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The role of life cycle thinking-based methodologies in the development of waste management plans

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ABSTRACT

The aim of this article is to examine how Life Cycle Thinking (LCT) contributes to the development of Waste Management Plans (WMPs). The case of Italy has been deeply investigated. The article first analyses whether and how the LCT methodologies were applied to the 21 regional WMPs; then, it draws indications for using LCT in the preparation of a WMP. Moreover, it outlines why the Life Cycle Assessment (LCA) methodology could be used as a powerful tool for regional planning in the waste field, analysing the indications for preparing a WMP that already exist at the European level and in the Italian National WM Programme. Results reveal that only four of the 21 regional WMPs include comprehensive and site-specific LCA studies. Building on these case study results, insights into the opportunities and benefits associated with incorporating LCT methodologies into WMP development and implementation are provided. This study underscores the critical importance of LCT and LCA in promoting sustainable waste management practices, ensuring compliance with European directives, and offering a foundation for more informed regional planning strategies.

1. Introduction

Municipal Solid Waste (MSW) management remains a pressing challenge in today's world. At the same time it is a key driver for a sustainable circular economy (CE), slashing resource losses and curbing environmental emissions. In Europe, over the last few years, the CE framework has guided policymakers in fostering sustainable practices for waste management (European Commission EC, 2019). Over the past decades, European policies have established objectives for urban waste management (WM) entities and municipal authorities. These include regulations pertaining to waste prevention and reduction, waste collection, recycling efforts to reduce landfill disposal, as well as the formulation of waste management plans (WMPs) (European Commission EC, 2008; European Union EU, 2018). In this context, the European Waste Framework Directive (WFD) requires that each Member State assesses a national WM Programme with mandatory requirements (European Union EU, 2018). From a policy and legislative perspective, guidelines to develop an ideal WMP have been established by the European Union (EU) (European Commission EC, 2012). The EC suggests a general requirement for the plan's preparation, which involves justifying any "deviation from the 2008 Waste Framework Directive's waste hierarchy as regards specific waste streams", providing "information on the life-cycle thinking behind it". The waste hierarchy is a structured approach to waste management that establishes a prioritized sequence of actions to reduce environmental impact and resource depletion. It consists of five basic steps, each of which builds on the previous one to promote sustainable waste management: prevention, reuse, recycling, recovery – of energy or material – and, lastly, the treatment and disposal. The EC suggests a general requirement for plan preparation, which includes justifying any "deviation from the waste hierarchy of the 2008 Waste Framework Directive with regard to specific waste streams"

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Nomenclature

ACRONYMS

CE	Circular Economy
EC	European Commission
EU	European Union
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCT	Life Cycle Thinking
MSW	Municipal Solid Waste
SLCA	Social Life Cycle Assessment
WFD	Waste Framework Directive
WMP	Waste Management Plan
WM	Waste Management

by providing "information on the underlying life-cycle thinking." Article 4 of WFD, for example, opens to potential deviations from the waste hierarchy for specific waste streams "where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste". Within the framework of Life Cycle Thinking (LCT), the Life Cycle Assessment (LCA), also called environmental LCA, has been listed among the methodologies that aim at supporting the assessment of the impacts and the benefits associated with different policy options (Sala et al., 2016). Concerning LCT and LCA, Sala et al. (2016) also stated that in recent years several policy documents referring to the environmental discussion have been published (i.e., 15 environmental policies, 8 EU Directives, 4 Regulations). In this context, a series of literature studies explored the evolution of LCA-oriented policies at European level (Sala et al., 2021; Di Maria et al., 2020; Lehmann et al., 2015) and they all conclude that strengthening the science-policy binomial would allow the decision makers to wholly benefit from LCA applications. For this purpose, the use of the LCA methodology applied to WMPs results particularly important when different waste management systems need to be analysed and compared (Fedele and Rigamonti, 2019; Rigamonti et al., 2020; Camana et al., 2020). As shown by Tutunchian and Altınbaş (2023), the use of LCA allows strategy developers to determine efficient integrated WMP, taking into account the CE approach.

The analysis started by conducting a literature review to evaluate the current state of utilizing LCT methodologies in WMPs on a European scale (EU-27). A study performed for the EC developed an assessment of the completeness and conformity of WMPs at national, regional, and local level (BiPRO 2016; BiPRO 2018). However, the application of LCT was not assessed. It was found that the life cycle approach was used to define a National Waste Management Plan (Ferrão et al., 2016). Additionally, some case studies that focus on specific aspects of the waste management system (e.g. Panagiotis et al., 2023; Andreasi et al., 2017; Hupponen et al., 2023) can be found in the literature. However, these examples do not encompass the full complexity of analysing an entire waste management system. Considering the above, it was decided to perform a study at the Italian level, as a representative case study. Italy was selected for proximity, linguistic reasons (WMPs are written in the local language, posing a significant analytical difficulty for foreign reviewers) and the authors' knowledge of the WM system and its diverse characteristics throughout the entire country.'Within the Italian context, some authors applied the LCA tool to assess the sustainability of waste prevention measures (e.g. Magrini et al., 2021), reuse and preparation for reuse options (e.g. Degli Esposti et al., 2021; Rigamonti et al., 2019), as well as regional treatment processes (e.g. Ferrari et al., 2018; Rigamonti et al., 2013), various waste valorisation processes (e.g. Cappucci et al., 2020; Cappucci et al., 2022), and discussed the influence of LCA methodological choices on WM results (e.g. Pini et al., 2018). However, in Italy, LCA is not yet broadly used as a decision–support tool (e.g. Camana et al., 2021).

The purpose of the article is to define a stepwise methodological approach to assess the application of LCT as a support tool for the preparation of WMPs. The application of this methodological approach to the Italian case results in a picture of the state of the art regarding the implementation of the LCT for the development of WMPs. After analysing whether and how the LCT methodologies were applied to the 21 regional WMPs developed in Italy, general indications were drawn.

The material and methods section (Section 2) describes both the assessment methodology and the reference to the National WM Programme (Section 2.2) and to the European Union indications (Section 2.3); the discussion part reports results obtained (Section 3), while final conclusions are delineated in Section 4.

2. Material and methods

2.1. Assessment methodology

The research questions of this study aimed to determine if and how regional WMPs in Italy reference the LCT approach and assess environmental, economic, and social impacts. It also explored how Italian regions have implemented LCT methodologies in their WMPs, if the methodology applied follows the indications given by European regulations and the National WM Programme, and whether it is possible to draw criteria from these cases for future WMPs. The research was conducted following a stepwise methodological approach that consists of five phases that are described in the following paragraphs and

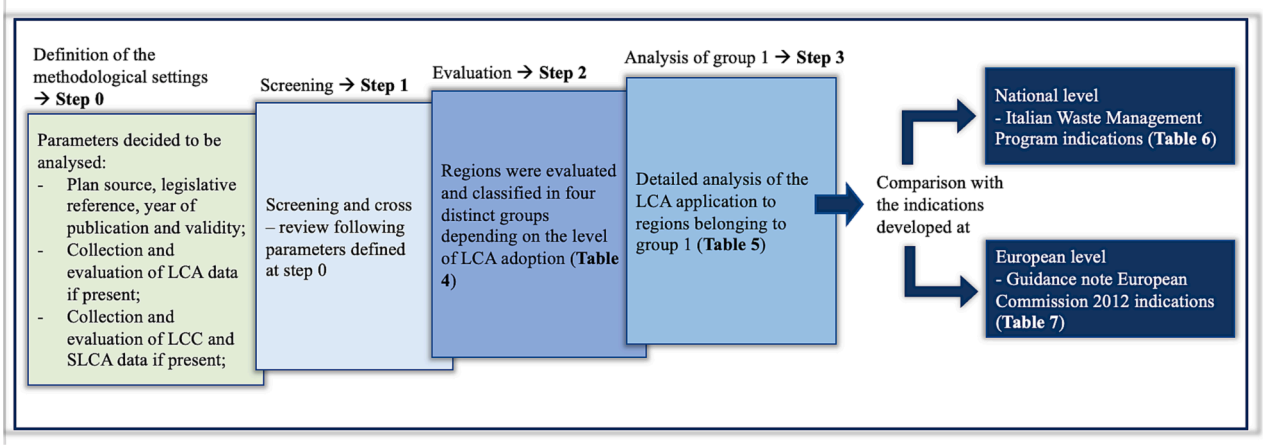

Fig. 1. Methodological approach.

Table 1
Overview of the criteria for the assessment of the 21 WMPs (Rigamonti et al., 2022).

Group	Definition	Characteristics
Group 1	Complete and site-specific LCA	1. The WMP considers LCA analysis as a base for regional plans 2. The WMP includes detailed information about the LCA studies used as a support tool for the plan drafting 3. LCA studies are conducted to support the WMP, considering assumptions and data consistent with territorial characteristics
Group 2	Simplified LCA	1. The WMP considers LCA analysis as a base for regional plans 2. The WMP includes detailed information about the LCA studies used as a support tool for the plan drafting 3. The LCA studies present simplifications that limit results consistency
Group 3	Generic reference of LCA	1. The WMP acknowledges the importance of LCA evaluations for medium - long-term planning and it considers the results and best practices derived from published LCA studies 2. Details on LCA studies are missing, and there is no a reference to specific territorial information and data
Group 4	No LCA	1. No LCA at all

summarized in Fig. 1.

Step 0: Methodological setting

First, the parameters to be analysed for each regional WMP have been defined, establishing the type of information to be gathered and the criteria for assessing the extent to which WMPs are supported by LCT studies.

The parameters were grouped into three different categories. The first category included information such as the source of the plan, the legislative references guiding its development, the year of its publication, and the duration of its validity. The second category collects data on LCA studies within these plans, if present. The assessment adhered to the ISO 14040 standard (ISO, 2006), considering the four key phases for conducting LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation. Additionally, regulatory guidelines set forth by the EC (EC 2021) were referenced, outlining the primary steps for Impact Assessment (IA): scenario definition, inventory analysis, consideration of policy objectives, solicitation of stakeholder feedback, evaluation of impacts, comparison of policy/decision-making options, and continuous monitoring and future evaluation. In the third category data on social and economic evaluations based on Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) methodologies were collected, if present.

Step 1: Screening

The first screening of WMPs was conducted verifying the criteria established in step 0: the results were appropriately recorded by each reviewer. All regional WMPs were then screened again, by different reviewers through a cross-reviewing process, applying the same criteria established in step 0: the results were recorded and compared with those obtained from the previous screening.

Step 2: Evaluation

The evaluations from the two screening phases were used to rank the regions according to the level of implementation of LCT methodologies in the relative WMP.

As regards LCA, the results of this phase lead to the creation of 4 groups (Table 1): WMPs that include a complete and site-specific LCA (Group 1), WMPs that include a simplified LCA (Group 2), WMPs that includes only a generic reference to the LCA methodology (Group 3), and WMPs where LCA is no present at all (Group 4).

The presence or absence of LCC or SLCA analysis was also reported for each region to have an overall picture of the LCT methodologies applied in the preparation of the WMP.

Step 3: Analysis of Group 1

The results were analysed following the research questions formulated. The regions in Group 1, that use a complete and site-specific LCA for their WMPs, were deeply examined. The completeness and consistency of all the LCA phases of the studies were evaluated according to the parameters established in step 0.

Table 2
Overview of the indications provided in the Italian WM Programme on how to conduct an LCA analysis.

LCA phase	General indications
Goal and scope definition	LCA should be applied to the whole waste management system, i.e. that takes into account all waste generated in the reference area. LCA applied to waste management requires an approach that extends the boundaries of the system to include material and energy recovery from waste and the resulting substitutions of raw materials and energy carriers. Knowing the waste composition is necessary to define the functional unit of the study and consequently also to define alternative management scenarios that are comparable with the existing situation.
Inventory	It is necessary to have up-to-date data on elements such as: – waste composition – number and type of collection containers, with an indication of which materials can be recovered at the end of the containers' life; – logistical facilities: Transfer Stations, Collection Centres; – vehicles, consumption and distances travelled to the first treatment plant and for subsequent transports; – existing treatment plants: type, number, capacity, energy consumption, scrap produced; – facilities used outside the region and destination of the resulting scrap; – biogas capture capacity of landfills. Data on the various plants already operating or whose inclusion in a system is to be evaluated: – type of technology adopted; – existing and planned capacity; – energy consumption; – energy carrier recovery capacity; – efficiency and scrap generated. Particularly relevant to define the effectiveness of strategies to support the CE is the uncertainty associated with the substitution values (offsets) that materials derived from waste offer towards virgin materials. Therefore, it is suggested to conduct studies in real operating plants to obtain accurate substitution values.
Impact assessment	No specific indications are given
Interpretation	It is suggested to present and discuss the results both with and without the inclusion of the avoided impacts from material and energy recovery.

Table 3
Overview of the correlation between the elements of the WMPs (European Commission EC, 2012), the possible use of LCA and the assessment criteria for evaluating WMPs.

Elements of a WMPs	Content (based on European Commission EC, 2012)	Possible link to the LCA	Related questions for evaluating WMPs / assessment criteria
General considerations and background	The general considerations and background part of the WMP includes considerations regarding the planning period and scope, boundaries, and the legislative framework of the EU	Goal and scope of the LCA analysis	Does the WMP include an LCA analysis?/ Does the WMP contain the following information on LCA: – Goal and scope definition? – LCA standards?
Status	The status part contains data, information, and consideration on the current situation in the waste management field	Inventory phase, Life Cycle Impact Assessment (LCIA) phase, results	Does the WMP include the following information on LCA: – Inventory phase? – LCIA? – Results? Does the mentioned information comply with the LCA standards?
Planning	Based on the previous parts, the determination of political objectives(e.g. for priority waste streams, definition of indicators for checking whether the objectives are met) and the way in which these objectives may be met most effectively are described	Interpretation phase	Does the WMP include information about the interpretation phase of the LCA? Does the interpretation phase include required elements under LCA standards? Have scenarios been developed to compare different options?
Implementation, monitoring, and plan revision	Following the adoption of the WMP, the orientations, initiatives, and the end of the planning period are described and scheduled	Recommendation from the LCA	Does the WMP include information about future orientations and revision based on an LCA study?

Step 4: Comparison with the indications developed at national and European levels

Two levels of comparison were subsequently developed, the first one analyses in which way the LCA could be useful to comply with indications set by the Italian WM Programme (details at 2.2) and the second one uses instead indications from the European guidance note (European Commission EC, 2012) to conduct a WMP (details at 2.3). Neither of the two documents refers to the economic and social evaluation of the view cycle.

2.2. LCA indications in the Italian WM Programme

On 24th June 2022, the new national waste management programme ("Programma nazionale di gestione dei rifiuti") was approved.[1] The programme, with a time horizon of six years (2022–2028), stands as one of the strategic and implementing pillars of the National Strategy for the CE together with the National Waste Prevention Programme and other policy instruments. It establishes the macro-objectives and defines the criteria and strategic guidelines that the regions have to follow in drawing up the WMPs. In accordance with Step 4 and taking advantage of the recent publication of this document, the Italian WM Programme was used as a reference tool to draw indications (Table 2) for good practices when performing an LCA study of WM systems. It was then checked if the WMPs already complied with these indications. This allowed the identification of the gaps still present in the different regional WMPs.

2.3. Preparing a WMP following the European guidance note

The methodological guidance note developed by the European Commission (European Commission EC, 2012) was used to derive indications at the European level on the development of a WMP. Table 3 provides an overview of the EC's indications on various elements, including general considerations and background, status, planning, implementation, monitoring, and plan revision. How LCA may offer practical instruments to comply with these indications has then been suggested and subsequently questions to be addressed while developing a WMP have been formulated (Table 3).

3. Results and discussion

3.1. Assessment and classification of the WMPs

Following steps from 0 to 2 of the proposed methodological approach, the WMPs of the Italian regions were classified in four groups depending on the level of LCA adoption. Results are shown in Table 4.

The Umbria Region, in addition to the LCA application for the environmental performance of its WMP, also reported a complementary economic assessment. For the remaining WMPs, no reference is made to analyses of the other dimensions of sustainability from an LCT

Table 4
Results of the classification.

Group	Regions
Group 1	Lombardia (Regione Lombardia, 2014), Friuli Venezia Giulia (Regione Friuli Venezia Giulia, 2012), Emilia-Romagna (Regione Emilia-Romagna, 2016), Umbria (Regione Umbria, 2009)
Group 2	Piemonte (Regione Piemonte, 2019), Toscana (Regione toscana, 2014), Puglia (Regione Puglia, 2013), Basilicata (Regione Basilicata, 2016)
Group 3	Autonomous region of Bolzano (Provincia autonoma di Bolzano, 2000)*, Molise (Regione Molise, 2015)
Group 4	Valle d'Aosta (Regione Val d'Aosta, 2015), Abruzzo (Regione Abruzzo, 2021), Autonomous region of Alto Adige, Veneto (Regione del Veneto, 2015)*, Marche (Regione Marche, 2015), Lazio (Regione Lazio, 2020), Molise (Regione Molise, 2015), Campania (Regione Campania, 2016), Calabria (Calabria, 2020), Sicilia (Regione Sicilia, 2018), Sardegna (Regione Sardegna, 2008), Liguria (Regione Liguria, 2015)

* For the Trentino-Alto Adige region, two plans were analysed: the plan of the autonomous region of Bolzano and the one of the autonomous region of Alto Adige. Together the two autonomous regions constitute the entire region.

[1] https://www.mite.gov.it/sites/default/files/archivio/allegati/PNRR/PNGR_Finale.pdf here the final version of the programme.

Table 5
Results of the analysis of WMPs in Group 1.

Region	Umbria	Emilia-Romagna	Friuli Venezia Giulia	Lombardia
Publishing year	2009	2016	2012	2014
Validity	Not specified	2014–2021	2012—2022	2014–2020
Functional unit	1 kg of municipal waste produced, collected, transported, treated, and finally disposed of in the different scenarios assumed by the proposed plan.	Amount of waste expected to be generated in 2020 in the Emilia-Romagna region, around 2,320,599 t.	Average amount of unsorted municipal waste and waste from separate collections produced in a year in the Friuli Venezia Giulia region.	Management of the amount of municipal waste produced and collected in Lombardia in 2009.
System boundaries	Cradle to gate	Cradle to gate	Cradle to grave	Cradle to gate
Scenarios	The LCA analysis compared two scenario phases: the first one analysed four possible end of life scenarios, the second one compared the baseline scenario to the best scenario resulting from phase 1 extending the boundaries to the collections and recovery of the different waste streams.	Four scenarios are compared: 1) The first one is based on a mixed energy recovery strategy with a fraction of unsorted waste sent directly to thermal treatment and a second fraction sent to mechanical pre-treatment (TM) and then to thermal plant. 2) The second one evaluates the construction of a new TM characterised by high efficiency in material recovery. 3) The third scenario adopts a waste management strategy that extensively applies pre-treatment of residual mixed waste, reducing the number of thermal treatment plants. 4) The fourth scenario assumes that all residual mixed waste is sent to incineration and does not envisage the use of mechanical pre-treatment.	Three scenarios related to trends in municipal waste generation, and three scenarios considering different waste management options have been elaborated: Evolutionary scenario 1: corresponding to a non-intervention in terms of waste prevention.Evolutionary scenario 2: stationarity of the generation (unchanged per capita compared to the 2011) . Evolutionary scenario 3: 12% reduction of per capita generation of to 2020. Scenario– 0 - no additional action implemented. Scenario– 1 - construction of a new secondary fluidised bed combustion plant.Scenario– 2 - modernisation of the three existing TM plants and construction of a new secondary solid fluid combustion plant.	Four scenarios are compared: 1) First scenario, which refers to the state of the art of the WM in Lombardia Region (year 2009); 2) Second scenario, Business As Usual (year 2020), with a separate collection level of 60.4%);3) Third scenario, which is based on a hypothesis of increase of separate collection (65%) ; 4) Fourth scenario, which is based on a hypothesis of further increase of separate collection (70%).
Software	SimaPro v. 7.1	WRATE - Expert version	SimaPro 7.1.0.	SimaPro 7.3
Type of data	Primary and secondary data	Primary and secondary data	Primary and secondary data	Primary
Database	BUWAL, Data Archive, ETH-ESU 96, IDEMAT and the ANPA I-LCA database	Ecoinvent v 2.1. and WRATE version Expert 3.0.1.5.	Ecoinvent Database 2.0	O.R.SO. (Osservatorio Rifiuti Sovraregionale)
Impact categories	Acidification, eutrophication, global warming (GWP100), ozone layer depletion, human toxicity, terrestrial ecotoxicity and photochemical oxidation.	100 - year GW global warming potential - climate change; Abiotic reduction potential; Acidification potential.	Damage categories: human health, ecosystem quality, resourcesImpacts: Carcinogens, Organic and inorganic substances that cause respiratory diseases if breathed in, Climate change, Stratospheric ozone layer depletion, Ionising radiation, Regional/local effects on vascular plants - land use, Acidification/eutrophication, Ecotoxicity, Energy surplus - mineral consumption, Energy surplus - fossil fuel consumption.	Cumulative Energy Demand, acidification, photochemical ozone formation, global warming, and human toxicity.

Table 6
Results of the comparison between Italian WM Programme indications and WMPs of Group 1 regions.

Goal and scope definition	Umbria	Emilia-Romagna	Friuli Venezia Giulia	Lombardia
Is the LCA applied to the whole waste management system?	NO	NO	NO	NO
The LCA extends the boundaries of the system to include material and energy recovery from waste and the resulting substitutions of raw materials and energy carriers?	YES	YES	YES	YES
Is the waste composition well known?	YES	YES	YES	YES
Is the waste composition up-to-date?	NO	YES Forecast to 2020	YES	YES
Inventory: it is necessary to have up-to-date data on elements such as:	**Umbria**	**Emilia-Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Number and type of collection containers, with an indication of which materials can be recovered at the end of the container life	NO	YES Production and cleaning of containers are included, but no indication on the end of life is given.	NO	NO Even if the type of collection containers is provided, no information on their quantity and end of life is provided.
Logistical facilities: Transfer Stations, Collection Centres	YES	YES	NO	YES
Vehicles, consumption and distances travelled to the first treatment plant and for subsequent transports	YES	YES	NO	YES
Existing treatment plants: type, number, capacity, energy consumption, scrap produced	YES	YES	YES	YES
Facilities used outside the region and destination of the resulting scrap	NO	YES	YES	YES
Biogas capture capacity of landfills	YES	YES	YES	YES
Inventory: Data on the various plants already operating or whose inclusion in a system is to be evaluated:	**Umbria**	**Emilia-Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Type of technology adopted	YES	YES	YES	YES
Existing and planned capacity	YES	YES	YES	YES
Energy consumption	YES	YES	YES	YES
Energy carrier recovery capacity	YES	YES	YES	YES
Efficiency and scrap generated.	YES	YES	YES	YES
Is the study conducted on operating plants?	YES	YES	YES	YES
Interpretation	**Umbria**	**Emilia-Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Does the interpretation of the LCA analysis show quantified values with and without the inclusion of the avoided impacts?	YES	YES	YES	YES

perspective.

3.2. Step 3: Analysis of Group 1

For Group 1 a detailed analysis was carried out. Table 5 depicts an overview of the key information on the documents (i.e., publishing year, validity), and on the LCA analysis (i.e., functional unit, system boundaries, scenarios, software, database, impact categories). First, a completeness and consistency check were performed, assuring that the studies developed followed the ISO Standard (ISO 14040). Following the compliance and coherence check, the results show that for all the LCAs the ISO standards indications are met.

3.3. Step 4: Comparison with the indications developed at national and European levels

The four regional WMPs of Group 1 have subsequently been assessed to see if they follow the Italian and European indications described respectively in sub-Sections 2.3 And 2.3.

Considering the indications presented in Table 2, it was found that the four WMPs include almost all the required information suggested in the Italian WM Programme, as summarised in Table 6.

In particular, all the regions did not apply the LCA to the whole waste management system, since bulky waste, waste from electrical and electronic equipment, street sweeping waste and other differentiated waste were not included. The main reason why some waste fractions have been neglected may be the high time requirement to carry out this type of study and the difficulty in obtaining primary data. Moreover, Umbria region didn't report up-to-date waste composition data, and Umbria and Friuli Venezia Giulia lacked information related to the type of collection containers. Friuli Venezia Giulia and Lombardia regions also did not report any information in relation to vehicle consumption and travelled distances.

Considering the indication at the European level (Table 3), it was possible to derive a further assessment on the characteristics of the LCA applied in the four WMPs. Results are reported in Table 7. The table answers to the indications derived from the European Commission Guidance note.

Table 7
Results of the comparison between the Guidance note European Commission EC, 2012 indications and WMPs of Group 1 regions.

Elements of a WMPs: General considerations and background	Umbria	Emilia - Romagna	Friuli Venezia Giulia	Lombardia
Does the WMP include an LCA analysis?	YES	YES	YES.	YES
Does the WMP contain the following information on LCA: -Goal and scope definition? -LCA standards?	YES	YES.	YES	YES
Elements of a WMPs: Status	**Umbria**	**Emilia - Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Does the WMP include the following information on LCA: -Inventory phase? LCIA? -Results?	YES A detailed paragraph was dedicated to the inventory analysis, explaining data characteristics and sources, databases and software used, graphical and tabular representation of input/output data. A paragraph was reported for the LCIA and results including a comparison discussion among the different scenarios proposed.	YES Information related to the inventory are provided. Three impact categories are selected but there is no reference to the characterisation method applied. The results are reported in a detailed way.	YES Detailed information related to the inventory and to the impact assessment are provided. Effective synthesis of results is reported.	YES Detailed information on inventory phase, LCIA and results are provided.
Does the mentioned information comply with the LCA standards?	YES	YES	YES	YES
Elements of a WMPs: Planning	**Umbria**	**Emilia – Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Does the WMP include information about the interpretation phase of the LCA?	YES A paragraph reported considerations based on the LCA results to further assess and design regional waste management.	YES The results of the different scenarios are compared, and some conclusions are drawn.	YES Detailed discussion of LCIA results is reported.	YES A short but exhaustive interpretation of the results is provided to support the waste management activities.
Does the interpretation phase include required elements under LCA standards?	YES	YES	YES	YES
Have scenarios been developed to compare different options?	YES	YES	YES	YES
Elements of a WMPs: Implementation, monitoring, and plan revision	**Umbria**	**Emilia – Romagna**	**Friuli Venezia Giulia**	**Lombardia**
Does the WMP include information about future orientations and revision based on an LCA study?	YES The LCA analysis was applied to identify the technological solutions with the best environmental performance to drive future decisions and strategies.	YES There is a list of strategic criteria and actions that indicate the direction to overcome over time the critical elements that each result brings to light.	YES	YES The LCA analysis identifies the technological solutions with the best environmental performance with a time frame of 11 years (from 2009 to 2020). The LCA analysis is used to guide strategies and future decisions.

3.4. Discussion

The classification of Italian regions, according to the level of LCA adoption, confirms that the implementation of LCT methodologies in WMPs remains a significant challenge. Only 4 regions have performed a complete and site-specific LCA to support the preparation of the WMPs. Moreover, just one region performed an economic evaluation whereas no region mentioned or applied SLCA. This result may be because, on the one hand, there are no legal requirements demanded at European, national, and regional level for incorporating environmental, economic, and social analyses into the development of WMPs. On the other hand, policymakers have difficulties understanding LCT methodologies and their potential applications and benefits on the ground. Furthermore, the lack of standardised practice to apply LCC and SLCA, also considering the relative novelty of the latter methodology, is another reason that explains why there are no references to specific studies or applications with primary data within the WMPs. Finally, the application of a complete and site-specific LCA to a WMPs is time-consuming, which may influence the will of decision-makers and be the reason why none of the LCAs in the WMPs included the whole waste management system. Bulky waste, e-waste, and batteries, for example, were never included.

The analysis of the WMPs that developed a complete and site specific LCA reveals significant variations in methodological choices. Functional units range from a single kilogram of waste disposed, to projections of total waste generated for a future year. It might be useful to define standardized functional units at the national and/or European level for conducting consistent analyses.

When addressing studies that depend on predictions of future waste generation, it is important to consider all potential factors that influence waste streams over time (e.g., changes in reuse, recycling, and collection rates). During the formulation of regional WMPs, it is essential to evaluate how waste compositions could potentially evolve over time, enabling the anticipation and mitigation of uncertainties. Future predictions should not cover excessively long time periods to minimize the uncertainty. Therefore, it is recommended to use shorter timeframes and implement dynamic analyses. These dynamic analyses can be adjusted over time to ensure that the results align with real-world waste management scenarios, making the process more reliable and adaptable.

Another thought-provoking aspect to consider that emerged from the study is how to deal with multifunctionality. In the majority of the LCAs conducted, multifunctionality has been addressed using the system expansion method with substitution. The recovery of secondary

resources must be modelled in accordance with technological advancements and the opportunities provided by the market for recovered materials to ensure alignment with achievable outcomes.

The impact categories analysed differ greatly in number, from 3 to 13, in the different LCAs. The definition of impact categories to be analysed should be standardized at the regulatory level to ensure consistent analyses at both national and European levels. Employing the same parameters in the development of LCA analyses (functional units, system boundaries, impact assessment methods) would improve the comparability of different regional plans, with the aim of implementing shared best practices and beneficial advancements across the entire sector. Therefore, it would be beneficial to establish common rules at European level for implementing LCT in the development of WMPs. These common rules would provide a body of knowledge to consolidate and standardise the methodological application.

4. Conclusions

The paper addressed a twofold objective: to analyse whether and how the LCT methodologies were applied to the development of WMPs in the context of the EU, and to propose a comprehensive framework to assess the adoption of LCT methodologies in the preparation of WMPs. More specifically, mainly LCA was observed and therefore analysed throughout the study. Results suggest that only 4 out of the 21 regional WMPs include a complete and site-specific LCA, and that the LCAs for these plans differ from one case to another by methodological settings. 11 WMPs do not consider at all LCA for the WM modelling, whereas 6 regions performed a simplified LCA or cited a generic LCA analysis with no references to the ISO 14040 series. Only one region included an economic evaluation in the WMP. No region includes social analysis in a life cycle perspective.

Even though almost all the LCAs developed for the WMPs in group one respect the proposed European and Italian indications, variations in methodological choices are present.

The five-step methodological approach could be used in similar European contexts, analysing the regional WMPs, to assess the degree of implementation of the LCT methodologies. Indications derived from European and Italian sources are not intended to be comprehensive or definitive. For this reason, the framework can be seen as a starting point for developing guidelines that provide detailed instructions on how LCA studies should be conducted during the preparation of a WMP.

In the discussion of the results, themes of comparison between different analyses have emerged that could provide an initial basis for standardizing the application of LCA in defining WMP. These specific insights, along with the indications provided, can be implemented to enhance the quality of LCA studies in the field.

Findings on the implementation of the LCC and SLCA highlight the necessity of consolidating methodological practices to enhance their application. Only through standardised, well-established, and widespread practices will it be possible to enable greater application of these methodologies.

For future research, it will be useful to focus on a broader context outside national borders. This will enable the assessment of potential discrepancies, the identification of different national guidelines, and potentially the development of harmonised suggestions that can contribute to enrich the proposed framework. Only through the integration of shared recommendations will it be possible to work towards developing robust guidelines to facilitate the application of LCA. Furthermore, the future analysis of LCC and SLCA studies in the sector will enhance the applicability of the methodological approach, enabling the inclusion of assessments regarding the social and economic dimensions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No primary or secondary data is used, as it is a literature review.

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