Elnaggar *Heritage Science* (2024) 12:7
https://doi.org/10.1186/s40494-023-01114-z

Heritage Science

REVIEW **Open Access**

Nine principles of green heritage science: life cycle assessment as a tool enabling green transformation

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Abstract

This literature review presents a comprehensive review of life Cycle Assessmernt (LCA), as an emerging tool in the field of cultural heritage research and demonstrate how this tool could be useful to support the development of green heritage science into an environmentally responsible field of scientific endeavour. LCA is a standardised, structured, comprehensive, international environmental assessment tool and a rapidly evolving field of research that leverages and harmonises efforts across many sectors to inform environmentally-friendly solutions and choices. LCA has been growing in importance as an evidence-based tool in the field of heritage science, being used as a decision-support tool at micro level (typically for questions related to specific products/processes) and macro levels (e.g. strategies, scenarios, and policy options). This review explores applications of LCA (and the complementary Life Cycle Cost Assessment (LCC), and Social Life Cycle Assessment (S-LCA)) to a wide array of conservation and preservation actions. The paper also examines challenges associated with the application of these life cycle-based methods in heritage science, in order to put forward a set of recommendations to guide the domain of heritage science towards greener and more sustainable practices and impacts.

Based on a review of the principles of green chemistry, green analytical chemistry, green engineering, and nature conservation, the paper also attempts to formulate nine principles of green heritage science, taking into account the complexity of research challenges and the environmental and socio-economic sustainability.

Keywords Green chemistry, Pollution, Energy consumption, Stakeholders, Decision making, Socio-economic aspects, Environmental impact, Conservation

Introduction

In 2021, the Joint Commitment for Climate Action in Cultural Heritage [1] of the International Institute for Conservation of Historic and Artistic Works (IIC), the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), and the International Committee for Conservation of the International Council of Museums (ICOM-CC) emphasised the importance of sustainable practices in relation to climate change. From the perspective of heritage science, scientific challenges arise from the need to understand the relationships between heritage and its physical and social environment. These relationships are fundamental, as they provide insight into the processes of creation of heritage as well as its preservation and use. In this context, the balance between use (e.g. tourism) and the environment should be considered and be informed by the interactions between heritage and its environment. The European Union Sustainable Tourism Strategy (2020/2038) sets out various

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measures in favour of the tourism sector to transition to sustainable and green tourism from an environmental and socio-economic point of view [2]. The European Green Deal [3] and the international United Nations Environment Programme's Declaration on Greener Production [4], with the urgent goal of making Europe the first climate-neutral continent by 2050, could provide guidance for all scientific disciplines to address risks to the society and the environment.

This review argues for the incorporation of life-cycle science concepts (Fig. 1) into the practice of heritage science (HS), in order to incorporate environmental impacts with consideration of the socio-economic aspects. Life cycle methods could work as tools to enable the green transformation of heritage science. A new, 'green' paradigm would promote the use of renewable or recycled natural sources, minimal intervention practices, minimal use of toxic chemicals, energy efficient solutions, minimal waste generation with consideration of socio-economic aspects. The principles formulated herein form a theoretical proposal to the community to launch a broader debate on the green transformation of heritage science. It is argued that new solutions based on environmentally friendly and sustainable materials, methods, procedures, and processes (including aspects of production, use and disposal) as elaborated using advanced environmental assessment tools, are needed to promote sustainable management and use of cultural heritage.

Life Cycle Assessment (LCA), as a standardized, structured, comprehensive, and internationally comparable assessment tool, is at the centre of a fast-developing research domain informing and promoting green solutions and sustainable decision-making [6]. LCA allows for a quantitative assessment of the environmental and human impacts associated with a process or a material, providing an evaluation of which solutions present a better environmental profile. While suitable environmental management can extend the expected lifetime of cultural heritage [7], sustainable preventive conservation is still a major challenge for decision makers in the heritage science sector, as evidenced by continuous revisions of environmental guidelines and standards. The global cultural, economic, and geographical contexts and diverse understandings of object value and conservation resources [8] are major factors [9]. The BSI PAS 198 guideline [10] graphically expressed the environmental and collection considerations of environemental management (see Fig. 2) but did not put forward a tool for the evaluation of the impact of collection cultural values and the three pillars of sustainability on it [11]. While the environmental and economical performances related to e.g. conservation products/processes are included into decision-making processes, social aspects are rarely considered. This is due to a lack of awareness and to the limits of methodologies for their evaluation. In the Social Life Cycle Assessment (S-LCA) [12], some social indicators have been developed to support stakeholders and policy development [13, 14] while Life Cycle Costing (LCC) focuses

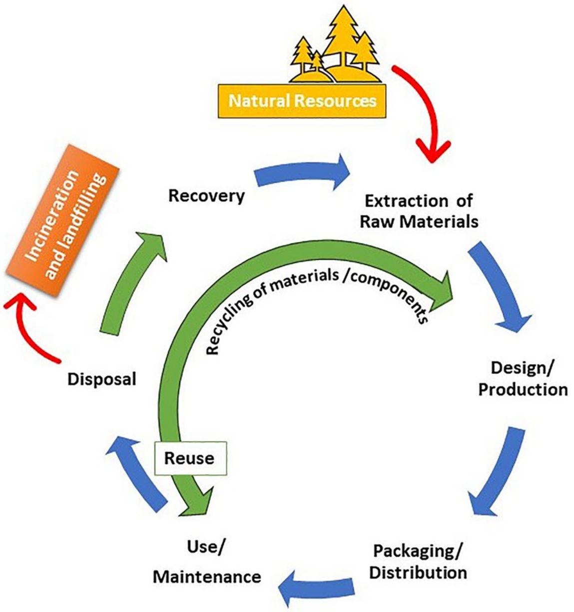

Fig.1 Generic life cycle concept (adapted after the Life Cycle Initiative [5])

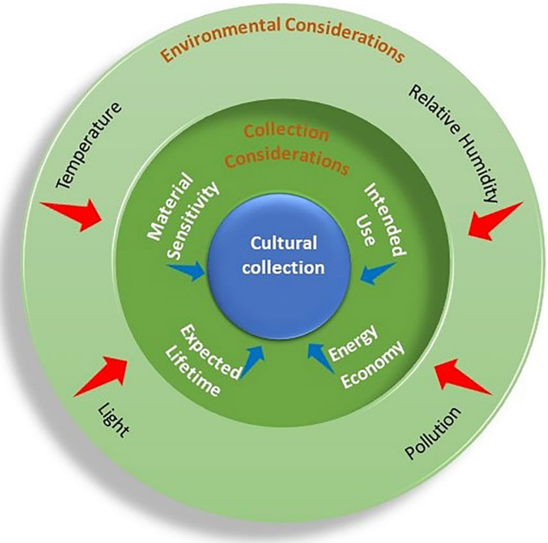

Fig. 2 Considerations relevant in the process of setting environmental conditions for cultural heritage (adapted after BSI PAS198 [10])

primarily on the direct and indirect costs which represent the economic benefits of LCA-based decisions [15]. LCC is a method of calculating the total cost of a product during its life cycle providing additional information to decision makers such as evaluation of economic and financial sustainability.

The history of LCA goes back to the early 1970s when it was developed by industries such as food, energy, and waste management [16]. Its origins can be traced to assessments of the environmental impacts and impacts on human health in sequential and interrelated stages, throughout a product's life cycle, from raw material sourcing, through extraction, preparation, manufacturing, processing, distribution, transport, use, disposal, and end-of-life with detailed analysis of inputs and outputs in each stage (Fig. 3). In the 1990s, under the auspices of the Society of Environmental Toxicology and Chemistry [17], efforts were undertaken to harmonize the LCA code of practice. Since 1994, the International Organisation for Standardisation (ISO) has formally handled the task of standardising methods, as now set out in the ISO 14040 and 14,044 series of standards [18]. However, this ISO leaves the practitioner with a number of choices that can affect the legitimacy of the results of LCA study including the handling of uncertainty and the reporting and review requirements [19, 20]. The (ISO) defines LCA as "a compilation and assessment of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14044). Since ca. 2000, the United Nations Environmental Programme (UNEP) has been promoting the use of life cycle approaches in practice. The European Platform on Life Cycle Assessment [21] aims to improve the credibility, acceptance, and practice of LCA in companies and public authorities, by providing reference data and recommended methods for LCA studies.

However, LCA is used to calculate a large amount of complex data by identifying environmental hotspot impacts and facilitating comparisons between product/system alternatives to investigate their environmental performance and enabling benchmarking, regulations and polices [21]. With the term "environmental impacts", different impact categories (or midpoints) are usually included. When we refer to damage, we usually refer to it as an endpoint, which represents the ultimate environmental or human health outcome resulting from environmental stressors measured by midpoint indicators [22]. In the recent years, there has been a growing

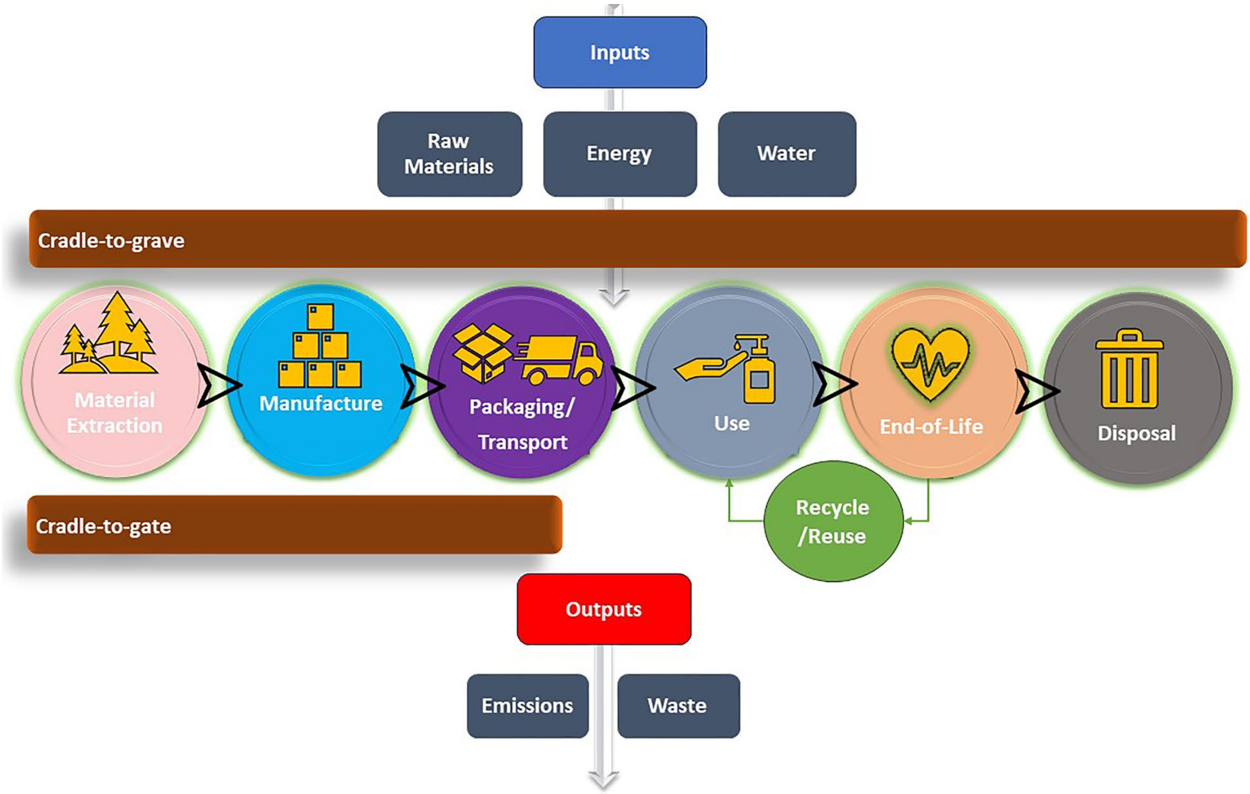

Fig. 3 LCA approaches and stages with examples of inputs and outputs to be considered in the comparison and quantification of impacts of a product, process, action, or procedure

interest in the inclusion of stakeholder approaches in S-LCA where the potential positive and negative impacts on the society are considered. Although some guidelines for social life cycle assessment (S-LCA) have been introduced [12], there is still a lack of S-LCA studies in heritage science. This is explained in the literature by the fact that S-LCA is a relatively new method and is still undergoing extensive methodological development [23] to harmonise social definitions, indicators and approaches, which are geographically sensitive and pose difficulties in assessing the local realities [24]. In addition, there are some challenges related to the identification, assessment and interpretation of social impacts. LCC and S-LCA do not have a general standard that would provide guidelines for their application, such as LCA. S-LCA builds on the general principles and the methodological approach based on ISO 14044 [25]. LCA can either be conducted separately or complemented by LCC and S-LCA. Combining LCA, LCC, and S-LCA through Life Cycle Sustainability Assessment (LCSA)[26] provides a comprehensive understanding of the overall sustainability performance, enabling decision-makers to balance environmental, economic, and social considerations, leading to more informed and sustainable choices.

While evaluating the environmental impacts of a product or process, LCA serves to identify hotspots which are points in the life cycle that have significant negative impact on the environment. Most often, resolving hotspots becomes the cornerstone of the sustainability plan based on a complete LCA. The four phases of LCA [21] include the following (Fig. 4):

- Goal and scope definition phase:

  During the LCA goal and scope definition phase, the goals and functional units are determined in terms of the boundaries of the assessment to be established, so the product or system being evaluated could be defined, along with its intended users. The system boundaries determine which unit processes are included in the LCA and must reflect the goal of the study.

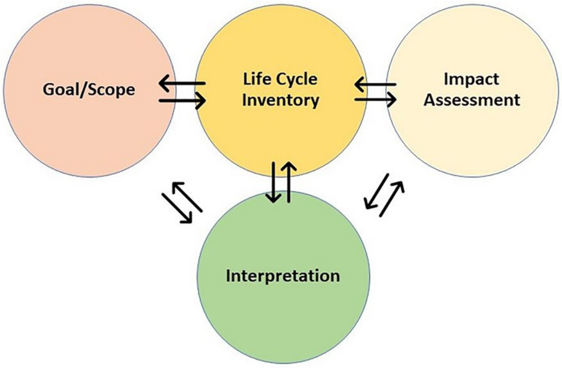

Fig. 4 The interlinked four key phases of LCA (adapted after Rochester Institute of Technology [27])

- Inventory analysis phase:
  The LCA inventory analysis involves collection and simultaneous quantification of data relevant to the functional units, e.g. energy and resource inputs, emissions and waste outputs, and environmental releases associated with each stage of the life cycle. If LCA is complemented by LCC and S-LCA, the data related to costs and social aspects could be either quantitative or qualitative. Both types need to be aligned with the scale used in the assessment, and weighting factors can be used [14]. Usually, LCA inventories are carried out using specific software that offers the possibility to model life cycle costs and social impacts alongside with the environmental ones [28].
- Impact assessment phase:
  In the impact assessment phase, data are used to assess the environmental and human impacts of a product, a measure, or a process including, e.g. acidification, global warming, ozone, smog, resource depletion, or fossil fuels. In LCC and S-LCA. Impact assessment can be carried out through two mandatory steps: (i) selection of impact categories and classification and (ii) characterisation, where the impact of (e.g., of emissions) is quantitatively modelled with a specific impact score in a unit that applies to all contributions within the impact category (e.g. $kgCO_2$). Impact assessment also contains two optional steps: (i) normalisation, where the different characterised impact scores are referenced to a common reference; and (ii) weighting, where a ranking and/or weighting of the different environmental impact categories is applied, reflecting the relative importance of the impacts considered in the study. The economic and social indicators of LCC and S-LCA could be seen as complementary to LCA, in consideration of geographical and cultural contexts and the involvement of stakeholders through e.g. participatory research [29], questionnaires, interviews, data collection, company reports, and social risk databases [12, 30]. However, in many cases, the social impact assessment for a full life cycle can be both complex and time consuming.
- Interpretation phase:
  In the interpretation phase, the results of assessment are appraised with the aim to answer questions posed in the goal definition. A simple format for a final

presentation of LCA is desired where data is visualised in graphs to make them easier to understand. Interpretation could also include other contexts such as grouping (where data is categorised, summarised to be more understandable and manageable), completeness and quality checks, as well as sensitivity and uncertainty analyses [31]. Uncertainty analysis can be conducted either quantitatively or qualitatively, depending on the available data and information. It should be carried out if two products are compared. Specifically, in the case of S-LCA, quantitative analysis can be applied to assess the uncertainty of scoring factors and impact subcategory indicator aggregation into e.g. stakeholder type. However, the results of the assessment are interpreted and used for decision making, strategic planning, marketing, product development and improvement, and direct applications (e.g. waste prevention, minimisation, recycling, or disposal).

LCA uses scientific software to model steady-state, comparative statistical, and dynamic global environmental and human health impacts by calculating comparative values of systems of similar functions e.g. raw material data, energy consumption, and end-of-life treatment [31]. When conducting LCA, it is important to choose an appropriate database and software that is tailored to the objectives and geographical scope of the study in order to conduct accurate and relevant environmental assessments. In LCA inventories, preference should be given to high-quality primary data (e.g. internal databases on health and safety, operations, human resources and purchasing) or secondary data (e.g. literature or data provided by public or thirdparty databases can be used for approximations when primary data is lacking). LCA databases and software are important tools as they have preexisting data on various stages of a product's life cycle and environmental impacts. They provide necessary calculations to estimate the environmental impacts using mathematical models and input data to quantify and visualise parameters like energy use and gas emissions. Such databases are usually uploaded into LCA software where some LCA software can also support LCC and S-LCA. The latter employs some of the modeling capabilities and systematic assessment processes of LCA combined with social science methods [32] where the impact categories and subcategories assessed in S-LCA are those that may directly affect stakeholders positively or negatively during the life cycle [33].

It is clear from the literature [34] and articles reviewed in this paper (Table 1), that there are several well-known examples of open-source and closed-source LCA databases, which are frequently updated and used in various LCA software tools. Ecoinvent [35], for example, is one of the most widely used databases in the world, providing comprehensive data on a wide range of materials, processes, and activities. Ecoinvent is integrated in the LCA software SimaPro [36] providing a user-friendly interface and access to a wide range of LCA data. GaBi [37] is another popular LCA database and software suite that provides a wide range of datasets and allows users to conduct detailed environmental assessments. OpenLCA [38] is an open source and user-friendly software, which can include both free and commerically available database of life cycle impact (LCI) databases. The collection of data to compile S-LCI for the heritage scienced sector will be challenging and complex. However, some social impacts were extracted from GaBi software database of Life Cycle Working Environment (LCWE) to perform S-LCA [39]. OpenLCA has also integrated social hotspots data through PSILCA [30] and the Social Hotspots Database (SHDB) [40]. The International Reference Life Cycle Data System (ILCD) is being developed to support the availability, exchange and use of coherent and quality-assured life cycle data, methods, and studies [41] to overcome the shortcomings of existing methodologies. When conducting LCA, LCC, or S-LCA, it is essential to select software that integrates multiple databases (such as Ecoinvent and other databases) that best fit the specific needs and goals of the assessment.

In practice, LCA is hampered by several limitations including data requirements, quality, precision, reproducibility, representativeness, and data entry errors, as well as methodological inconsistencies [28, 42, 43]. In LCA, data is often taken from databases and literature, and not based on actual measurements, official reports, surveys, and interviews, and may not reflect the actual material or process well [44, 45]. Uncertainty in LCA may come from a variety of sources including data variability and data quality. However, uncertainty can be reduced through sensitivity analysis methods [46]. Currently, LCA software cannot deal with uncertainty. In order to reduce it during the interpretation phase, checks on the completeness, sensitivity, and consistency of the data and reliability of the results are crucial as are peer-reviews, expert consultations and stakeholder input are advisable [47].

Life cycle assessment (LCA) applications in heritage science

LCA has been growing in importance as an emerging evidence-based tools in the field of heritage science, being used as decision-support tool at micro level (typically for questions related to specific products) and macro levels (e.g. strategies, scenarios, and policy options).

Despite the growing number of publications, to the best of the author's knowledge, there currently is no

Table 1 LCA applications in heritage science with an outline of the studies systems, examined environmental hotspots, frequently used databases and software, and observed limitations

Studied system	Hotspots	Impact Methodology/Software/database used	Uncertainty/Sensitivity analysis	Limitations	Reference
Sample preparation in analytical chemistry	Energy, materials, CO_2 emissions, waste, ecotoxicity, acidification, etc	Ecoinvent 3.7.1 database; ReCiPe 2016; Brightway2 software; French and European environmental data (the assessment is focused on the local context)	Yes	Lack of data in databases, use of generic database; exclusion of some components in the LCA calculations	[51]
Urban strategies	Energy, water, waste, materials, global warming, etc	Review of life cycle thinking tools	No	Limitation of studies in social life cycle assessment due to the complexity of the field	[54]
Restoration scenarios of buildings	Energy consumption; carbon emissions	Literature; One Click LCA; BIM/Revit	No	Lack of more detailed choice of materials and technologies in an advanced design process; and lack of socio-economic indicators	[55]
Restoration scenarios of buildings	Building materials, construction and energy; the 16 ILCD impact categories	OpenLCA 1.10.3 software; Ecoinvent 3.7 database	Yes	Results cannot be used to make generalization on the environmental performance of restoration for historical building due to the different context; uncertainty related to the future; and lack socio-economic indicators	[56]
Energy production systems in buildings	Power/energy CO_2 emissions, waste, damages on health and biodiversity	Ecoinvent 3.4 database; CMA C1 and CMA C2	No	The reliability of long-term planning/modelling is questionable and there is a need for a simplified model as running	[57]
Conservation materials of built heritage	Materials used, energy CO_2 emissions and others	GaBi 6.115 software; Ecoinvent 3.1 database; CML 2001	Yes	Lack of data in databases; the impacts of nano-particles were not considered, Uncertainties of some of the results still exist	[58]
Seven cleaning methods and materials	Types and amounts of materials used, energy, water emissions, waste, etc	Data gathering from companies; SimaPro 8.5.2.2 software; Ecoinvent 3.4 database; IMPACT 2002+; CML-IA baseline; IPCC GWP 100a; TRACI 2.1	Yes	Lack of consistent precise data in LCA databases; lack of analysis of the nature, thickness, and hardness black crusts; the need to take into account the skills and experience of the conservators involved in the cleaning processes	[59]
Tourism	Materials, waste, energy, footprint, water, toxicity, smoge, ozone depletion, etc	Review of LCA tools in tourism; CML-2001; ReCiPe etc	No	Almost half of the studies of LCA in tourism examined only the environmental aspects of tourism without including the social and economic aspects; complexity of tourism sector and products; lack of relevant LCA database, and the neglect of local context	[60]

Table 1 (continued)

Studied system	Hotspots	Impact Methodology/Software/database used	Uncertainty/Sensitivity analysis	Limitations	Reference
HVAC system shutdowns	Energy cost reduction	SimaPro 7.3.; Ecoinvent 2.2; EPA's Tool for TRACI	No	The individual nature of building structures, outdoor climate and gallery usage make the findings to other institutions problematic	[62]
Exhibition loans aspects	Energy and materials used. footprints, costs	SimaPro 7.3.; Ecoinvent 2.2; EPA's Tool for TRACI	No	No social indicators	[62]
Cleaning systems	Climate change, ozone depletion, smog, acidification, water, toxicity, etc	Ecoinvent; TRACI	No	Other tools involved in cleaning were excluded, such as tools used to apply the cleaning systems	[64]
Cardboard archive box	Raw materials, energy, water, waste, costs, etc	EcoInvent database v3.6, SimaPro LCA software, ReCiPe 2016 endpoint and midpoint methods, data collection, questionnaires	Yes	Several assumptions were made due to lack of data, modelling and uncertainty results need to be improved, and sensitivity analysis was not performed in all phases	[65]
Anoxia systems	Acidification, carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, global warming, non-carcinogens, ozone depletion, respiratory effects, and smog	OpenLCA (v1.10.3); Ecoinvent database (v3.7, APOS); TRACI v2.1	Yes	Excluding the materials and inputs required to produce the original artwork as well as the humidity control	[66]
Conceptual protocol on Cultural Heritage Life Cycle Management	LCA, LCC, S-LCA impacts including Stakeholder Engagement Strategy, heritage value	–	No	Lack of framed sustainability analysis tool	[67]

literature related to the applications of life cycle methods in the heritage science sector. In this review paper, the analysis of literature (available through Scopus, Google Scholar, ScienceDirect databases and policy documents) has revealed a number of relevant LCA, LCC, and S-LCA case studies, involving the domains of conservation, chemistry, characterization, and tourism. General keywords related to life cycle methods and their applications in cultural heritage, analysis and characterisation, building restoration, conservation, archaeology, and tourism were searched for, along with hotspots related to heritage science (such as emissions, energy, waste, resources and polices). The selected articles were subject to analyses in terms of the studied system, environmental hotspots, impact methodology, and limitations. The reviewed articles are in some aspects very similar, but they differ in the typology of cultural heritage and the type of application (e.g. analysis, restoration, preventive conservation and tourism). This allowed the assessment of the progress of LCA and the types of practices to which these methods have been applied in the field of cultural heritage over the last decade. Frameworks were identified, in which LCA has been applied and the possible methodological challenges related to heritage science, specifically.

The analysis of environmental and socio-economic hotspots used in LCA, LCC and S-LCA applications in heritage science supported the development of a framework for green principles in heritage science. This theoretical framework followed the examples of exiting green principles in other sectors such as green chemistry, green engineering, green analytical chemistry, and nature preservation. This development is in alignment with the objectives of the three funded EU programme on green conservation [48] within the EU-funded projects to green the economy [49].

While LCA is widely applied in many sectors, it still is at its early stages in the field of heritage science. The aspects most frequently examined by LCA are energy consumption, pollutant and greenhouse gas emissions, waste production and treatment, and resource consumption. The S-LCA framework calls upon a stakeholder approach where the potential impacts, both positive and negative, on different stakeholders are considered. The consumption of chemicals and solvents, as well as energy requirements to run instruments and equipment as well as data processing, are an essential part of material characterization and analysis, and through LCA, the environmental friendliness of an analytical method in terms of its carbon footprint can be assessed. The latter has been the topic of a general study of the environmental footprint of chemical analysis [50]. Table 1 summarizes the key aspects of the papers reviewed here.

Raccary et al. [51] investigated and compared the environmental impact of sample preparation techniques using LCA, where the boundaries included laboratory consumables, chemicals, gas, waste, and electricity consumption. The results showed that the manufacture of vials and vial caps is responsible for most of the environmental impact while the study limitations include the lack of data in databases, use of generic databases, and the exclusion of some components in the LCA calculations. Near infrared spectroscopy (NIR) was assessed as a green technique in terms of eliminating the need for chemical reagent consumption and waste generation [52]. The results showed that the NIR system is inherently fast and clean and can avoid hazardous residues generated by conventional analytical methods. This saves energy and materials and minimises waste generation. It has been shown that inert and non-volatile solvents with a low vapour pressure and high thermal stability in sample preparation, including ionic liquids, represent a greener choice in comparison to conventional volatile organic solvents in analytical chemistry procedures [53]. The built heritage sector is one of the main sources of greenhouse gas emissions and resource consumption in relation to material extraction, construction, maintenance, and operation phases. The number of literature studies dealing with LCA of the environmental impact of built heritage and construction materials is rapidly increasing. Researchers have drawn inspiration from the literature on the development of LCA models for the assessment of building and construction materials and some work looked at the impact of construction materials and energy consumption/efficiency. In some contributions, the analysis focused on the links between LCA (among other tools) and broader concepts such as environmental sustainability strategies for urban heritage. In a review paper, Petit-boix et al. [54] recommended that life cycle tools might benefit from revising the methodology with relevant stakeholders to optimize the understanding and communication of life cycle results for urban heritage policy and decision-making processes in terms of green infrastructure in cities (e.g. energy, food and green areas). The review showed a shortage in S-LCA in urban planning. Gravagnuolo et al. [55] investigated two restoration scenarios including minimum intervention with a new construction nearby or retrofitting and reuse of a heritage building, calculating the energy consumption and carbon emissions in all life cycle phases. She pointed out that LCA can provide important insights at the design stage of adaptive reuse to make better decisions, carefully considering carbon emissions as one of the most important evaluation criteria. However, other social, cultural and economic criteria should complement the environmental assessments when taking choices on historic buildings reuse. Other factors need to be considered in the building restoration decision making including the conservation of cultural values of the historical building and the user behavior and energy consumption during the building operation and adaptive reuse. Serrano et al. [56] investigated LCA in two decision-making scenarios at micro-level related to restoration of historical buildings (using minimal intervention or traditional materials) and renovation (using modern materials) for a 50 year adaptive reuse plan. Impacts (such as acidification, toxicity, ozone, and resource depletion etc.) related to building materials, energy consumption due to heat loss in different building parts were investigated. The results show that while the impacts of the two scenarios are similar in magnitude, the restoration scenario performs slightly better in most impact categories of the standard LCA model. The study also indicated that the choice of assessment period (50 years) did not substantially change results and the selection of the assessment period duration (from 50 to 100 years) is not likely to affect the conclusions that can be drawn from this study. However, the results of this study cannot be used to make generalizations on the environmental performance of restoration for historical buildings due to the different contexts of the historical buildings. While most LCA studies of planning approaches look at the immediate future and short-term impacts, Frapin et al. [57] considered long-term planning and short-term variations (i.e., seasonal, daily, and hourly) of electrification/energy production in different types of buildings by simulating 50 year scenarios with 5 years steps in terms of greenhouse gas emissions and waste. He evaluated the uncertainties in LCA related to future evolution of the energy systems with a scenario of 100 year lifespans of buildings, 30 years for windows and doors, 20 years for equipment and 10 years for painting, considering environmental hotspots such as CO_2 emissions, waste and damage to humans and biodiversity. Results show that the environmental impacts vary more depending on the power production scenarios than on the types of building. The study pointed out that the reliability of long-term planning/modelling is questionable and there is a need for a simplified model as running such detailed models would not be compatible with the present building LCA practice.

In building conservation, Pranjić et al. [58] identified and quantified the environmental impacts during the life cycle of three conservation consolidants and proposed solutions for further optimisation of their environmental performance. However, the impacts of nano-particles were not considered in this study. LCA analysis showed that the bulk of the emissions are due to the synthesis of the ingredients used to produce the consolidants and packaging materials. The study also recommended cleaner forms of electricity generation to reduce environmental impact and waste generation. Franzoni et al. [59] applied LCA to study cleaning methods and materials of stone buildings (water-based, solvent-based, mechanical, poultices, ion exchange resins, and laser). The results showed that for some cleaning methods, the impacts related to manufacturing and disposal are very similar, which underlines the importance of conducting LCA including end-of-life scenarios. Solvent-based methods had the greatest impact, followed by laser cleaning, water-based methods, and finally micro sandblasting. In terms of water consumption, laser cleaning had the largest impact, mainly due to the water consumption for electricity generation, which is required throughout the cleaning process. In terms of waste generation, solvent gels have the biggest impact, followed by poultices. The study also pointed out the limitations resulting from the lack of specific databases and the need to take into account the skills and experience of the conservators involved in the cleaning processes.

Herrero et al. [60] provided a review of LCA applied to tourism (using different types of impact methods, databases, and questionaries, and addressing different stages of accommodation, restaurants, and transport etc.). The study showed that almost half of the studies of LCA in tourism examined only the environmental aspects of tourism without including the social and economic aspects. The study showed the challenges in LCA application in tourism due to the complexity of tourism sector and products, lack of relevant LCA database, and the neglect of local context. For example, Fig. 5. shows the carbon emissions associated with tourism before and after the COVID-19 pandemic considering the existing polices and strategies to achieve sustainable tourism based on life cycle considerations. The study also pointed out that the most important environmental indicator was carbon footprint. Although the CO_2 emissions have been reduced by a large percentage after COVID-19, transport was shown to be one of the biggest contributors to most environmental impacts in the sustainable tourism sector [61]. LCA applied to tourism has been used to assess the environmental impacts of services and infrastructures in the travel and tourism sector, including transport, accommodation and sightseeing, and influence decisions that lead to more sustainable practices in the tourism industry. This could include changes in transport options, promoting energy-efficient accommodation, reducing waste generation, and supporting the Ecolabels and environmental certification of tourism infrastructure. LCA in tourism can help stakeholders, including tourists, businesses and policymakers, to make informed decisions that minimise the negative environmental impacts associated with travel while maximising the positive

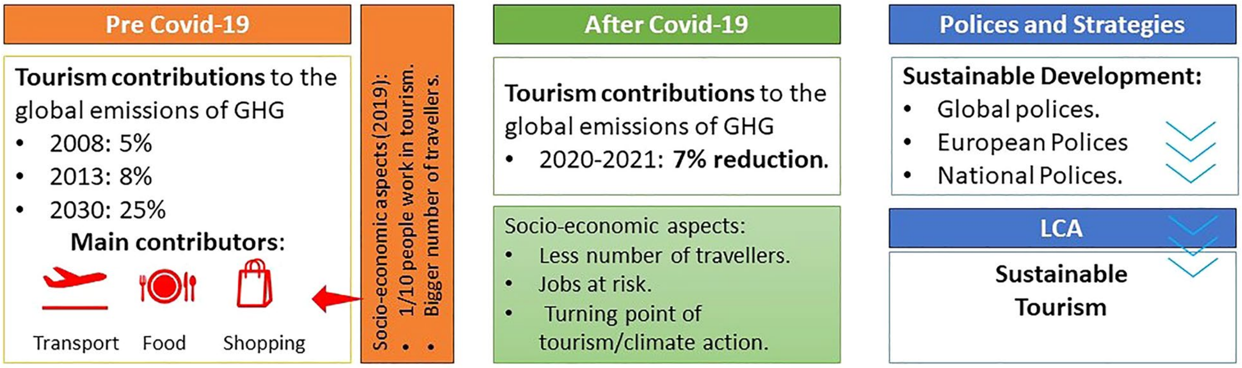

Fig. 5 The environmental, social and economic aspects required for achieving sustainable tourism as well as the carbon emissions associated with tourism before and after the COVID-19 pandemic considering the existing national, European and global policies (adapted after Herrero et al. [38])

economic and social benefits. It also promotes a holistic approach to sustainability by considering the entire life cycle of tourism activities.

In 2016, Nunberg et al. [62] conducted LCA studies at the Museum of Fine Arts in Boston (USA) that examined the environmental hotspots (including footprints, costs, energy demand and materials used) in environmental management in exhibition loans (in terms of the exhibition installation, use of crates, packing, lighting, and air condition etc.). The results showed that lighting, maintenance of the exhibition space, and construction of the exhibit cases for the short period of the exhibit was responsible for the highest contribution to loan GHG emissions while unpacking and repacking contributed the least amount to the carbon footprint of the loan. Although the study clearly demonstrated the benefits of using shorter-life light-emitting diodes (LED) in galleries by reducing the carbon footprint, the analysis of HVAC systems clearly shows that caution should be exercised in applying the results of LCA too broadly in terms of the building structure context and outdoor climate.

In the frame of STiCH project, Nunberg and Eckelman provided a carbon calculator for LCA case studies in libraries including boards, coatings, adhesives, fillers, taps, wood, etc. [63]. This calculator allows an educated decision with an easy comparison for selection of products based on their carbon footprint. The platform allows browsing the products and quantifying and visualising the total impact of their footprint (kg CO_2 eq) with linked human toxicity data.

Nunberg and Eckelman also presented a practical overview [64] of the two quantitative tools, LCA and LCC, based on several case studies (identifying actions and materials that impact the environment and human health, with the aim to compare short- and long-term costs and benefits to enable informed decisions. The case studies include investigation of the environmental and human impacts (such as climate change, toxicity for humans, and freshwater aquatic toxicity) of cleaning systems to remove white paint on sculpture. The study showed that water-based cleaning systems result in significantly less climate change and human health impacts than solvent-based systems. They also provided another case study [64] to understand the future operational and maintenance costs and long-term decision making (10 year time horizon) regarding the use of halogen and LED lighting systems in museums exhibitions. Considering the electricity cost, disposal cost, replacement cost, time, inflation, and real Interest rate in the decision-making process, the study recommends the preference of LED over halogen lighting systems.

Menegaldo et al. [65] evaluated the environmental and economic life cycle impacts of corrugated cardboard archive box using LCA and LCC, which employ nanotechnology, for the preventive conservation of cultural objects stored in museums. The study looked at the raw materials used and the costs of staff and components, energy, waste treatment, water and equipment maintenance. While the study showed a major impact related to the procurement of raw materials, including transport, there was a limitation in data availability and conducting a detailed assessment. In a recent publication by Sanchez et al. [66], LCA was conducted to investigate the environmental performance of different anoxic systems for the long-term preservation (up to 5 years) of oxygen-sensitive organic materials. The study focused on examining the environmental impact of the inputs (electricity, fuel, materials, and gases used in the manufacture of the enclosure), taking into account the aspects of transportation, while the output focused on emissions and waste. The study highlighted the importance of reusing the components to reduce emissions and waste. Anoxia is used for long-term storage and display of oxygen-sensitive organic materials in a sealed enclosure filled with inert gas (e.g. nitrogen, carbon dioxide or argon). Anoxic storage can extend the lifetime of the artwork, but it requires significant energy and produces waste. However, when considering environmental impacts of long-term storage (e.g. 50 years) comparing to a short period of five years, additional uncertainty is introduced into LCA due to the expected differences in annual emission inventories and reuse of anoxic components. Compared to passive systems, long-term anoxic storage of a single object leads to continuous energy and material consumption. When deciding on the use of anoxia, socio-economic and cultural aspects must also be taken into account, such as the significance of the stored objects as well as the availability of space, budget, and expertise. These need to be considered if anoxia needs to be terminated for financial reasons. The preservation of cultural heritage sites, buildings, artifacts, and artworks is carried out to maintain their cultural and historical significance. These activities can involve the use of energy, various materials, and resources, and processes. In addition, cultural heritage is not an independent element, but exists in different contexts, technical complexities, and decision-making processes in which a variety of actors are influenced by different socio-economic micro and macro factors. In the context of heritage science, research on the social, economic, and environmental impacts is recommended to ensure heritage sustainability. A conceptual protocol called "Cultural Heritage Life Cycle Management, CH-LCM"[67], was proposed on the basis of a review of literature and mainstream local restoration and conservation practices to define methodological guidelines for assessing the sustainability of restoration processes by converting the existing environmental LCA technique into a triple-bottom-line sustainable development technique considering different technical and managerial strategic options. The protocol is based on description and systematisation of the phases of the restoration process and its supply chain; implementation of tools for the evaluation of impact of the process on the value chain, and systematic integration of these instruments through the different stages of the process following a life cycle logic. This could be done by a close collaboration between all stakeholders, with awareness of effects upstream and downstream relative to each position in the value chain, and the strategic and operational responsibilities of each actor affecting the decision making.

Blundo et al. [68] proposed an interesting framework integrating LCA with LCC, and S-LCA encompassing the three pillars of sustainability to improve sustainable management practices in cultural heritage restoration by assessing environmental impact, economic feasibility, and social impacts, the latter through implementation of a stakeholder engagement strategy. The study showed that a life cycle approach can be considered an effective method for improving innovative managerial practices towards the restoration and sustainability of cultural heritage. S-LCA application included the involvement of stakeholders to assess the satisfaction of their expectations and the impact they have on restoration projects by integrating different artistic, technical, and managerial skills.

There may be multiple and different expectations of different stakeholders in terms of perceptions of sustainability, manifesting themselves not only in the environmental dimension but also in terms of economic growth. The life-cycle assessment of an artwork or collection is quite complex, e.g. due to the resources used for the production of an artwork or the previous conservation measures/processes. In addition, relevant databases of cultural heritage materials are required, and specific tools are needed to manage a large collection of environmental data. In the available literature on the environmental impact of conservation products/processes and the deterioration of cultural heritage materials, few scientific papers have been published on the conservation of movable heritage. This is compounded by the complexity of data collection, e.g. in relation to the extraction, production, transport, packaging and disposal of conservation products. However, the increasing availability of LCA data from other sectors, e.g. chemistry, and nature conservation and built heritage, may enable the development of a quantitative environmental assessment protocol that combines environmental and human impacts with socio-economic indicators in a structured and consistent manner.

Discussion

The review of LCA studies has shown neither systematic nor exhaustive coverage of areas of application directly relevant to cultural heritage. There appears to be no application related to archaeology and applications to digitisation and archiving are few while the potential environmental impact of digital transformation is expected to grow in the next decade [69]. The lack of LCA applications could be due to several reasons, such as technical, legal, geographical, cultural and socio-economic contexts and differences [70], as well as the lack of available information and lack of consistency between relevant databases [71]. The available literature indicates that there is currently no specific LCA database for use in heritage science, which requires slow and difficult data collection. Although the LCA methods are becoming more sophisticated and specific software packages and databases are also being developed, it is not straightforward to make general recommendations for heritage science as some are very good but only for a limited area of application, e.g. building materials. Another important limitation for the applications of LCA in heritage science, as well as more generally, is the uncertainty related to long-term planning. This is true for heritage itself, its constituent materials, as well as environmental variables and energy considerations. More accurate models and estimates of expected lifespans would be important to reduce the overall uncertainty of the LCA results.

In general, the social and ethical aspects associated with the value of cultural heritage need to be considered in future life cycle-based studies (based on LCA complemented by LCC and S-LCA) and me the challenges in combining the environmental, economic, and social aspects need to be overcome. This could be possible by, e.g. involving relevant stakeholders to identify cultural and social indicators relevant to the LCA analysis that consider the local context and resources in the short and long terms and capture the relationships between the three pillars of sustainable development [72]. In addition, stakeholders (such as conservation decision makers/takers) should not limit their responsibilities to the phases of the life cycle of a conservation product, process, or activity in which they are directly involved, but they should extend their responsibilities throughout the entire life cycle of cultural heritage assets.

Case studies show how LCA could become an effective environmental sustainability assessment tool to study and compare the life cycle of heritage products, processes, actions, or procedures. We have highlighted several cultural heritage applications that identified critical aspects related to environmental impacts of the practices of heritage management and use. The importance of LCA as a tool is also underlined by European Commission (EU) having undertaken to produce a handbook on LCA [31]. The International Reference Life Cycle Data System (ILCD) manual provides a basis for ensuring the quality and consistency of life cycle data, methodologies, and assessments, as well as technical guidance for detailed LCA studies. The Life Cycle Initiative, a public–private multi-stakeholder partnership, promotes the understanding, adoption and application of the life cycle concept by decision-makers and facilitates access to environmental, social and economic life cycle knowledge (LCA data, methods, indicators, etc.) [5]. The Sustainability Tools in Cultural Heritage (STiCH) [63] can be put forward as an example of good practice. It is clear that LCA needs to be promoted to ensure that heritage science practices and outcomes become sustainable. In the next section, we will review the drivers for such development, and propose a framework for green heritage science.

The rapid development of green principles in diverse fields, e.g. chemistry or engineering, could provide a framework for heritage science based on greener, more sustainable practices. However, there is no single definition of 'green': in relation to e.g. chemistry [73] it is associated with the environmental protection or causing as little damage to it as possible [74]. Green (or sustainable) chemistry [75] is associated with the development of chemical products and processes that, reduce or eliminate the use and production of hazardous substances and energy consumption.

In response to the US Pollution Prevention Act of 1990, the idea of green chemistry was first introduced with the aim of preventing pollution through the cost-effective use and recycling of natural materials and processes and reducing the impact on human health and the environment. In addition, twelve green chemistry principles were introduced by Anastas in 1998 [76] to make chemicals, processes, and products more environmentally friendly. Subsequently, these principles inspired the development and formulation of the twelve principles of green engineering [77]. Similarly, the twelve principles of green analytical chemistry [78] consider negative impacts on the environment using destructive/invasive analytical methods, sampling, chemicals, energy and waste generation. Related to heritage, the IUCN (International Union for Conservation of Nature) has based its Green List of Protected Areas [79] on seventeen globally consistent and locally relevant sustainability standards [80]. The List is a global certification scheme based on scientific evidence, experiential, local and traditional knowledge and aims to promote effectively, equitably, and successfully protected conservation areas. The Green List demonstrates that local context, stakeholders, social needs, demographic and geographic characteristics, community engagement, natural and cultural values, transparency in decision-making, monitoring and best practices in working to protect nature and people need to be considered in relation to the short and long-term impact of nature conservation on climate change, health and well-being.

Many principles of green chemistry and engineering may be straightforward to apply to heritage science, such as energy efficiency, reduction of pollutant emissions and waste, or development of safer chemicals. For example, while traditionally, aromatic, and non-aromatic cleaning agents (e.g., chelating agents), consolidants and adhesives (such as acrylic and vinyl, or silicone-based polymers) are widely used in the field of cultural heritage conservation, they do not necessarily need to be considered harmful due to their efficiency and low consumption. However, the main issue associated with their use is their relatively large footprint. The Chemicals Strategy for Sustainability (CSS) identified a number of actions to reduce negative impacts on human health and the environment associated with chemicals, materials, products and services commercialised or introduced onto the EU market [81]. In addition to environmental sustainability, IUCH has brought strong elements of economic and socio-cultural sustainability elements into its standards, which should be relevant to green heritage science as well. Building on the experience of both scientific (green chemistry, green engineering) and nature conservation sectors, it is proposed that heritage science should enshrine environmental, economic, and socio-cultural sustainability aspects in its principles. Therefore, the nine principles of green heritage science are proposed here (Fig. 6).

1) Minimal intervention, maximum prevention.

This principle embodies scientific practices related to 'minimal intervention' in restoration and conservation based on ethical concepts of reversibility [82]. This includes practices based on the Ethical Sampling Guidance developed by the Heritage Science Group of the Institute for Conservation (ICON) [83]. The principle could be supported through life cycle assessments of methods for heritage documentation, characterisation, diagnosis, and analysis, favouring non-destructive, non-invasive and in-situ spectroscopic analyses with high selectivity and sensitivity [84] as well as automated instrumental methods [85]. Preventing damage to cultural heritage is also of paramount importance to ensure its preservation through a combination of risk assessment, conservation planning, public engagement, and effective management.

2) Inherently non-harmful materials and processes.

Recent heritage science research intensified the development of green chemistry-based products and methods. LCA should be used universally to assess the environmental hotspots associated with the resources and raw materials used in heritage science as well as in products and processes for sustainable conservation, as attempted by the recently

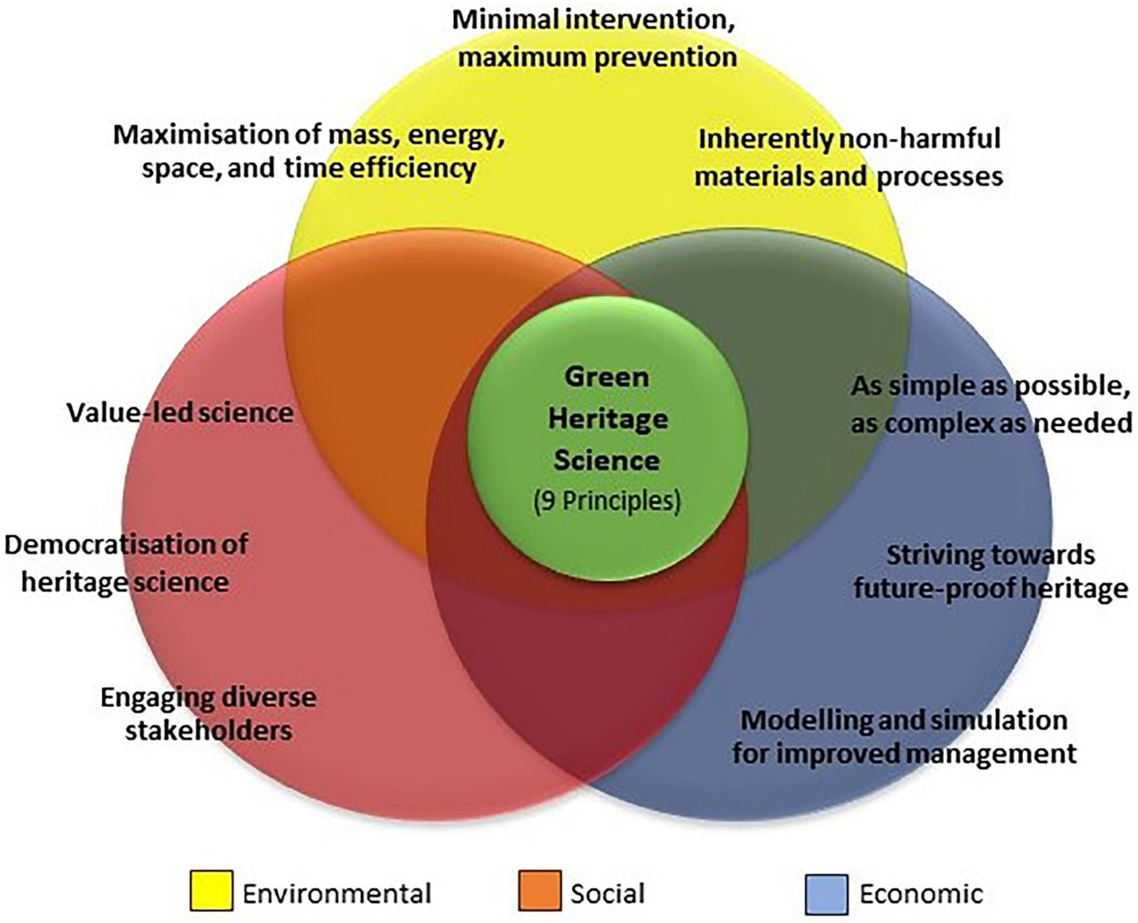

Fig. 6 The proposed nine principles of green heritage science overlaid on the three pillars of sustainability (environmental, social, and economic)

funded EU projects focusing on green conservation [48].

3) Maximisation of mass, energy, space, and time efficiency.

Achieving efficiency can maximise impact through cost savings and environmental benefits. This could be delivered through optimization of sustainable material design, reduction of energy waste and use of renewable energy resources, optimization of space allocation and design, workflows, and automation [86, 87]. Another aspect is related to resource and energy-intensive [88] heritage management practices requiring heating, cooling, humidifying/dehumidifying, lighting, and transportation etc.

4) Modelling and simulation for improved management.

Modeling and simulation are powerful tools that can often lead to optimisation of resource-intensive experimentation. In addition, environmental monitoring, and simulation to predict the impact of environmental stressors [89] or heritage use (e.g. tourism) can enable the development of simulation-based decision support systems enabling informed choices about resource allocation.

5) Value-led science.

The principle acknowledges that heritage science is far from being isolated from social and ethical considerations arising from heritage values, and that it needs to consciously integrate them into the scientific process and decision-making while avoiding bias [90]. The scientific priorities should address societal concerns and challenges, prioritising research questions that support positive social change.

6) As simple as possible, as complex as needed.

This concept emphasises the importance of balancing the simplicity of heritage science approaches and methods with the complexity and uniqueness of heritage. Simple solutions are often more sustainable, practical, cost-effective, easier to implement and accessible to diverse users. This principle underscores the importance of tailoring the level of complexity to the specific context and objectives of research.

7) Striving towards future-proof heritage.

Sustainable management of heritage requires potentially very long planning horizons. Heritage science should be based on clear plans, policies and procedures that are appropriate and sufficient to achieve the planned long-term objectives [91], while taking into account material sensitivity, modelling and simulations, as well as economic and socio-cultural contexts, as suggested by BSI PAS198 (Fig. 2). Lifecycle assessments should be adapted to such long-term planning, embracing the lifecycle of cultural heritage, from manufacture, use, conservation, and storage to exhibition and deaccession.

8) Democratisation of heritage science.

Heritage science currently relies mainly on Western knowledge systems and methodologies although heritage scholars started to de-colonise heritage interpretation based on diverse cultural and ethical approaches [92]. Similarly, heritage science should strive to benefit local communities and overcome barriers resulting from underrepresentation, incorporate multiple worldviews and epistemologies, facilitate access to heritage science research infrastructure, recognizing the value of diversity of understanding and interaction with cultural heritage.

9) Engaging diverse stakeholders.

Participatory research models should be used to prioritize the needs and goals of the communities involved, with research conducted in partnership rather than imposed by 'experts'. To increase its relevance and to respond to the needs of diverse stakeholders, heritage science should develop priorities responding to local environmental, economic and socio-cultural requirements. In addition, stakeholders should actively take part in research to ensure that heritage science impacts are sustainable.

Conclusions

Refinement of the green principles of the heritage science should be a collaborative process, based on transparency and commitment from all stakeholders to drive positive change and promote sustainability within the sector. Clearly, the proposed principles require a wider debate among heritage scientists and other stakeholders through conferences, workshops, and participatory research. The principles suggested here are intended to provide the basis for a practical and adaptable tool for scientists and stakeholders to engage in a meaningful and informed dialogue about green and sustainable heritage science, and in the fullness of time, develop indicators and quantitative models applicable to LCA and S-LCA to assess the green credentials of scientific approaches and of the developed methods and processes.

There is an ongoing debate about sustainability in the heritage science field, to which life cycle approaches, such as LCA, LCC and S-LCA could contribute. Heritage and research institutions should develop capacity to enable the application of life-cycle approaches through guidelines, education, and training.

In the coming years, ongoing improvement is expected in the application of life cycle approches to heritage. To enable widespread use, a dedicated database is needed to support LCA, LCC, and S-LCA studies, while taking into account local environmental, economic and socio-cultural aspects to ensure that the assessment results are relevant in the local context and for the relevant stakeholders.

Despite the identified shortcomings, the findings of this paper provide a clear pathway for green and sustainable transformation of the heritage science sector enabled by life cycle approaches.

Abbreviations

LCA	Life cycle assessment
gHS	Green Heritage Science
IIC	International Institute for Conservation of Historic and Artistic Works
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOM-CC	International Committee for Conservation of the International Council of Museums
ISO	International Organisation for Standardisation
UNEP	United Nations Environmental Programme
LCC	Life cycle costing
S-LCA	Social-Life Cycle Assessment
VOCs	Volatile organic compounds
ILCD	International Reference Life Cycle Data System
NIR	Near infrared spectroscopy
IUCN	International Union for Conservation of Nature
ICON	Institute for Conservation
EU	European Commission

Acknowledgements

The author expresses his sincere gratitude to prof.dr. Matija Strlič for his critical feedback and thoughtful discussions, which further enriched the content of this publication and shaped the nine principles.

Author contributions

The author wrote the main manuscript text.

Funding

Open access funding provided by the European Union (GREENART project, Horizon Europe research and innovation program under grant agreement no. 101060941). Views and opinions expressed are, however, those of the author only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them. Further funding by the Slovenian Research and Innovation Agency (projects N1-0271, N1-250, N1-0241, N1-0228, J4-3085 and infrastructure programme I0-E012) is acknowledged.

Data availability

Not applicable.

Declarations

Competing interests

The authors declare no competing interests.

Received: 11 October 2023 Accepted: 10 December 2023

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