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Review of Studies adopting LCA-based Absolute Environmental Sustainability Assessment Methods

MASTER THESIS IN ENVIRONMENTAL AND LAND PLANNING ENGINEERING

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Abstract

This study presents a review of studies adopting Life Cycle Assessment (LCA)-based Absolute Environmental Sustainability Assessment (AESA) methods. The primary goal of this systematic review is to explore the AESA framework and understand the differences between absolute and relative LCA approaches. Peer-reviewed academic articles from Scopus and Web of Science platforms were examined, identifying 15 studies published between 2018 and 2024. The review examines the methodologies, system boundaries, and shared principles within the AESA framework. The findings demonstrate that the AESA framework is crucial for determining whether production or consumption activities are sustainable in absolute terms. Additionally, a key challenge identified is the application of the Planetary Boundaries (PB) framework within LCA. This review emphasizes the increasing relevance of absolute sustainability approaches; as traditional relative methods often fail to ensure that impacts remain within planetary boundaries.

Key-words: Life Cycle Assessment (LCA), Absolute Environmental Sustainability Assessment (AESA), Planetary Boundaries (PB), Environmental Impact, Relative vs Absolute Sustainability, Environmental Sustainability

Contents

Introduction

A methodical investigation of the potential environmental effects of goods or services over the course of their whole life cycle is known as a life cycle assessment, or LCA. This methodology examines the possible effects on the environment at each stage of a product or service's life cycle, including manufacture (generation of raw, auxiliary, and operating materials), distribution, use, and end-of-life stages (such as waste incineration). [1]

The LCA can be done in absolute way or by using the more common relative approach. An absolute environmental sustainability assessment (AESA) evaluates whether a production or consuming activity may be deemed environmentally sustainable in an absolute sense. This involves a comparison of its environmental pressure to its assigned environmental carrying capacity. [6]

It is recognized that LCAs are sometimes carried out independently without any comparisons. However, in the vast majority of cases, LCA deals with inquiries, such as, (i) which product is better, A or B? (ii) Does the updated version of this product outperform the current one on the market? (iii) Is it more advantageous to generate electricity internally or to outsource it? Comparisons are employed to make decisions regarding investments and purchases. [3] Our discussion will delve further into the absolute assessment of environmental sustainability.

With the rapid growth of population, Life Cycle Assessments are required due to growing waste concerns and the need for more sustainable products. By identifying and quantifying the energy and materials used as well as the wastes released into the environment, as well as assessing the impact of those energy and materials used and released into the environment, life cycle assessment is used to evaluate the environmental burdens associated with a product, process, or activity. [4]

In this review, Chapter 1 will make a background of key terms and concepts referred throughout. Chapter 2 will discuss in detail the goal of the research and the methodology adopted. Chapter 3 will discuss about mapping. Finally, Chapter 4 will conclude the study and give future perspective

1 Background

1.1. Life Cycle Assessment (LCA)

The process of evaluating the environmental effects of anthropogenic systems—such as goods, businesses, and countries is known as life cycle assessment, or LCA. It addresses several types of environmental impacts. Decisions intended to reduce environmental impacts are frequently made using life cycle assessment (LCA). For example, when comparing products, one should ideally take into account all life cycle stages (such as manufacturing and use) and impact categories (such as freshwater use and climate change) to determine which performs better overall. [6]

The four distinct stages that make up the LCA framework are the definition of goals and scope, inventory analysis, impact assessment, and interpretation. [5]

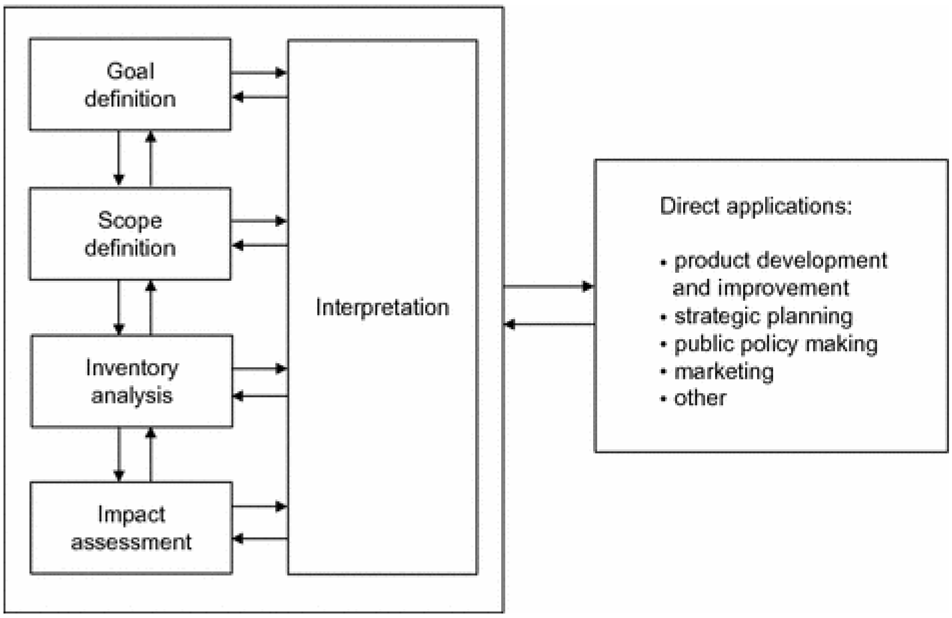

Figure 1: LCA framework adapted from ISO 14040

i) Goal & Scope Definition: An LCA begins with a carefully thought-out definition of the study's objective. This phase gives answers to what, why, how, and for whom the LCA is relevant. The study's objective, and in connection with it, the scope and depth of the investigation are determined. It's a critical step in LCA because it dictates the outcomes and how to interpret and verify them. The goal definition serves as the foundation for the scope definition and establishes the framework of the LCA study. In this phase, the functional unit is defined, which is a quantitative description of the function or service for which the assessment is conducted. It is necessary for determining the reference flow of the product that scales the data collection in the subsequent Life Cycle Assessment (LCA) phase, the inventory analysis.

ii) Inventory Analysis: The inventory analysis gathers data regarding the actual flows of resources, materials, semi-products, and final products; on the other hand, it records emissions, waste, and value products for the product system. Every process that was found to be a part of the product system is examined in the analysis, and the flows are scaled to match the product's reference flow as established by the functional unit.

iii) Impact Assessment: The impact assessment is the use of environmental science information and models to transform the physical flows and actions of the product system into environmental impacts, commencing with the life cycle inventory. The ISO 14040 standard mandates that the first three of the five components of the impact assessment be completed: Selection of impact categories, Classification of elementary flows, Characterisation, Normalisation and Grouping or weighting.

iv) Interpretation: The study's findings are analyzed to provide a response to the question or questions included in the goal definition. Both the inventory analysis results and the impact assessment items' characterization—as well as any potential normalization and weighting—are taken into account in the interpretation. The purpose and scope definition must be kept in mind while interpreting the data, as well as any limitations that the scoping decisions may have placed on a valid interpretation of the findings—such as assumptions about geography, time, or technology. [5].

1.2. Absolute vs relative LCA

In relative LCA a thorough list of factors can be used to compare the life-cycle impacts of two types of appliances when they are used for the same purpose over the same course of time. One of them may be deemed more environmentally sustainable than the other if it proves to have the best overall environmental performance (e.g., based on a weighted total of impacts). The selection of reference has therefore a significant impact on the result of a relative assessment.

On the other hand, an absolute assessment compares the environmental effects to an external list of environmental carrying capacities. For instance, the life-cycle climate impact of an individual's yearly commute from different modes of transportation may be compared to a portion of the carrying capacity. One or more sharing principles can be used to compute this carrying capacity share. For instance, the "equal per capita" concept may be applied first to determine a person's carrying capacity share, and then another principle may be applied to determine the value of commuting in relation to the other consuming activities the person engages in. Then, impact within its designated carrying capacity is checked.

1.3. Absolute Environmental Sustainability Assessment

Due to human activities, there is a growing need for techniques that support LCA and allow for the absolute environmental sustainability assessment (AESA) of anthropogenic systems. With an allotted share of the environmental carrying capacity for various impact categories, these approaches allow the comparison of the environmental impacts of different products, of different companies, etc. A number of LCA-based methods for AESA have emerged as a result of the growing emphasis on the limited character of the environment. [6]

"Is the environmental pressure of this activity sufficiently low for it to be considered environmentally sustainable, and if not, how much lower should the pressure be?" is the question that AESA is intended to address. Comparing the estimated environmental pressure of an activity to the environment's carrying capacity—which may be thought of as its maximum anthropogenic pressure that can be sustained over time—is the basis for the solution. [2]

Assessing if an anthropogenic system can be deemed ecologically sustainable in the strictest sense for a wide range of impact categories is the main goal of LCA-based AESA. The word ‘absolute’ signifies that AESA entails a comparison between the impacts of an anthropogenic system and the local or global boundaries of the environment, in contrast to relative (or comparative) assessments suggested by standard LCA techniques. A few AESA techniques also make it possible to determine future environmental impact targets. [6]

A collection of evaluation techniques known as AESA are intended to examine environmental sustainability in relation to absolute environmental boundaries. AESA includes a number of methodological methods, one of which is called "Absolute LCA" and is based on LCA. By directly contrasting environmental effects with Earth's carrying capacity, this approach assesses sustainability. [2]

1.4. Environmental impact assessment

The estimated environmental impact of one or more elementary flows (i.e., resource consumption or emission) that take place at any point during the life cycle of a studied anthropogenic system is known as an environmental impact assessment. An environmental process at the start of the environmental impact cause-effect chain, or even farther down this chain's end could be described by such a measure. For example, in terms of climate change, this would be the equivalent of CO2 emissions.

Similar to traditional LCA, the output of environmental models in the form of characterisation factors is used to connect the environmental impacts of the examined anthropogenic system's elementary flows, or the life cycle inventory result. Moreover, the impact categories pertaining to human health—which are frequently addressed in LCA - do not apply to AESA. This is so because AESA is more concerned with potential violations of environmental carrying capacities than it is with the direct effects that resource consumption and emissions may have on human health. [6]

1.5. Carrying capacity

Bjørn et al. [6] came up with the definition of carrying capacity as “the maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems or, in the case of non-renewable resource use, that corresponds to the rate at which renewable substitutes can be developed”. The carrying capacity in AESA refers to the maximum sustainable total anthropogenic effect.

Assigning a carrying capacity share based on one or more sharing principles is required when evaluating a single anthropogenic system. Different ethical standards underpin different principles, and the choice of sharing principle is normative. By putting one or more sharing principles into an equation and creating a connection to the necessary data, an operational AESA method enables its users to put them into practice. An assessment of an anthropogenic system's environmental sustainability with regard to the impact categories taken into consideration can be made by comparing the system's environmental impact to its allotted carrying capacity. There are approaches that could enable users to determine assigned carrying capacity targets for subsequent years if the system is shown to be environmentally unsustainable, meaning if the impact is greater than allocated carrying capacity. Each environmental indicator's environmental impact is compared to its allotted carrying capacity. Environmental impacts are not aggregated into a single score, for example through normalization and weighting processes, as per classical LCA. [6].

1.6. AESA method framework

AESA methods usually consist of four primary phases:

i. Definition of Activity: Clearly stating the nature and extent of the activity being studied.

ii. Quantification of Environmental Pressure: Calculating the effects that the specified activity has on the environment.

iii. Comparison of Environmental pressure to allocated carrying capacity: This phase is exclusive to AESA techniques. Here, the activity's compliance with sustainable resource use is assessed by comparing the environmental pressure to a predetermined "carrying capacity" level.

iv. Presentation of results: presenting a concise and useful summary of the results. [2]

The third phase, which compares environmental demand to carrying capacity, is crucial to Absolute LCA (LCA-AESA). It sets absolute LCA apart from relative LCA. Absolute LCA bases its study on absolute environmental criteria, verifying if the analyzed activity does not go beyond the thresholds. [2]

1.6.1. Methodological differentiators

To further clarify, six methodological choices that direct the approach to conduct assessments further differentiate the various AESA techniques. These choices consist of:

i. Approach to Setting System Boundaries: determining the system's scope for evaluation.

ii. Environmental Sustainability Objective: defining clear sustainability objectives for the evaluation.

iii. Quantification of Carrying Capacity: establishing measurable thresholds for environmental impacts based on the ecological constraints of Earth.

iv. Data Collection Approach: locating and compiling pertinent study data.

v. Allocation Principle: describing the distribution of affects across the different components of the system or procedure.

vi. Aggregation: combining impacts from several areas to produce a comprehensive evaluation.

In conclusion, six methodological choices and four assessment steps make up this framework. While phase III, which compares pressures to assigned carrying capacity, is specific to AESA methods, the other three assessment phases are present in all sustainability assessment methods. Similarly, three of the six methodological choices are present in all sustainability assessment techniques, but AESA approaches only use choices (ii), (iii) and (v). The foundation of Absolute LCA is determined by specific answers related to choices (ii), (iii) and (v).

1.6.2. Distinction between AESA and absolute LCA

To elaborate, absolute LCA is a subset of AESA that emphasizes adherence to absolute environmental limits, such as those defined by planetary boundaries or regional carrying capacities. In contrast, general AESA methods may adopt broader approaches, that are not strictly tied to fixed thresholds. Table 1 provides a comparative summary.

Table 1: Comparative summary

Aspect	AESA Framework	Absolute LCA
Key Focus	Sustainability assessment based on carrying capacities	Strict adherence to absolute thresholds
Environmental Limits	May include relative and absolute metrics	Based exclusively on absolute metrics
Methodological Choices	Broad set of choices	Specific focus on choices (ii), (iii) and (v). (See 1.6.1)

1.6.3. Current applications and growing interest

While the overall number of sustainability assessment techniques remains limited, their recent growth reflects increasing interest and application by various decision-makers.[2] More than 400 businesses, mostly big ones, have agreed to set "science-based targets" (SBT) for GHG emissions, or goals that fit within a worldwide emission reduction plan intended to meet the two-degree warming goal. The scientific and business communities are being urged by the World Wildlife Fund (WWF) to create approaches that allow corporate-level SBT to be defined for environmental challenges other than climate change.

The Global Thresholds & Allocations Council seeks to support the Global Reporting Initiative's recommendation that businesses report pollution loads "in relation to the capacity of the regional ecosystem to absorb the pollutant." Furthermore, national governments have expressed interest in using the concept of planetary boundaries to governance. [2]

1.6.4. Reference to sustainability assessment techniques

In 2018, Bjørn, Richardson, and Hauschild reported that Zijp et al. (2015) provided the most comprehensive review of sustainability assessment techniques, including:

1. Context-based sustainability
2. Ecological footprint

3. Human appropriation of net primary production (HANPP)
4. Methods originating in LCA community (i.e. absolute LCA)
5. Planetary boundaries
6. Science-based targets
7. Water footprint

This comprehensive list underscores the diverse approaches within the broader framework of AESA, emphasizing the critical role of absolute metrics in promoting sustainable practices.

2 Methodology

2.1. Research objectives

The aim of this systematic review is to address these questions:

1. What is Absolute Environmental Sustainability Assessment (AESA)?
2. What are the differences between absolute and relative LCA approaches?

2.2. Conducting the review

Scopus offers a thorough summary of global research output in the social sciences, arts and humanities, and technology domains. Scientific journals, books, and conference proceedings are some of the peer-reviewed materials found in this database. Scopus was therefore selected as the database to find the pertinent peer-reviewed papers for the purpose of this research. Some publications for the literature study were also found using the scientific libraries of Web of Science.

The research strings used include "absolute LCA" OR "absolute environmental sustainability assessment" AND "definition" OR "framework". "absolute LCA" AND "relative LCA" AND "differences" OR "comparison". "absolute LCA" OR "AESA" AND "application" OR "implementatio

3 Mapping

3.1. Studies selection

We took into consideration peer-reviewed academic articles. The following were the inclusion criteria:

i. A life cycle perspective must be taken for the study, which entails connecting a production or consuming activity to the anthropogenic processes that enable it.

ii. The study must be compliant to ISO standards ISO 14040 and ISO 14044 (which provide the principles, framework, requirements, and guidelines for conducting Life Cycle Assessments (LCA))

iii. For AESA purposes, carrying capacity estimations must be included in the study.

15 studies published between 2018 and 2024 were identified.

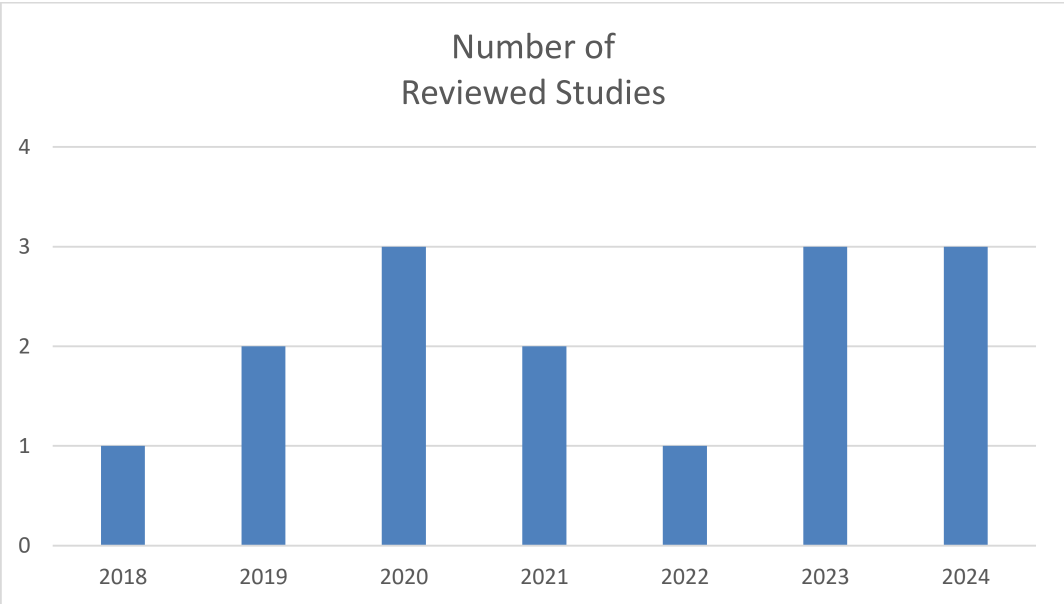

Figure 2: Number of reviewed studies in years

3.2. Detailed analysis of the reviewed studies

This section provides an overview of the 15 reviewed studies, highlighting their methodologies, system boundaries, and the sharing principles applied in the context of the Absolute Environmental Sustainability Assessment (AESA) framework. (See table 3). The studies focus on diverse systems and adopt varying functional units, reflecting their distinct scopes and objectives. Despite these differences, all studies offer valuable insights into the environmental impacts of their respective industries, utilizing AESA methods to analyze sustainability in absolute terms. The methods primarily fall into two categories: LCIA-based AESA and PB-based AESA.

3.2.1. LCIA based AESA

LCIA is a component of the Life Cycle Assessment (LCA) that measures the environmental impacts of goods and services throughout the course of their life cycles. In LCIA-based AESA, these impacts are analyzed against global or regional sustainability thresholds to determine if they are within sustainable boundaries. This method provides a relative evaluation of environmental performance by combining traditional life cycle assessment (LCA) with absolute sustainability criteria. While LCIA-based methods retain some characteristics of traditional LCA, they incorporate absolute limits, bridging the gap between relative assessments and absolute environmental sustainability.

3.2.2. PB based AESA

The Planetary Boundaries framework outlines the fundamental processes of the Earth system and the thresholds at which rapid environmental change threatens humankind. PB-based AESA assigns a portion of the planetary boundaries to particular goods, services, or industries in order to determine whether activities surpass these global limits. By directly connecting environmental impacts to the Earth's carrying capacity, this approach provides an absolute measure of sustainability. Unlike relative LCA, which evaluates impacts relative to a baseline or comparator, PB-based AESA measures impacts directly against ecological boundaries, emphasizing a stricter adherence to sustainability principles.

3.2.3. Key differences between LCIA-based AESA and PB-based AESA

Table 2: key differences between LCIA based AESA and PB based AESA

Aspect	LCIA based AESA	PB based AESA
Reference framework	It converts impact categories from conventional LCA techniques into terms of absolute sustainability.	It uses the Planetary Boundaries framework directly, emphasizing ecological limits on a global scale.
Allocation of limits	It frequently employs sector-specific or regional thresholds, which can change depending on the circumstances in a given area.	It calls for assigning a section of the world's planetary limits to particular entities, a complex process that may include arbitrary judgments.
Assessment nature	It compares impacts to predetermined thresholds (which might not necessarily be exact ecological limitations) to produce a relative assessment.	It provides a definitive evaluation by directly comparing impacts to global ecological boundaries.

In conclusion, whereas evaluating environmental sustainability within absolute ecological boundaries is the goal of both LCIA-based and PB-based AESA approaches; their frameworks, allocation strategies, and evaluation types vary. It is essential to comprehend these differences in order to choose the best approach for a given sustainability evaluation. Moreover, table 2 also indirectly highlights the key differences between absolute and relative approaches to LCA. Traditional LCA typically focuses on comparing impacts across systems or against a baseline (e.g., conventional versus innovative processes). In contrast, AESA methods aim to determine whether impacts remain within absolute ecological thresholds, ensuring environmental integrity.

In this review, 10 studies utilized the PB-LCIA method. Sensitivity analysis was performed in 11 studies, while 9 conducted uncertainty analyses. Regarding system boundaries, 7 studies adopted a cradle-to-gate approach, 7 used cradle-to-grave boundaries, and one study did not specify the system boundary. The variation in methodologies and boundaries highlights the need for harmonized approaches in AESA applications

3.2.4. Sharing Principles

The reviewed studies employ various sharing principles to allocate the Safe Operating Space (SOS)—the permissible environmental impact within planetary boundaries—across activities. For instance, CO2 emissions, freshwater use, or biodiversity loss. The SOS defines the limits that must be distributed across various activities to prioritize actions that ensure impacts remain within these boundaries. The most commonly used principles are the Equal Per Capita (EPC) and Grandfathering (GF) approaches:

1. Equal Per Capita (EPC): The Equal Per Capita (EPC) principle allocates environmental burdens equally across the global population, based on the assumption that all individuals have an equal right to resource use.

2. Grandfathering (GF): The Grandfathering principle is a more conservative approach, distributing environmental burdens based on historical usage patterns..

Other sharing principles identified include:

i. Gross Value Added (GVA) measures the value of products and services generated in a region, industry, or sector. It gives higher environmental responsibility to sectors or activities that make larger economic contributions.

ii. Economic Value Added (EVA) is the value generated over and beyond a company's shareholders' mandated return. It ties environmental responsibility to profitability.

iii. Agri-Land and Caloric Sharing distributes environmental resources according to agricultural land use and caloric production. It highlights how agriculture contributes to sustainability.

iv. Cumulative Impacts Per Capita takes into account the population divided by the total environmental impacts collected over time. It emphasizes long-term sustainability.

3.2.5. Geographical context

The location is not specified in 7 studies. Most of the reviewed studies have been published in 2023 and 2024, demonstrating the increased interest in this subject in the recent years.

Figure 3 reports the geographical context of the examined studies. The outcomes indicate a good representativeness of different context, including New Zealand, Europe and Asia.

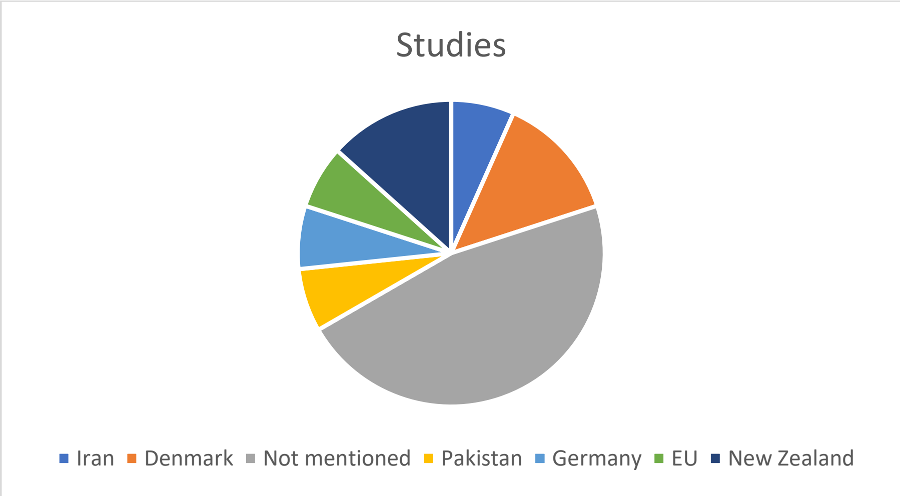

Figure 3: Geographical Context

Table 3: Features of the identified studies

No.	Name	Author	Year of Publication	LCIA Method	LCA based AESA Method	Allocation Principle	FU	System Boundary	Sensitivity analysis	Uncertainty Analysis
1.	Urea production: An absolute environmental sustainability assessment	Khadem Masjedi et al.	2024	ReCiPe 2016	PB-LCIA	Physical production output (PO)	1.8 million metric tons of urea per year	cradle to gate	Yes	Yes (Monte Carlo)
2.	Absolute environmental sustainability assessment of a Danish utility company relative to the Planetary Boundaries	Ryberg et al.	2020	Planetary Boundaries-based Life-Cycle Impact Assessment (PB-LCIA)	PB-LCIA	Equal Per Capita (EPC) for the global share and scaling based on consumption patterns	Annual supply of 8.36 million m^3 of water and management and treatment of 29.3 million m^3 of storm- and wastewater.	Cradle to gate	Yes	Yes

3.	Evaluating the Environmental Sustainability of Alternative Ways to Produce Benzene, Toluene, and Xylene	Zuiderveen et al.	2024	ReCiPe2016 Endpoint (H), ReCiPe2016 Midpoint (H) (V1.1), Environmental Footprint (EF) Method	PB-LCIA	Equal per Capita basis and then downscaling it to the product level (BTX) based on its price	production of 1 kg of mono-aromatics BTX	cradle to grave	Yes	Yes
4.	Achieving absolute sustainability across integrated industrial networks – a case study on the ammonia process	Samaroo et al.	2020	ReCiPe 2016	PB-LCIA	Grandfathering (Status-Quo)	one metric tonne of ammonia (NH_3) produced per hour.	Cradle to gate	yes	Yes
5.	Process design within planetary boundaries: Application to CO2 based	Vázquez et al.	2021	PB-LCIA	PB-LCIA	Egalitarian Principle based on Gross Value Added (GVA)	one ton of methanol (CH_3OH) produced.	Cradle to gate	Not specifically reported	Not specifically reported

	methanol production									
6.	How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology	Ryberg et al.	2018	PB-LCIA	PB-LCIA	Egalitarian: FCE, EU per cap & FCE, EU per cap & GVA. Grandfathering: Status-Quo	doing 34.3 billion washes per year of 4.5 kg of normally soiled dry fabric at medium water hardness with a model liquid detergent	cradle to grave	Yes	Yes
7.	Planetary metrics for the absolute environmental sustainability assessment of chemicals	Tulus et al.	2021	PB-LCIA	LCIA based	Equal Per Capita and Grandfathering	one kg of the reference product (chemical) of a specific global market	Cradle to gate	Not mentioned	Not mentioned

8.	Framework for developing technology roadmap based on absolute environmental sustainability assessment: A case study on electric vehicles	Ali et al.	2023	PB-LCIA	PB-LCIA	Equal Per Capita	the number of person kilometres travelled (pkt) by German population in a given year			
9.	Absolute environmental sustainability assessment of rice in Pakistan using a planetary boundary-based approach	Mahmood et al.	2023	ReCiPe 2016 (v 1.02) with Hierarchist (H) perspective	PB-LCIA	equal per capita, economic value, agri-land, and caloric values	1 tonne of milled rice at factory-gate	Cradle to gate	Yes	Yes
10.	Absolute environmental sustainability	Charalambous et al.	2023	PB-LCIA	PB-LCIA	full-SOS approach	global freight trucking	Cradle to grave	Yes	Yes

	assessment of renewable dimethyl ether fuelled heavy-duty trucks						demand supplied by the "business-as-usual" (BAU) scenario			
11.	Assessing buildings' absolute environmental sustainability performance using LCA focusing on climate change impacts	Ohms et al.	2019	PB-LCIA	PB-LCIA	Not explicitly mentioned	annually house one family in a stand-alone dwelling in Denmark	Cradle to grave	yes	Not mentioned
12	Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings	McLaren et al.	2020	Not mentioned	LCIA based	cumulative impacts per capita	construction and occupation of a residential dwelling over its	Cradle to grave	Not mentioned	Not mentioned

							reference service life			
13	Absolute Environmental Sustainability of Materials Dissipation: Application for Construction Sector	Baabou et al.	2022	MACSI model (Materials' Anthropogenic Carrying Capacity for Sustainability Implementation)	LCIA based	equal per capita and grandfathering	use of steel within the life cycle of a school building	Cradle to grave	yes	not mentioned
14	Absolute Sustainability Assessment of the Danish Building Sector Through Prospective Lca	Horup et al.	2024	EF 3.1	LCIA based	acquired rights	the provision of materials required for the construction of all new buildings in Denmark over the period 2025-2050, measured in	cradle to grave	yes	Yes

							terms of square meters of building area			
15	Evaluation of New Zealand's Absolute Environmental Sustainability Performance: Development and Application of a Method to Assess the Climate Change Performance of New Zealand's Economic Sectors	Chandrakumar C.	2019	Not mentioned	LCIA based	grandfathering and economic value	construction and occupation of a detached house over its lifetime	Cradle to grave	yes	yes

4 Discussion

This review investigates a new method in environmental research: the life-cycle-based Absolute Environmental Sustainability Assessment (AESA) framework. This framework compares the estimated environmental burden that a system generates over the course of its life cycle to the carrying capacity that can be assigned to this system—that is, the amount of impacts that the system can cause without unacceptably impairing the functional integrity of the ecosystem. This is because stakeholders must do more than just perform a relative environmental sustainability assessment to evaluate how their actions are affecting the environment, for example comparing two systems with comparable functions to identify which one is best. From a strong sustainability perspective, they must decide if their efforts to lessen their impacts are in line with the limits of the planet. [7]

In this context, the reviewed studies demonstrate that the AESA framework is essential for determining whether production or consumption activities are sustainable in absolute terms. Most studies reviewed use the Planetary Boundaries-Life Cycle Impact Assessment (PB-LCIA) method. A control variable that can be either an environmental state or a flow rate is used to express the PB's metric and the Earth System process's state. [11] Alarmingly, anthropogenic pressures have already caused the exceedance or near exceedance of multiple PBs, even though in theory none of them should be violated. [12]

One of the key challenges in applying the PB-framework to life cycle assessment (LCA) lies in the translation of PB metrics to LCA impact categories. The translation of the metrics in the PB-framework to the impact categories in LCA is not straightforward. It is because the two systems quantify environmental impacts using different measures and scales. It's not a straightforward one-to-one connection. The PB-framework evaluates impacts at a global scale, whereas LCA concentrates on impacts at the product level. There are some planetary boundaries that have no direct parallel in LCA. For instance, species extinction rates may be a component of biodiversity loss in PB, whereas habitat damage or land use may be used to represent this in LCA. Another example can be the eutrophication or acidification categories of LCA, which may not be immediately correlated with the nitrogen and phosphorus flows in PB.

Furthermore, the PB-framework's control variables are based on the Earth System's Holocene state, whereas LCA indicators focus on protection areas such as resources, ecosystems, and human health. This divergence limits the PB-LCIA method's applicability to production-oriented activities, as its indicators are pre-allocated into equal yearly per capita budgets. While effective for guiding consumers on sustainable living, this approach is less suitable for assessing the impacts of production activities on planetary boundaries. [11]

5 Conclusion

The review highlights the growing importance of absolute sustainability approaches over traditional relative methods, as the latter often fail to ensure impacts remain within planetary boundaries.

Regarding absolute sustainability approaches, many societal actors, including governmental agencies and businesses, have embraced the PB-framework in order to verify sustainability in connection to the PBs. This can be seen in this review. However, despite this interest, there are currently no steady and practical ways to measure human activities (such as the development of technology and products) in connection to the PBs. Therefore, work is needed in this area. [11]

The AESA framework and PB-LCIA methods offer significant potential for advancing environmental sustainability assessments. They provide essential insights into whether human activities remain within planetary boundaries. However, substantial gaps remain in the integration of PB metrics with LCA impact categories. Future research should focus on developing methodologies that align the PB framework's global-scale metrics with LCA's product-level indicators. This includes exploring ways to address gaps, such as the absence of direct parallels between PB metrics (e.g., species extinction rates) and LCA categories (e.g., land use or biodiversity impacts). Additionally, tailored approaches are needed to assess production-oriented activities within the context of planetary boundaries, moving beyond the current consumer-focused, per capita-based frameworks.

Bridging these conceptual and methodological differences is critical to creating actionable tools for evaluating and mitigating the impacts of human activities. By advancing these connections, researchers and policymakers can develop more robust tools to ensure that production and consumption systems contribute to a sustainable future within Earth's limits.

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A Appendix A

A.1. Table 1

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List of Figures

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Acknowledgments

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