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Review

Green Roofs' End of Life: A Literature Review

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Abstract: Green roofs are increasingly being used in urban settings because of the many benefits they are capable of providing. Because of their widespread use, the issue of how to conduct proper disposal of green roofs once they have reached their end of life is beginning to be raised. The present study is a review of the scientific literature published between 2007 and 2022. Specifically, the contribution of this review study is to clarify whether a waste scenario exists and if so, identify the methodological frameworks and/or criteria used in green roof-related studies to establish the end-of-life scenario of a given green roof, which will then be used to analyze its environmental and economic performance. The literature analysis indicated that a standardized method, widely adopted, which allows identifying recovery and/or disposal treatments to be assigned to waste from the disposal of a green roof, is missing. In general, the feeling one gets from reading all these articles is that when it comes to the end of life of green roofs, everything is rather vague, and that one proceeds in no particular order. The main results of the study are a collection of the criteria currently proposed in the literature to identify the end-of-life scenario of green roofs. These essentially include predominant waste management practices in place in the country where the green roof is located, safety sheets of products constituting single layers of the green roof, and statistical data on the management of specific types of waste. The results also include an overview of the current body of knowledge related to the management of the end-of-life of these building components. This study also intends to serve as a starting point for opening a debate on the disposal of green roofs, a current hot topic and still open as it has not yet been codified. Finally, some recommendations for future research work in this field are proposed.

Keywords: green roof; end of life; disposal; recovery; environmental assessment; LCA

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1. Introduction

Green roofs are gaining in popularity because they are among the leading innovations that increase the performance of buildings and reduce their energy requirements. In this regard, it should be noted, indeed, that the building sector is responsible for a substantial part of the energy consumption of communities and performs an important mission for the quality of life of the population, providing building occupants with adequate levels of comfort and livability. The building sector has recently proven itself, in fact, to be responsible for 25–40% of the overall energy use [1–3], and CO_2 emissions associated with the energy use in this sector range from 17.5% to 39% of total carbon emissions at global, European, and Italian levels [4,5].

In this context, standards at the European level have been issued for improving energy efficiency in buildings [6]; the use of technologies such as green roofs—as well as, for instance, the use of natural fiber composites [7]—have been regarded with particular interest to improve building envelope performances as to achieve energy saving and environmental pollution reduction in the building sector.

There are many reasons for green roof popularity, including the fact that they are able to reduce thermal (electrical) loads for cooling buildings [8–16], which in turn, other than reducing the environmental impact of buildings [17], returns better indoor and outdoor comfort conditions to occupants [15,18,19], and also for the objective of building energy certification [20]. They also contribute to the reduction in the "Urban Heat Island" phenomenon [21–23] as well as improve the urban CO_2 balance due to their property of sequestering a significant amount of this greenhouse gas and improving air quality in cities [24–26].

Among the major types of green roofs, extensive green roofs dominate market share; in fact, this segment accounted for the largest share of the green roof market in 2020 and is expected to account for more than half of the total market share by 2027, specifically estimated to reach USD 3.6 billion in 2027 [27].

However, due to their broad deployment, waste generation in this area will increase significantly in the future, and attention will need to be paid to how to handle the waste deriving from these coverings, especially considering the possible impact of their disposal in municipal settings [28]. In other words, even if a green roof has a longer service life than a traditional roof (most studies mention a lifespan of 30–50 years [29]), someday all these plants, which exist and are bound to grow, will sooner or later come to the end of their lives and become waste for disposal. In light of this, the issue of how much the dismantling of green roofs impacts the environment becomes increasingly important. Answering questions such as "Will the waste from the green roof be dangerous to the environment?", "And if so, to what extent?" would allow an understanding of whether their current—and presumably future—large-scale implementation may pose a problem, despite the many benefits that these components can bring.

On the other hand, it would also allow for a full understanding of the actual environmental impact of this technology. Indeed, the real impact exerted by a product is better assessed throughout its entire life cycle, including its end of life.

Assessing the environmental impact of green roof disposal, i.e., a stratigraphic roofing system, clearly requires detailed knowledge, i.e., layer by layer, of the end-of-life treatments to which individual green roof components are and/or will be subjected (if the roof is still in existence). Unfortunately, the identification of these treatments (on which precisely the impact will depend) is complex to date [30]. One reason for this can be traced to the fact that by looking at green roof legislation, it emerges that there is currently a lack of ad hoc technical standards from which to derive useful guidance on the disposal of green roofs and especially on the treatments to which individual green roof components should be sent at the end of their life. To the best of the authors' knowledge, no such guidelines have been issued internationally either, which could have been a useful comparative reference. This is probably because green roofs are a technology that has become particularly attractive in relatively few years and is characterized by a longer service life than that of a traditional roof (as previously stated); therefore, the need to regulate its disposal has not yet arisen. Such a circumstance is totally at odds with the production, installation, and maintenance phases of green roofs, for which both internationally recognized guidelines, namely the FLL guidelines [31] and nationally valid technical standards and regulations, have been issued [32–37].

The question that arises is whether it is possible to trace widely applicable standard methodological frameworks for defining such green roof waste treatments within the currently available research on the environmental (as well as economic) performance of green roofs.

To achieve this goal, this study reviews the published literature related to the environmental and economic performance of green roofs, particularly that dealing with their dismantling. Specifically, the present authors adopted a three-step approach, which consisted of the following steps: selection of articles (step 1), analysis and discussion of the selected articles (step 2), and conclusions and recommendations for future work (step 3). These three steps are described in Sections 3–6, respectively.

Before going into the details of each step of the adopted approach, a description of the technological system underlying this type of coverage is provided in the next section, as it is functional for a better understanding of the results of the literature analysis conducted by the present authors.

2. Green Roofs: System Description

Generally speaking, a green roof is a type of roof that incorporates vegetation planted on a layer of growing medium. In this section, the present authors focus on describing the types of existing green roofs, the layers that make up a typical green roof, and the materials commonly used to make each layer.

2.1. Greenery Typologies

In general, two main types of green roofs can be distinguished: intensive and extensive green roofs. However, some authors also consider an additional type, namely, semi-intensive. This classification is mainly based on substrate thickness, maintenance intensity, cost, and the type of vegetable species planted.

In the case of intensive green roofs, the substrate thicknesses are generally not small (more than 15–20 cm), different types of plants are planted, and they are characterized by high costs (USD 25 per square foot) and high weight (180–500 kg/m^2). Extensive green roofs are characterized by thinner substrate thicknesses (less than 15 cm) and lower weight than intensive green roofs. Only certain types of plant essences, including grasses, mosses, and a few succulents, can be planted; this is mainly due to the low substrate thicknesses [38]. In more detail, regarding vegetable species, Sedum, possibly because of its strong adaptive skills, is widely used in extensive green roofs, while in intensive ones, larger vegetation such as shrubs and small trees are also used [39].

2.2. Common Layers and Material Types for Individual Roof Layers

A green roof is a stratigraphic system, thus composed of a succession of layers, which are simply superimposed. Regarding the structure of a green roof installed on continuous roofs of varying shape and pitch, the number of layers may vary from case to case, as well as their arrangement, depending on the type and complexity of the roof. Figure 1 illustrates a typical sequence of layers of a green roof.

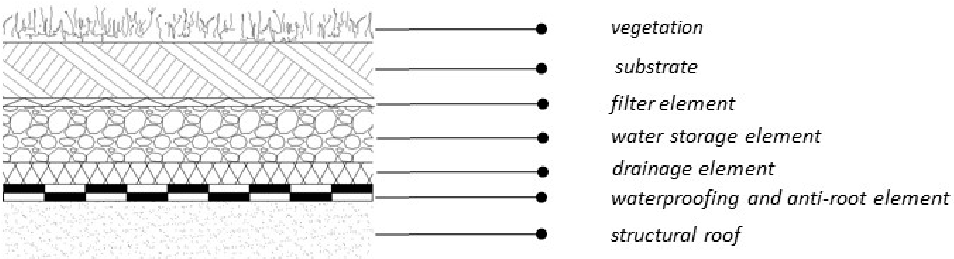

Figure 1. The different layers of a standard green roof.

Sometimes two different layers perform the functions of sealing against water and protecting against root action. The role of the root barrier is to protect the sealing element and the underlying roof structure from plant roots entering from the overlying layers; roots indeed could mechanically break down and chemically change the sealing element [38]. In general, in green roofs, each layer must perform a certain function, which is necessary for the proper functioning of the green roof itself. In addition, it should be mentioned that this type of covering is a complex system because it is not a simple assembly of elements in which these elements are independent of each other; for example, the close relationship between the choice of the type of vegetation and the thickness of the substrate to be adopted should not be overlooked, as well as the fact that the thickness of the water storage layer depends greatly on the water demands of the chosen plant essences [40] and also on the water retention potential of the growing substrate [39]. It should be noted that each layer has its own design criteria, which are generally defined in the green roof design and construction standards. In this regard, the case of UNI11235 [33], which is the normative reference, at the Italian level, for the design, construction, and maintenance of green roofs, is presented as an example. Within it, in fact, there is a section specifically devoted to designing the layers that are generally found in a green roof.

Table 1 shows the corresponding requirements for each layer of Figure 1, except for vegetation and the structural roof.

Table 1. Requirement and commonly used materials for the single layers of a standard green roof.

Layers of a Standard Green Roof (Figure 1)	Requirement	Material Types
Substrate	To promote and maintain over time the agronomic conditions necessary for proper vegetation development according to the context.	This element is a mixture of inert porous minerals (such as lapillus, pumice, and expanded clay) and organic materials (such as compost and peat) [39]. In these mixtures, the inert fraction accounts for 50% to 90% of the soil volume [38].
Filter element	To prevent fine-grained materials contained in the cultivated layer and transported by water from obstructing the underlying layers.	This layer is generally made of a geotextile composed of polymeric materials [38,39], but it can also be made of granular aggregates [33,38].
Water storage element	To accumulate water during rainfall or irrigation and release it later during times of need.	The materials normally used for this layer are granular aggregates or preformed plastic elements [33].
Drainage element	To drain excess water of meteoric origin or from irrigation, avoiding pore saturation that may prevent appropriate root oxygenation.	The materials normally used for this layer are granular aggregates, prefabricated plastic elements, or geosynthetic materials [33,39].
Anti-root element	To protect the roof from potential root action	Root barriers are usually made of bitumen or PVC membranes. However, other polymeric membranes can also be used [39].
Waterproofing element	To protect the roof from potential water infiltration	Materials normally used for this layer are bituminous or PVC elements. Synthetic rubbers can also be found, such as ethylene propylene diene monomer (EPDM) and styrene-butadiene-styrene (SBS) [39].

In addition, since the fate of a green roof, once it must be removed, depends largely on the materials that make up the individual elements; material types commonly used to make up each layer are also indicated in Table 1.

For the structural roof, its requirement is to support the entire sequence of layers, while as for the vegetation, it should be noted that the choice of vegetable essences to be planted depends mainly on the climatic and spatial context, generally preferring native species because this ensures chances of survival. The choice also depends on the specific objectives of the project.

3. Methodology for Selecting Literature

The literature search was conducted using databases such as Scopus and Web of Science (WOS) to find articles on green roof disposal. The following terms were included in the literature search string for papers: "green roof and disposal", "green roof and life cycle", or "green roof and end-of-life". Articles' titles had to contain the words in the string. The search was conducted in October 2022, and there were no limitations on the year of publication, search field, or article type.

After eliminating duplicates, this study collected 27 scientific articles essentially dealing with the life cycle assessment of green roofs from both environmental and economic perspectives, published from 2007 to 2022. These articles were published as peer-reviewed scientific papers in peer-reviewed journals, conference proceedings, and book chapters.

Among these, five articles were excluded because they were not retrievable (first screening). The result was that only 22 articles were included in the analysis.

Among these 22 articles, two review articles and twenty original research articles published in journals and conference proceedings were identified. A second screening was then performed on the latter group to remove irrelevant articles that did not meet the objectives of the present study. In particular, because this review explores the disposal phase of green roofs, studies that only deal with the life cycle of the green roof without making a distinction between the different phases (this is the case of 3 articles out of 20) and articles that, although making a distinction among phases, do not include the disposal one among the phases analyzed (this is the case of 5 articles out of 20) were excluded; the same was performed for articles that address the issue of green roofs in terms of the entire building (this is the case of 1 article out of 20).

Finally, only 13 papers out of 22 were thoroughly studied. Figure 2 illustrates the process of selecting articles for inclusion in this review work.

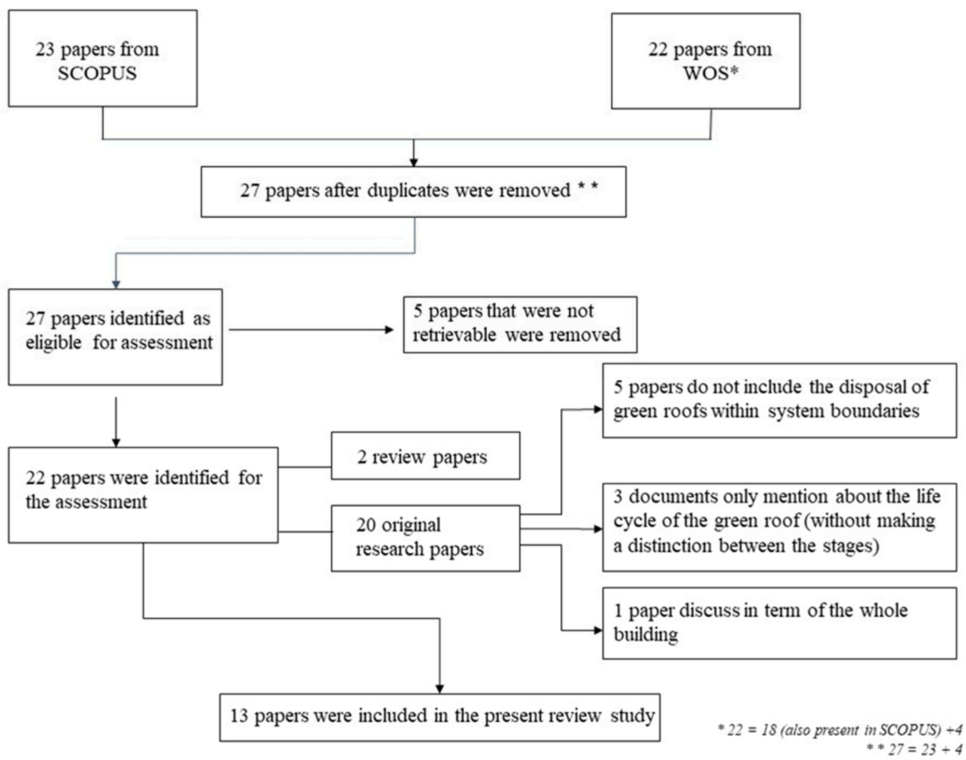

Figure 2. Selection of papers for the literature review.

In order to analyze systematically, we classified the 13 articles according to publication type (review or original research) and editorial placement (journal proceedings or conference). The results are shown in Table 2.

Table 2. Summary of the publication types and editorial collocation, i.e., journal or conference proceedings, of 13 papers thoroughly analyzed in the present work.

Article Type	Total	International Conference Proceedings	International Scientific Journal
Original research article	11	2	9
Review article	2	-	2

Table 3 provides general information on the eleven original research articles; specifically, for each of them, it gives the aim of the study, the methodology used, and the country to which the study refers.

Table 3. General information on the eleven analyzed original research articles dealing with the end-of-life of green roofs.

Article Code Assigned Here	Reference (in Chronological Order)	Study Contribution	Methodology	Country
1	Kosareo and Ries [41]	The study compared the environmental performance of three roof types, namely, a conventional ballasted roof, an extensive green roof, and an intensive green roof.	LCA	USA
2	Peri et al. [42]	The study evaluated the life cycle cost of an extensive green roof. The analysis covered the green roof disposal costs.	LCC	Italy
3	Peri et al. [43]	The study evaluated the potential environmental impact of the life cycle of an extensive green roof. The analysis included the whole life cycle of the substrate.	LCA	Italy
4	Lamnatou and Chemisana [44]	The study explored the opportunity to combine the use of green roofs with photovoltaics (PVs). Specifically, the study compared the environmental performance of five roof configurations: (1) gravel (reference case), (2) PV-gravel, (3) extensive green roof (Gazania), (4) PV-green (extensive: Gazania), (5) intensive green roof (with shrubs and small trees).	LCA	Spain
5	Rincon et al. [45]	The study investigated the potential environmental benefits of using recycled materials for the drainage layer of extensive green roofs. Specifically, the use of recycled rubber crumbs was evaluated against the use of natural pozzolana volcanic gravel (i.e., a conventional material).	LCA	Spain
6	Gargari et al. [46]	The study evaluated the change in overall building impact when extensive or intensive green roofs replace the standard pitched roof. The study focused on warm climates.	LCA	Italy
7	Bozorg Chenani et al. [47]	The study compared the potential environmental impacts of the different layers of two lightweight green roof systems.	LCA	Finland
8	Lamnatou and Chemisana, [48]	The study explored the opportunity to combine the use of green roofs with photovoltaics (PVs). Specifically, the study compared the environmental performance of six roof configurations: gravel roof, PV gravel roof, PV-bitumen roof, extensive green roof, (4) PV-green roof (extensive), (5) intensive green roof, (6)	LCA	Spain
9	Sangakoool et al. [49]	The study evaluated the life cycle costs of a specific type of green roof, i.e., air plant green roofs, and compared them with those of intensive and extensive green roofs.	LCC	Thailand
10	Vacek et al. [50]	The study analyzed the environmental performance of semi-intensive green roofs (SIGRs), specifically comparing four SIGR assemblies, two with intensive substrates and two with extensive substrates, below which hydrophilic mineral wool panels are placed.	LCA	Czech Repub-lic
11	Pushkar [51]	The study investigated the potential benefits of replacing natural perlite with industrial byproducts, coal bottom ash (CBA), and fly ash-based aggregates (FAAs) in the substrate and drainage layers of extensive green roofs.	LCA	Israel

The two review articles shown in Table 2 are the work conducted by Shafique et al. [29] and that by Scolaro and Ghisi [39]. These two articles—precisely literature reviews—were reviewed with the intention of tracing any additional articles concerning the topic of green roof disposal, which had escaped the selection process operated according to the scheme in Figure 2.

In more detail, Shafique et al. [29] identified 27 articles dealing with the life cycle assessment of green roofs. In addition to investigating the temporal evolution of green roof LCA studies and the geographic distribution of publications, the contribution of the review is to compare the studies with respect to life cycle inventory, impact categories evaluated, and life cycle stages. Regarding the latter, the researchers provide an overview of the life cycle stages considered by these existing LCA studies (considering that the article was published in 2020). The analysis shows that only 14 out of 27 articles take the cradle-to-grave approach; that is, they include the end-of-life phase of the green roof.

Therefore, the present authors analyzed these 14 studies individually. Among them, they found that the number of articles that actually address the disposal of green roofs is less than 14; it is 10 instead. In fact, four studies do not include the disposal phase in their analysis.

In any case, seven of these ten articles had already been identified through the scheme illustrated in Figure 2. Therefore, only three articles were added to the list of those to be reviewed for the purpose of the present work, namely those carried out by Angelakoglou et al. [52], Dabbaghian et al. [53], and Brachet et al. [40].

Scolaro and Ghisi [39] reviewed the LCA studies on green roofs in the literature (the article was published in 2022) with the main objective of comparing them with respect to six topics, including the materials used and processes dealt with at each stage of the life cycle, as well as the strategies adopted to limit the impact of green roofs on the environment and the methods implemented to assess the economic viability of green roofs during their life cycle. Among the articles dealing with disposal cited by the authors, only one, namely the study by Kim et al. [54], is in addition to those selected according to the scheme in Figure 2.

Therefore, ultimately from the two review articles, 4 (=3 + 1) papers were identified that escaped the selection method illustrated in Figure 2.

Table 4 provides general information on the above-mentioned four extra original research articles, especially for each study; as Table 3, it gives the aim of the study, the methodology used, and the country to which the study refers.

Table 4. General information on the four extra studies dealing with the end-of-life of green roofs identified through the two review papers.

Reference (in Chronological Order)	Study Contribution	Methodology	Country
Angelakoglou et al. [52]	The study compared the environmental performance of four flat roofing alternatives, namely: the gravel ballasted roof, the green roof, the ventilated covering, and the insulated false ceiling.	LCA	Greece
Dabbaghian et al. [53]	The study compared the sustainability performance of three roofing systems: an intensive green roof, an extensive green covering, and a gravel ballasted roof.	Fuzzy-Analytical Hierarchy Process (FAHP)—LCA	Canada
Brachet et al. [40]	The study compared the performance of four roofing options with the aim of identifying the roof type that least produces biodiversity loss. The roof options investigated are a conventional roof, an extensive green roof, a semi-intensive green roof, and an intensive green roof.	LCA	France
Kim et al. [54]	The study addressed the issue of using green roofs for urban farming. In detail, it investigated the economic and environmental costs of two green roof options (i.e., a garden and a farm) and a conventional flat roof. In addition, the study examined how green roofs are perceived by individuals along with their preferences.	LCC and LCA	Korea

Therefore, ultimately the articles taken into consideration in this review study were 15 (=11 +4).

4. Results of the Literature Review

4.1. Original Research Articles

The present authors analyzed the previously mentioned studies with the main objective of identifying assumed end-of-life scenarios for green roofs, and attention was paid to any considerations made by the researchers on this life cycle phase to understand the present body of knowledge related to the management of the end of life of these building components. In addition, specific focus was placed on any methodological framework or criteria used by researchers to define such waste scenarios.

The following emerged: in the study conducted by Kosareo and Ries [41], despite the article stating that disposal of end-of-life materials is included in the analysis, it does not state disposal and/or recovery treatments for individual green roof elements. Peri et al. [42,43] assumed the following waste treatments for the case study: the substrate and bitumen are supposed to be sent to the sanitary landfill (that is, landfill for municipal solid waste); the expanded perlite goes to an inert landfill. Plastic materials, namely HDPE, PP, and PET, go to an incineration plant with energy recovery. Lamnatou and Chemisana [44] hypothesize the following waste scenario: asphalt, plastics, and bitumen are assumed to go to a chemical landfill; the soil substrate is hypothesized to be reused in agriculture, while plants are expected to be composted. The manner in which the scenario has been established is actually not very clear since researchers only state: "landfill is considered as the mainstream waste management for most of the materials. For the disposal of materials for which there are no available data, similar materials are considered". The waste scenario hypothesized by Rincon et al. [45] is as follows: rubber (as well as pozzolana) is supposed to go to recycling, while asphalt goes to a sanitary landfill. The assumed treatment for the substrate and plants is composting. Gargari et al. [46] assume that the substrate is to be disposed to a sanitary landfill, while HDPE (filter layer), EPS (drainage), and bitumen (root barrier) go to municipal incineration. Concerning the waste treatment for substrate, researchers state that "there are no regulations regarding the reuse of green roof soils in agriculture" and recall what was declared in the study conducted by Peri et al. (2012) [43], namely "incineration is excluded because a large amount of inert and the sanitary landfill is the only waste processing available due to the potential/real presence of peat". However, researchers express the complexity of defining the end-of-life scenario mainly because, on the one hand, the Waste European Catalogue does not contain most of these materials and, on the other hand, data on operations such as collection, treatment, recycling, and reuse of construction materials in Tuscany (where the study takes place) are missing. This being the case, researchers state that the hypothesized waste treatments have been defined based on the actual market framework near Pisa and have been sourced from a degree thesis. The waste scenario hypothesized by Bozorg Chenani et al. [47] is as follows: 50% of all layers (except substrate) is recycled, and 50% is incinerated. However, no specification is given for individual materials. The substrate is expected to go to a landfill. Researchers express the difficulty of finding data about the disposal phase for green roofs because of their long lifespan and state the following: "Information about the end of life of different layers should be gathered from product safety data sheets from manufactures, but we could not find such data. Thus, we chose a reasonable waste treatment from literature and used that in our analysis". However, the article does not mention the previous studies referred to for achieving the purpose of the study. Lamnatou and Chemisana [48] assumed that landfill was appropriate for each considered material. Concerning substrate and vegetation, it is stated: "Plants are supposed to be composted while substrate is supposed to be reused in agriculture". Sangakoool et al. [49] declared the following: "The main costs of disposal or recycling of green roof includes disposal growing mediums, transportation materials, plant demolition". In the case of air plant green roofs, no waste scenario is actually depicted since, as researchers state, in this green roof typology, soil or substrate are not necessary, and the vegetable species, namely "Cotton Candy" and "Spanish moss", may be reused. In the study conducted by Vacek et al. [50], all green roof materials are expected to be landfilled. This green roof waste scenario considers information provided by the Prague Environmental Information Agency; the latter states that reuse (e.g., for landscaping) and landfilling are the treatments to which most of the waste generated in the Czech Republic is sent. In the study performed by Puskar [51], all materials in both the substrate and drainage layers (perlite, CBA, and FAAs) are sent to a landfill. As researchers claim, this assumption is based on the management practices for construction and demolition debris (CDB) that are currently implemented in Israel. Specifically, researchers state that nearly 70% of all CDB is sent to landfills in Israel.

Table 5 summarizes the above, specifically illustrating for each study the end-of-life (EoL) scenario hypothesized for the considered green roofs.

As can be seen from Table 5, several different waste scenarios (to which different impacts clearly correspond) have been proposed in the literature, from which it follows that the ways in which a green roof can be discarded appear to be quite varied. This variety probably stems both from the wide variability in terms of materials used, which in turn depends on design options, and from the different waste management methods employed in different states.

In Table 6, a comparison of the above-mentioned studies regarding the presentation of a criterion/procedure to identify the proposed scenario is presented. In addition, the table provides a summary description of the selection criteria adopted.

Table 5. Waste treatments assigned to each layer of the considered green roofs in the eleven analyzed LCA and LCC studies (ND = not declared in the article; - = not present in the considered green roof options).

	Material Types						
Article Code Assigned Here	**Waterproof Layer**	**Root Barrier**	**Water Storage Layer**	**Drainage Layer**	**Filter Fabric**	**Substrate**	**Vegetation**
1	Bitumen	-	-	HDPE	HDPE	ND	ND
EoL scenario	**ND**	**-**	**-**	**ND**	**ND**	**ND**	**ND**
2	Bitumen		Expanded perlite within pillows, the nonwoven geotextile whose pillows are made of, is in PET.	HDPE geo-net heat bonded to a polypropylene nonwoven geotextile	-	Mixture of lapillus, pumice, zeolithe, peat, compost, and NPK slow-releasing fertilizer (substrate).	ND
3							
EoL scenario	**Landfill**		**Landfill/ Incineration**	**Incineration**	**-**	**Landfill**	**ND**
4	Bitumen	-	-	HDPE	HDPE	ND	Gazania in the extensive system, while shrubs/small trees are in the intensive system.
EoL scenario	**Landfill**	**-**	**-**	**Landfill**	**Landfill**	**Reuse in agriculture**	**Composting**
5	Asphalt	-	-	Recycled rubber crumbs or pozzolana volcanic gravel	-	ND (Only product commercial name and layer thickness are given).	Sedum, Lampranthus, and Delosperma.
EoL scenario	**Landfill**	**-**	**-**	**Recycling**	**-**	**Composting**	**Composting**

Table 5. *Cont.*

	Material Types						
EoL scenario	**-**		**50% of all layers go to recycling and 50% to incineration**			**Landfill**	**ND**
8	Bitumen	-	-	HDPE	HDPE	The complete composition of the substrate is not given in the article; it is only stated that it is based on clay.	Shrubs and small trees are for the intensive green roof, while seeds are for extensive green roofs.
Article Code Assigned Here	**Waterproof Layer**	**Root Barrier**	**Water Storage Layer**	**Drainage Layer**	**Filter Fabric**	**Substrate**	**Vegetation**
6	-	Bitumen	-	Expanded polystyrene "EPS"	HDPE	Mixture of pumice, lapillus, zeolite, and peat; a mix of pumice, lapillus, and compost; or a mix of expanded clay, recycled bricks, and compost (substrate).	Sedum in extensive and intensive, grass in intensive
EoL scenario	**-**	**Incineration**	**-**	**Incineration**	**Incineration**	**Landfill**	**ND**
7 *	-	LDPE or PVC	Recycled textile fibers or Rockwool -Grodan	Recycled polystyrene "recycled HIPS" or virgin polystyrene "virgin HIPS"	Nonwoven "PP" lighter or heavier	Mix of expanded clay, crushed brick, and compost or a mix of compost, sand, and pumice	ND
EoL scenario	**Landfill**	**-**	**-**	**Landfill**	**Landfill**	**Reuse in agriculture**	**Composting**
9	No information has been provided concerning the composition of air-plant green roofs						Cotton Candy and Spanish moss
EOL scenario	**-**						**Reuse**
10 **	Bitumen		Hydrophilic Mineral Wool "HMW" panel (water	HDPE	PP geo-textile	ND It is only stated "intensive substrate" and "extensive substrate"	ND it is only stated that all SIGR assemblies share the same thickness of this layer.
EoL scenario	**Landfill**		**Landfill**	**Landfill**	**Landfill**	**Landfill**	**ND**
11	Bitumen		Perlite or FAAs		ND	Mixture of perlite and compost or a mix of CBA and compost.	ND
EoL scenario	**Landfill**		**Landfill**		**Landfill**	**Landfill**	**ND**

* A protection layer made of nonwoven polypropylene lighter or heavier is also present; ** A protection and separation layer made of polypropylene geotextile is also present.

Table 6. Comparison among the eleven LCA and LCC studies with respect to the delivery of criteria and/or procedures to define the presented EoL scenarios of green roofs ND = not declared in the article).

Article Code Assigned Here	Is an EOL Scenario Provided for Green Roofs?	Is a Procedure Provided to Determine the EOL Scenario Presented?	Criterion/Procedure Description
1	NO *	NO	-
2	YES	YES	The waste scenario presented has essentially been defined based on (a) the predominant waste treatment practice in the Italian context, especially in the southern regions; (b) the current Italian legislation regulating the reuse of a product in agriculture and waste admission in landfill; (c) the information provided in the safety sheets of individual products constituting the case-study; and (d) considerations on material types.

Table 6. *Cont.*

Article Code Assigned Here	Is an EOL Scenario Provided for Green Roofs?	Is a Procedure Provided to Determine the EOL Scenario Presented?	Criterion/Procedure Description
3	YES	YES	The waste scenario presented has essentially been defined based on (a) the information provided in the safety sheets of individual products constituting the case study, (b) interviews with experienced waste management consultants, and (c) considerations on material types.
4	YES	NO	-
5	YES	NO	-
6	YES	YES	The waste scenario presented has supposedly been defined by referring to (a) regulations regarding the reuse of green roof soils in agriculture, (b) the previous literature, (c) the real market contest near Pisa (Tuscany), and (d) a work reported within a degree thesis.
7	YES	YES	The waste treatments were chosen from the previous literature. However, no references are given on purpose.
8	YES	NO	-
9	NO	NO	-
10	YES	YES	The waste scenario was defined based on the information provided by the Environmental Information Agency of Prague regarding waste management practices commonly adopted in the Czech Republic.
11	YES	YES	The waste scenario was defined based on the currently accepted Israeli construction and demolition debris landfilling practices.

* Although the disposal stage is included in the analysis, no disposal scenario is given in the article.

4.2. Extra Original Research Papers Identified through the Review Papers

As earlier, the present authors analyzed the extra four studies identified through the review papers with the main objective of identifying assumed end-of-life scenarios for green roofs, and attention was paid to any considerations made by the authors on this life cycle phase. In addition, specific focus was placed on any methodological framework or criteria used by researchers to define such waste scenarios.

The following emerged: in the study of Angelakoglou et al. [52], disposal scenarios of waste from the construction of the green roof were detailed, as opposed to those related to the waste from the dismantling of the green roof. However, it seems that the demolition waste goes partially to landfill and partially to the recycling process. Waste treatments for each individual element are not explicitly stated. In the study carried out by Dabbaghian et al. [53], it was declared that the end-of-life stage is included in the analysis. However, no information on the assumed waste treatments for the individual green roof elements is given in the article. In addition, it is claimed that the end-of-life scenarios were defined based on the available literature, which in any case, is not even stated. Brachet et al. [40] referred to European statistics concerning the management of plastic waste, based on which this type of waste is generally incinerated at 42%, recycled at 31%, and landfilled at 27%. Regarding inert construction products, the researchers consider data on recycling (65 percent) and landfilling (35 percent) from a National Union of Quarry and Construction Materials Industries (UNICEM) report on the recovery and recycling of inert construction products. Based on this information, it can be inferred that assumed waste treatments for plastic materials of the considered green roof options probably cover incineration, recycling, and landfilling (according to that shares) and that the waste treatments assigned to substrate include recycling and landfilling (in that proportion). However, such a waste scenario is not explicitly provided in the article; therefore, these are only assumptions made by the present authors based on the information given in the article. They declare explicitly only the waste treatment for vegetation, namely composting. Kim et al. [54], similarly to Dabbaghian et al., did not provide information on the disposal scenario hypothesized, despite their state to include the disposal of the system components directly related to the construction of green roofs in the analysis. The authors also state as follows: "the disposal cost, which includes the removal, hauling, and disposals of roof garden materials, such as the lightweight soil and concrete block, was calculated based on the general waste disposal costs in Korea set by the Korea Recycled Construction Resources Association".

Table 7 summarizes the above, specifically illustrating the end-of-life scenario hypothesized for the considered green roofs for each study.

Table 7. Waste treatments assigned to each layer of the considered green roofs in the four analyzed LCA and LCC studies (ND = not declared in the article; - = not present in the considered green roof options).

Bibliographic Citation	Material Types						
	Waterproof Layer	**Root Barrier**	**Water Storage Layer**	**Drainage Layer**	**Filter Fabric**	**Substrate**	**Vegetation**
[52] *	Bitumen	-	-	Polystyrene sheet	Polyethylene	Perlite	ND
EOL scenario	**Demolition waste goes partially to landfill and partially to the recycling process.**						
[53]	-	Non-rotting PP fibers or PP	-	Recycled polyethylene or polystyrene waffled panels	Non-rotting thermal consolidated PP or micro-perforated PP	ND Growing medium for semi-intensive green roofs or growing medium for extensive green roofs is only stated.	Drought-resistant plants and Sedum.
EOL scenario	**-**	**ND**	**-**	**ND**	**ND**	**ND**	**ND**
[40] **	-	Polyethylene	Rock wool—Grodan	Polystyrene foam slab	Polypropylene	Expanded clay, crushed brick, and compost.	Sedum, Grass seeds, Centaurea Montana, Shrubs
EOL scenario	**-**	**ND**	**ND**	**ND**	**ND**	**ND**	**Composting**
[54] ***	Bitumen	-	-	Fiberboard	-	ND Only the thickness is given.	Red poppy (Papaver rhoeas) and potatoes (Solanum tuberosum)
EOL scenario	**ND**	**-**	**-**	**ND**	**-**	**ND**	**ND**

* Extruded polystyrene is also present; ** A polypropylene protection layer is present; *** Wire mesh is also present.

In the same way as Table 6, Table 8 presents a comparison of the studies regarding the presentation of criteria and/or procedures to identify the proposed scenario.

Table 8. End-of-life (EOL) scenarios of green roofs and criteria/procedures to define the presented EOL scenarios, reported in the four selected review papers (ND = not declared in the article).

Bibliographic Citation	Is an EOL Scenario Provided for Green Roofs?	Is a Procedure Provided to Determine the EOL Scenario Presented?	Criterion Description
[52]	YES	NO	-
[53]	NO	YES	Waste treatments were defined based on available pertinent literature. However, no references are given on purpose.
[40]	YES *	YES	The waste scenario presented was defined based on European plastics production, demand, and waste data, and also data from the National Union of Quarry Industries and Building materials (UNICEM) on the recovery and recycling of inert construction products.
[54]	NO	NO	-

* Waste treatment is clearly stated only for vegetation. The remaining elements can be inferred based on some information given in the article.

5. Discussion

The study presented here stems from the consideration that, to date, there are no guidelines or technical standards to assist a technician when they are tasked both to deal with dismissing a green roof and accessing the environmental impact of this phase of the life cycle of green roofs. This research has thus been performed with the precise aim of investigating the availability in the literature of either standardized procedures or criteria to define the end-of-life scenario of green roofs to be used for the analysis of these building components.

The literature review highlights some definition criteria adopted by researchers; these particularly include predominant waste management practices in place in the country where the green roof is located (this is the case reported, e.g., by Vacek et al. [50] and Puskar [51]) and statistical data, at the European level, on the management of specific types of waste (this is the case reported by Brachet et al. [40]). Moreover, these include safety sheets of products constituting single layers of the green roof and interviews with experienced waste management consultants, and considerations on material types are adopted for this purpose (this is the case reported in [42,43]).

However, it should be noted that as clearly illustrated in Tables 6 and 8, only a few studies clearly state the manner in which waste treatments were identified; in most cases, only the end-of-life scenario of the green roof is provided, and sometimes, it is not even explicitly described. Some researchers then, in describing how individual waste treatments were defined, refer to the "available literature", but no references are purposely provided. In general, the feeling one gets from reading all these articles is that when it comes to the end of life of green roofs, everything is rather vague.

The present review study also signals another aspect, which is the fact that in the current literature, a standardized method that allows identifying recovery and/or disposal treatments to be assigned to the waste from the disposal of the green roof is missing; the feeling one gets is rather that one proceeds in no particular order.

The uncertainty about the treatments, which will be applied to waste at end-of-life, deriving from the absence of ad hoc technical standards and current practice, as well as the absence of a methodological framework commonly adopted by the scientific community to identify such treatments, contributes to making the task of estimating the environmental impact of this phase of green roofs' life cycle rather complex.

A criticality emerges from this situation, which essentially refers to the fact that a technician tasked to assess the environmental impact of this technology, might be:

- Discouraged from including this phase in the analysis. Not including this phase in the analysis, in turn, could make their assessments too imprecise to be useful. Therefore, neglecting this phase in the analysis will not allow for applying the LCA methodology in an appropriate way to reach a more realistic image of the environmental impact of a green roof;
- Discouraged from selecting this technology among potential design or upgrading options. Consequently, they might be directed to adopt other types of roofs for which more and more appropriate data are available instead.

Clearly, further and more in-depth studies and a significant research effort are needed to bring the analysis of green roof disposal to the same level as that with which the disposal of other components of the building envelope is addressed.

6. Conclusions and Future Recommendations

This study reviewed the current literature dealing with the modeling of green roof disposal, particularly LCA and LCC studies.

Based on the results of this review study, it can be stated that the end-of-life phase of green roofs is a phase in their life cycle that is still an open issue not only from the regulatory point of view (absence of ad hoc technical standards) but also from the point of view of methods for their analysis.

The paper, in fact, shows to the reader the criteria currently proposed in the literature to identify the end-of-life scenario of green roofs, which essentially apply to the disposal techniques in place in each country or to European waste statistics. Most importantly, however, this paper signals that a standardized method for identifying recovery and/or disposal treatments to be assigned to waste from the disposal of the green roof is missing (treatments that will serve to simulate the end of life of green roofs).

Such a situation contributes to rendering the task of the environmental modeling of the end-of-life stage as well as of the total life cycle of green roofs rather complex. In order to facilitate the analysis of these building components, in the opinion of the present authors, consideration should therefore be given to the enactment of technical regulations on the disposal of green roofs; alternatively, while waiting for guidelines to be issued that give instructions on how to handle the disposal of these envelope components, attention should be paid to the development of feasible methodological frameworks to define the waste treatment, disposal and/or recycling, for the individual component of the green roofs. Further research should therefore be conducted along these two lines.

The scientific potential of the present work is in that it allows us to understand the present body of knowledge related to the management of the end-of-life of these building components and the methodologies available in the literature to define the end-of-life scenarios of green roofs and so assessing their environmental performance. Therefore, it might represent a useful starting point to open a discussion aimed both at the formulation of future guidelines for the analysis of the decommissioning phase of this technology and the drawing of operational schemes to support technicians in their task of assessing the environmental performance of this technology.

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