, participation of associations, and stakeholder support are minimally measured. The researchers who included these indicators acknowledge that they were useful but that they have not been adequately disseminated in the scholarly literature; therefore, they recommend them for use in future studies [63,132]. Bartzas and Komnitsas [133] underline that stakeholder support is crucial for the success of any change and that its measurement is linked to the social sphere. They quantified this indicator as the total number of training programs followed by the farmer. The measurement of most social indicators is qualitative and does not follow the guidance provided by S-LCA.

Analyzing the social aspects of biomass management, such as AWB, in a circular bioeconomy can have several important benefits for participation, equity, effective policy development, sustainability, and social acceptance. However, evaluating it can present significant challenges, including complexity, a lack of data, different perspectives, and cultural change [105]. Social aspects are inherently complex and multifaceted. Biomass management can have implications for different social groups, cultures, and values, which can complicate the identification of suitable solutions and strategies [134,135]. The circular bioeconomy may require a significant cultural change and a new focus on the relationship between society and natural resources, which requires novel approaches to promote it [12]. Although the reviewed studies did not state that strategies based on the circular bioeconomy on AWB can have negative social consequences, it should not be assumed that these strategies generate added social value automatically. Recent research has found that circular economy practices can have negative social consequences, implying that each practice should be evaluated individually for its social implications [136].

There are several calls that the academic community has promoted so that the social sphere in sustainability is not neglected [137,138]. As LCA, MCDA, and their combined use are involved, every practitioner must be certain that the social categories require more attention. Murphy [139] states that elucidating how the social pillar relates to the environmental pillar will allow a clearer understanding of its significance in sustainable development. He poses the following two questions: *How might the goal of global equity be made compatible with environmental objectives? And how might participatory mechanisms incorporate the aspirations of vulnerable groups, current and future?* The answers to these questions are key inputs for formulating an alternative set of social impact categories. Gutowski [140] reported a criticism of LCA, questioning where the people are. He provided a framework and examples to illustrate how human behavior can alter the environmental outcomes suggested by LCA. In response to this cross-sectoral challenge, Leipold et al. [141] suggest that social policies and initiatives should be at the heart of circular bioeconomy narratives, highlighting collective equity issues over individual opportunities for consumers and employees.

The economic dimension has had an impact on categories related to financial costs. The cost of production leads the list of categories, followed by the revenue generated.

Raw material costs and capital costs share the third position. Most studies ambiguously describe production costs, without specifying whether feedstock costs, common goods, utility costs, and maintenance costs are measured. The detail of the estimates has been previously suggested [142]. Since economic activities can have a wide range of positive and negative consequences, the need to broaden the scope of economic evaluations in LCA has been suggested [143]. This criticism applies to the circular management of AWB, since the impact categories used are limited to current economic structures and indicators that do not denote the search for resilient economies. Valdivia et al. [144] invite us to rethink the approach to the economic field in LCA based on inclusive paths that do not neglect social stability.

The studies' environmental, economic, and social developments revealed that there are holistic assessments of sustainability. The impact categories that cover the three pillars were balanced at the beginning of the studies, but when carrying out the discussion with the stakeholders, the indicators decreased due to their level of association with the defined problem.

Technology and government impact categories were included in the MCDA/LCA analyses. The technological aspect was described by the level of technological readiness, the level of readiness for demand, the level of readiness for integration, and the renewability of resources. The aspects of government were analyzed in relation to the strategy, the brand image, and the experience of the company [145]. The inclusion of these two aspects played a key role in the decision-making process for the studies. However, its low prevalence in the reviewed literature indicated that there is a negligent alignment between the purposes of MCDA/LCA investigations and the objectives of business and government. Implications arise when LCA findings are scaled up to make claims about possible future outcomes within a scenario that ignores public and private sector goals.

6. Synergies and Trade-Offs in the Methodological Association

The complex links and trade-offs between AWB, the environment, and people under a transformative circular vision are now sharply in focus. The growing understanding of this three-way interaction has prompted the development of sustainable assessment frameworks. This review reports that the MCDA/LCA framework has benefited AWB's circular bioeconomy. The primary motivation for its use has been to maximize economic performance while minimizing environmental footprints. The predominance of eco-efficiency and technical-environmental approaches demonstrate this. Debates have been published about this motivation, since it does not represent the essence of sustainability [146]. Nevertheless, the social sphere's connotations are gradually being captured.

The relevance of the MCDA/LCA framework lies in promoting a multiple approach based on dimensions, indicators, and stakeholders to assess and make decisions from the perspective of the life cycle. The methodological synergy that the integration of MCDA techniques into LCA tools has shown lies in the impact assessment phase. MCDA has not been integrated into the processes or actions of the other three phases of LCA (Figure 7). MCDA has traditionally been used to group and weight the outputs of LCA. As previously stated, the weighting methods used were classified as "objective weighting methods" using mathematical methods and "subjective weighting methods" using stakeholders. Although the ISO standards on LCA do not require normalization, grouping, or weighting, LCA practitioners see these as beneficial in simplifying the analysis of the overview for decision making. This influence of MCDA is crucial to resolving trade-offs between impact categories. It has been notably applied in different areas of sustainability [27,42].

The methodological trade-offs of incorporating MCDA into LCA have revolved around three aspects: poor integration in the three phases of LCA, uncertainties, and operability. Unfortunately, few authors either mentioned or applied recommendations and limitations exposed in other works.

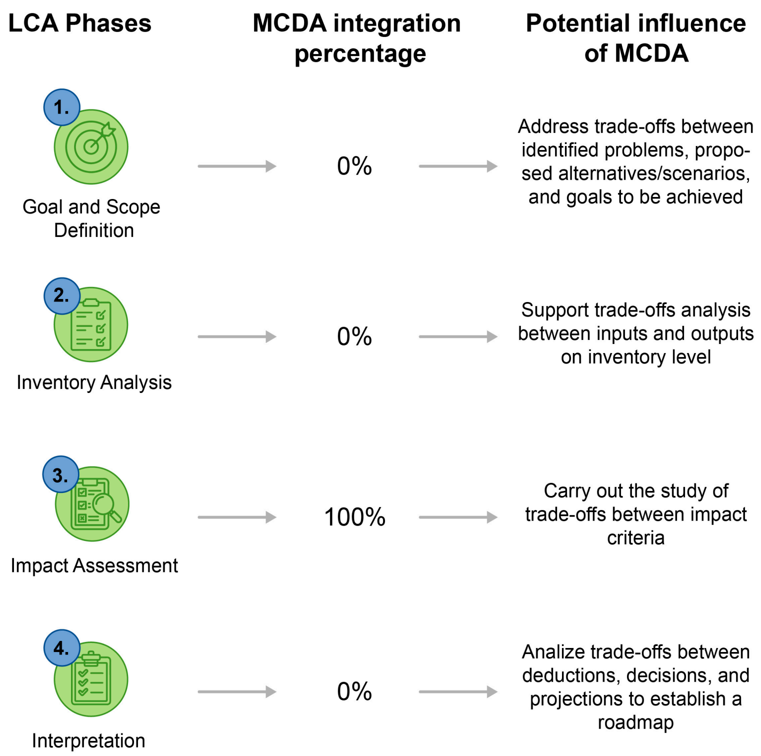

Figure 7. Integration of MCDA into the LCA phases in the studies framed in the circular bioeconomy of AWB and the benefits that MCDA can trigger if its complete integration is carried out—own elaboration.

The absence of MCDA in the first, second, and fourth stages of LCA diminishes its potential impact. The benefits provided by MCDA in the objective and scope definition phase are the structuring of the problem and the mitigation of uncertainty in methodological decisions. The description of the study context can present various challenges and numerous solution alternatives that are not dimensioned and projected by the authors of the paper. Likewise, recently proposed methodological innovations can be incorporated, or methodological gaps can be identified and strengthened.

Including MCDA in the inventory phase supports the analysis of trade-offs between inputs and outputs. Depending on the objective of the study, it is necessary to select different typologies and numbers of categories. A greater diversity of typologies and number of categories does not translate into a greater validation of the work. Tedious processes can be simplified by including a small step based on MCDA. Furthermore, some indicators are measured qualitatively, and for this, MCDA is suitable.

The primary benefit of incorporating MCDA in the interpretation phase is that it strengthens decisions and projections. The establishment of roadmaps is uncommon, which limits the dissemination of concatenated publications that can be used to justify policy changes. Many more research efforts are needed to determine the acceptability of various approaches and their adequacy to inform decision making in real-world situations [44]. Integrating MCDA into these three phases of LCA may represent small efforts compared to the impact assessment phase.

The possibility that MCDA could introduce uncertainty through a loss of information by adding subjective, value-laden data is an identified trade-off. To assess the effect of these changes, for example, on the overall sustainability index weighting, a sensitivity analysis is performed. Unfortunately, more than half of the reviewed studies did not have sensitivity analyses. A robust treatment of uncertainty is often omitted or partially accounted for by assuming selected key scenarios [147]. Several researchers have mentioned that the MCDA/LCA framework is not operationally feasible as another trade-off. It implies a considerable alignment of efforts that does not depend entirely on the scope of the researchers.

To improve sustainability assessments under LCA, one or more MCDA processes may be needed throughout its phases. This decision, however, must be carefully considered on a case-by-case basis. In line with Dias et al. [44], two expectations of this review are that LCA and MCDA practitioners collaborate more closely to investigate the potential of this framework and that its use serves as a bridge between science and practice.

7. Key Issues for a Comprehensive AWB Recovery Sustainability Assessment through the MCDA/LCA Framework

Research on AWB and sustainability issues has been prolific, and it relates to the call to become sustainable for a cleaner planet [148–150]. It has produced an amount of information that was not previously available, and the MCDA/LCA association has contributed to this. Based on the shown potential of this framework and its adoption by researchers and practitioners, it is expected that its use will continue to grow and be implemented in other types of biomass. To enrich the methodological innovation of MCDA/LCA research and thus support the emerging challenges and opportunities of AWB's circular bioeconomy transition in society, this review establishes the following five suggestions:

First, explore new roles for MCDA throughout the phases of LCA, identifying which techniques are feasible and which factors are necessary and deducing pros and cons. This consideration will break with the routine adoption of the MCDA process.

Second, design an appropriate process for stakeholder identification and engagement. Holistically articulating the stakeholders in the phases of LCA leads to benefits that depend on the study contexts. It will also require novel forms of interaction and consensus building to address bottlenecks and map out options for improvement among stakeholders.

Third, strengthen social and technological categories. The social dimension can be analyzed through S-LCA and thus investigate the social consequences of a given change, for example, the adoption of a new technology [70]. Both the United Nations Environment Development Program's life-cycle initiative and social hotspot database provide detailed guidelines for the S-LCA of products [84], which can be adapted to the AWB recovery context to advance in measuring their social feasibility. Likewise, it is necessary to deepen technological implications that in some instances can be a limitation.

Fourth, examine what relevant legislation applies to the AWB in question in terms of permits, taxes, and relevant financial incentives that might be available. Against this background, Stone et al. [146] propose a qualitative impact indicator called political/regulatory compatibility that can be considered and diversified into more indicators for future studies. The impact of MCDA/LCA results must be aligned with government and company goals.

Fifth, promote the articulation of studies at the micro-, meso-, and macro-scales that allow moving from quantification to action. Processes of articulation and discussion of the perspectives that unite the environmental, economic, social, technical, managerial, and political spheres to create a shared vision and a road map will be necessary later [151]. The work published by Lopes et al. [152], which offers a description of how to perform a collaborative process involving stakeholders to support the circular transition with a projection to 2035 in the food and beverage packaging sector in Portugal, can be used as a reference guide.

This review paper considered the literature within the parameters of the search criteria used to find publications in databases. This implies that the search criteria (keywords and Boolean operators) used do not allow for results to be generalized beyond the scope of the study. Moreover, the final version of the published journal articles was considered. There is the option of searching for additional articles that are not yet ready for publication. Although these two factors may be limitations of this study, these are inherent in database operation.

8. Conclusions

The use of the MCDA/LCA framework has aided in the advancement of AWB's circular bioeconomy. It has been versatile due to the various applications, technologies, and AWB reports at micro-, meso-, and macro-scales.

The operability of the MCDA/LCA framework has presented divergences in different aspects. Stakeholders are partially considered in the studies, and neither their role nor the characteristics of their selection are described in sufficient detail. Its potential is limitedly exploited, which could reduce the impact, effectiveness, and practicality of processes. The MCDA/LCA framework has shown the integration of various multi-criteria techniques and life-cycle tools. The predominant methodological approach of life-cycle tools is to use E-LCA and measure independently of various economic and social parameters. Barriers still exist to using S-LCA, LCC, and LCSA. In contrast, the TM-LCA methodology is gaining ground. The AHP and TOPSIS techniques are frequently used in MCDA. Its integration in the LCA tools has focused solely on the impact evaluation phase, with the main purpose of grouping and weighting the outputs of LCA. MCDA has the potential to generate benefits per the LCA phase that need to be examined and proven.

The MCDA/LCA framework has supported holistic assessments of sustainability. Environmental, economic, and social factors have been studied together with technical, business strategy, and governmental aspects. The assessment of these last three categories is still immature. The social dimension has received interest, but it must be strengthened, while the economic dimension has not reflected innovation. Future studies are expected to address and answer the questions discussed here.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su15065026/s1, Table S1: Search equation applied to the Scopus and Web of Science databases to consolidate the reviewed literature, Table S2: Description of aspects and categories scrutinized in the publications, Table S3: Indicators found by dimension in the publication set.

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