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E DELL'INFORMAZIONE

Sustainability indicators in the manufacturing industry: a Systematic literature review and a framework proposal.

THESIS FOR MASTER'S DEGREE IN
MANAGEMENT ENGINEERING

Author: **Luis Miguel Andraus**

Student ID: 10825017
Advisor: Prof. Federica Acerbi
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Contents

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For my wife, without her this wouldn't have been possible.

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Abstract

This thesis aims to identify which sustainability indicators can be used by the manufacturing industry, in order to propose a more organized guideline since there is no consensus on which indicators to implement, or how to effectively do it. This research was carried out using a Systematic Literature Review using the scientific database SCOPUS, this research aims to analyze within the context of the Triple Bottom Line, which categories of sustainability are the most studied as well as which indicators are being used to measure them and accordingly propose a framework which is composed by a sequence of steps as well as a selection of general and adaptable indicators, that aims to facilitate the process for companies to include sustainable practices in their operations. Finally, this review also elucidates some scientific literature gaps found and suggests future research directions.

Keywords: Sustainability indicators, sustainable manufacturing, sustainability assessment framework, systematic literature review.

1. Introduction

The first time the concept of sustainable development came into discussion was in 1987 when Gro Harlem Brundtland wrote about it in a report for the World Commission on Environment and Development, even though, moving towards a sustainable society had been a concern long before it had a name. This concept entails the "meeting the needs of the present without compromising the ability of future generations to meet their own needs." ((WCED), 1987). Today, almost 40 years later, we are still trying to figure out the best way to achieve this goal.

Moreover, sustainability development takes into consideration a wide range of factors, which is why its study has been divided into 3 main fields, known as the Triple Bottom Line (TBL) that includes social sustainability, economic sustainability and environmental sustainability (Elkington & Rowlands, 1999), this model allows researchers to deepen their understanding in the area that is more relevant to the industry or topic they aim to study.

Nowadays, companies are obliged to adopt sustainable practices in all their operations thanks to the enforcement of rigorous environmental, social and health legislations due to the need of slowing down the use of non-renewable resources, as well as the rapid increase in customer consciousness regarding sustainable practices and their importance when choosing products. (Biju et al., 2015). To achieve this, companies are compelled to measure, assess and then reevaluate their practices in order to render them as sustainable as possible.

Pertaining to the manufacturing industry, an exhaustive definition states that "sustainable manufacturing at product, process and system levels must demonstrate reduced negative environmental impacts, offer improved energy and resource efficiency, generate minimum quantity of waste, provide operational personnel health while maintaining and/or improving the product and process quality with the overall life-cycle cost benefits." (Jawahir et al., 2013)

From this definition we can deduce that the pillar that is mostly related to sustainable manufacturing is the environmental one, because resource planning is highly linked to the environmental dimension of sustainability (Medne & Lapina, 2019) and in the words of Barbieri (2002 as cited in Murad et al., 2021) the actions targeting the elimination or reuse of waste in the early stages of the manufacturing process result in an increase in productivity. To simplify, the environmental aspect of sustainability refers to the "preservation of the ecological conditions of human survival" this equal to the ability to maintain the natural resources over time. (Sherif et al., 2022) and the manufacturing sector is considered one of the main contributors to environmental degradation. (Zeng et al., 2008).

Furthermore, organizing and deepening the available knowledge of the sustainable manufacturing has gained even more relevance due to the recent world events, according to a New York Time's article after the pandemic of COVID-19 there has been a shortage of goods in most industries due to a disruption of the supply chains and lack of raw materials (Goodman & Chokshi, 2021), for this reason it has become even more crucial to increase the effectivity in the supply chain so that the processes are as sustainable as possible which would mean for example a wiser use of materials, a reduction in waste, a decrease of the emissions and more.

Finally, to be able to assess sustainability correctly, companies need to use metrics or indicators, these indicators "should depict a clear picture of the problem under observation and make the measurement possible. Indicators are expressed in real values or binary units." (Diaz-Chavez, 2014 as cited in Ahmad et al., 2019) therefore, these indicators translate complex issues into understandable information that helps the decision-making process of all stakeholders (Samuel et al., 2013) and even though there is not a framework able to work for all industries, a more consistent and standardized approach on sustainability indicators allows companies to monitor and compare their performance. (Eastwood and Haapala, 2015). However, the "lack of practically applicable and measurable indicators discourages practitioners to undertake a sustainability assessment of their activities" (Ahmad et al., 2019). As well as the vast number of indicators present in the literature. In consequence, there is a strong need to identify and organize the sustainability indicators that can be used by the manufacturing industry and establishing the purpose of each indicator. This will allow us to provide guidance to companies that want to start evaluating themselves in terms of sustainability or want to improve their assessment methods.

2. Methodology

To address the research objective of proposing a sustainability indicators framework for the manufacturing sector, it was crucial to understand what companies have been doing until now, what previous research has found and reunite and analyze that information, to do so a Systematic Literature Review was developed.

This research is valuable for the manufacturing sector because an effective implementation of sustainability practices, allows companies to ensure economic growth, conserve natural resources, minimize the negative environmental and social impacts as well as meeting the requirements of stakeholders. (Mengistu & Panizzolo, 2023). However, even though this topic is widely studied, researchers have yet to agree on a standardized or diffused method to analyze or compare themselves in terms of sustainability criteria. Hence the need for a framework that collects the most relevant sustainability indicators for companies to use as a guideline.

1.1. SLR methodology

A Systematic Literature Review (SLR) is a structured process that elucidates the current state of research of a subject and allows to identify gaps and areas requiring further research. (Transfield et al. 2003).

A SLR comprehends different steps which are defined differently in the literature as follows: (Fink 2014, p. 4, Transfield et al. 2003).

1. Defining research questions
2. Selecting databases and other research sources

3. Defining search terms
4. Merging hits from different databases
5. Applying inclusion and exclusion criteria
6. Perform the review
7. Synthesizing results

1.1.1. Selecting databases

Taking into consideration that sustainability is a wide concept and broadly studied, by using the SLR we are able to address the results of the research properly. The research relies on papers accessible on Scopus, due to it being the most diffused scientific database for engineering subjects. The recollection phase stopped on 14th May 2023. The process included a screening process as well as keyword and eligibility criteria definition.

1.1.2. Keyword definition

The definition of the keywords was preceded by a random search dealing with the topics of this paper. This process allowed the discovery of the right combination for the query by eliminating those keywords that brought up inaccurate results that were not about assessing sustainability or those who didn't talk about the manufacturing sector. Hence the keywords used were: "Sustainability indicators" AND "manufacturing."

This query allows the research to be limited to the papers focused on the evaluation of sustainability within the manufacturing industry.

1.1.3. Eligibility criteria

The platform chosen for the recollection of articles was SCOPUS and the search was limited to results in English with no restriction of publication year.

Firstly, an elimination took place in order to be able to select the relevant papers to be included in the review according to the keywords and the intended output of the research, this phase was based on reading and assessing the title and abstract. After this the final phase consisted in reading the whole document and selecting those that are relevant to the purpose of this study. The main criteria used to discard articles were:

- Papers that involved solely sustainability indicators from the social or economic denomination.

- Papers proposing new indicators not yet proven or not broadly used.
- Papers talking about indicators from the entire supply chain without specifying indicators for the manufacturing sector.
- Papers proposing mixing indicators to measure them better.
- Papers mentioning established frameworks instead of single indicators.
- Papers that address sustainability in the manufacturing sector in general but not its evaluation or measurement.

These criteria helped limit the sample to papers that measure sustainability in the manufacturing industry in terms of measurable, common indicators.

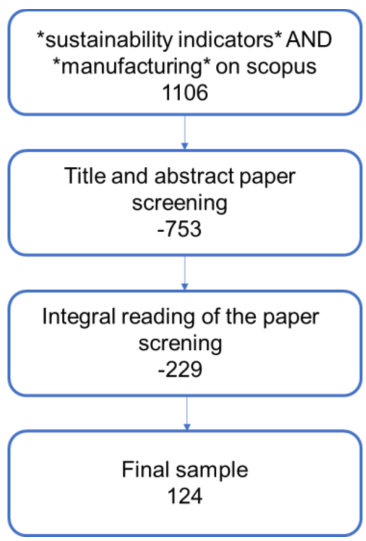

Figure 1. Paper screening process.

1.2. Theoretical Framework

This theoretical framework intends to describe how the review process was conducted.

1.2.1. Manufacturing stages

First, the final sample of papers was divided into the manufacturing stages that each of them tackles.

1. The design stage: here were grouped those studies referring to the planning stage of the manufacturing process this includes raw material scheduling and acquisition and inventory control. (Beamon, 1998)

2. The operation stage: here are included those papers focusing on measuring sustainability on the manufacturing operation itself.

3. The distribution and logistics: this stage of the manufacturing process refers as to "how products are retrieved and transported, this entails management of inventory retrieval and delivery." (Bete an, 1998)

4. General: this category groups the papers tackling sustainability indicators without specifying the stage of the manufacturing process or those who studied more than one of the previously mentioned manufacturing stages.

1.2.2. Classification of sustainability indicators

Subsequently, the sources were divided into the sustainability indicators that they studied.

- **Environmental indicators**

The indicators pertaining to the environmental dimension of sustainability refer to the idea of eco-system, meaning both renewable and non-renewable resources as well as the waste-absorption capacity of the earth (Moldan et al., 2021). These indicators, also called physical dimension of sustainability, are valuable to assess and prevent damage to the natural environmental system. (Huang et al. 2009).

Among the common environmental indicators studied in this SRL we can mention: amount of water used, amount of recycled material used, energy consumption, hazardous waste generation, etc.

- **Social indicators**

The concept of social sustainability considers human needs (Zarte, Pechman, & Nunes, 2019) and relies on the ideas of equity, accessibility, sharing and institutional stability. Its purpose is "to preserve the environment through economic growth and alleviation of poverty." (Basiago, 1998).

Within the social indicators we can find: health & safety, training/development, working conditions, employee satisfaction, frequency rate of accidents.

- **Economic indicators**

Lastly, the economic dimension of sustainability entails "the economic welfare of stakeholders as well as local and national economic systems (Butnariu and Avasilcai, 2015).

This dimension can be recognized as the most important goal for manufacturing industries (Zarte, Pechman, & Nunes, 2019). Inside it we have indicators such as: operating costs, investments for sustainability, labor costs, energy cost, quality costs.

1.2.3. Synthesizing results

The first step to analyze the contributions relies on the typical dimensions of the research literature, this allows us to perform descriptive statistics in order to screen the papers and have an overview of the sample tackled in this study. The dimensions presented are as follows:

- Publication year
- Type of publication
- Source title (i.e the journal name)
- Manufacturing stages
- Sustainable pillars (i.e environmental, economic and social)

3. Results of SLR

3.1 Descriptive statistics

In order to have a clear overview of the sample of contributions included in this study, some descriptive statistics are presented below:

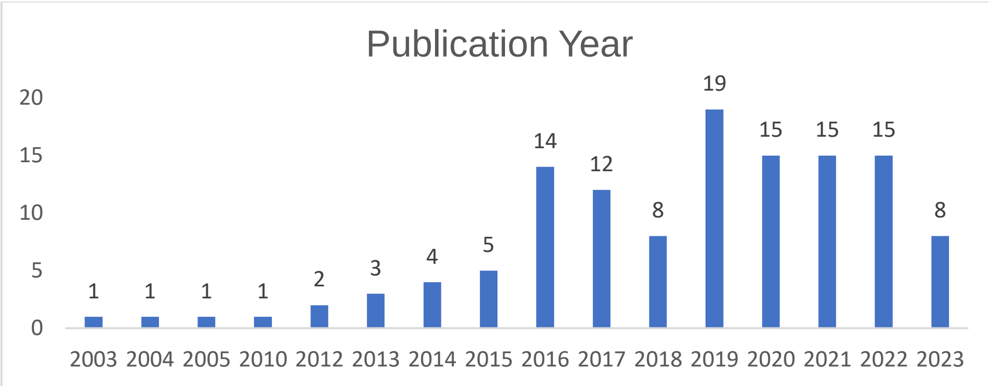

Figure 2. Descriptive statistics: Publication year

First, even though the time frame of the articles was not restricted, we can see that most of the selected papers were written from 2016 to 2022, as shown in **Figure 2.** Which evidences that sustainability indicators started to arouse interest in 2016 and has maintained its relevance until today.

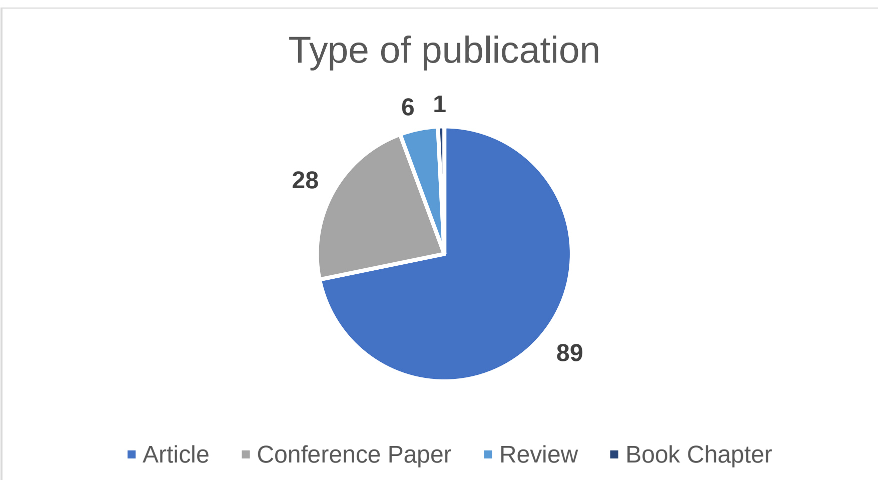

Figure 3. Descriptive statistics: Type of publication

Second, we can highlight that the majority of contributions are articles being the 71.8% of the total sample, followed by conference papers that amount to 22.6%, as reported in **Figure 3**.

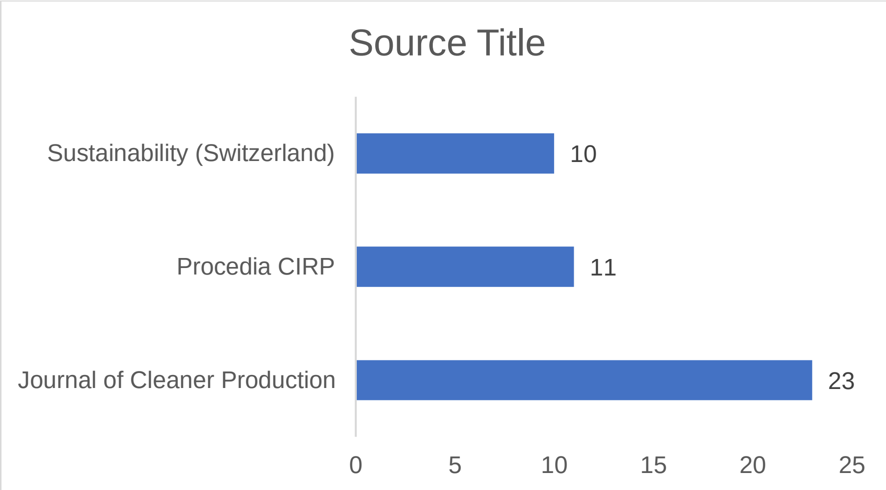

Figure 4. Descriptive statistics: Top 3 Journals

Leveraging on **Figure 4** we can identify the journal with a higher percentage of included publications was *Journal of Cleaner Production*, seconded by *Procedia CIRP* and closely followed by *Sustainability (Switzerland).*

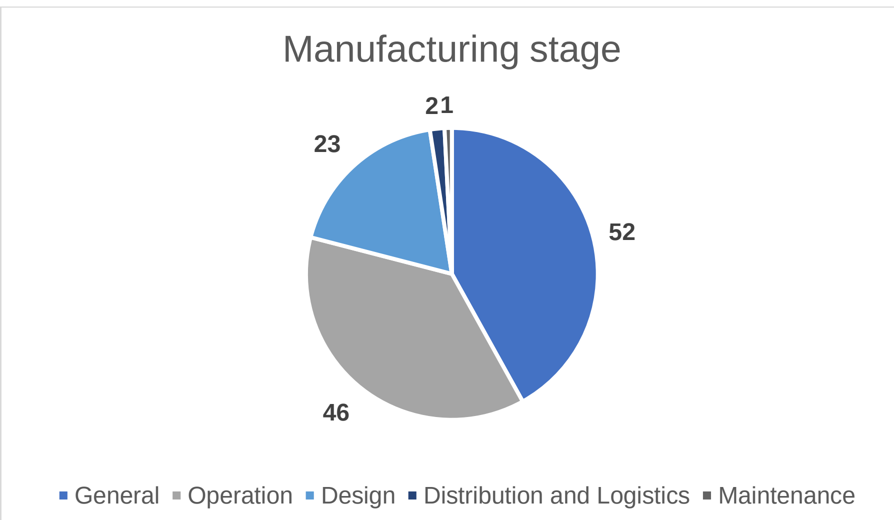

Figure 5. Descriptive statistics: Manufacturing stage

As reported in **Figure 5**, we can highlight that the literature found refers mostly to the general manufacturing process, but it's worth noting that the manufacturing stage with most contributions is *Operation*, with 41.9%. Lastly, the *Distribution and Logistics* and the *Maintenance* stages were the ones with the least articles found.

1.3. Analysis by type of sustainability indicators

To be able to analyze the sources properly, the analysis was divided into two tables since not all the contributions proposed an actual measurable indicator but just studied how to improve sustainability in their manufacturing processes. For example, in their study, Saxena et al., (2020) centered on reducing aspects such as waste, power consumption and prices and increasing "environmental friendliness" and operational safety. This division helped carry out the analysis in a more comprehensive manner.

Moreover, a further classification was carried on among the macro division of sustainability indicators (Environmental, social and economic), in this division we identified which indicator was studied or measured in each of the contributions. To construct categories in the tables, the base was a categorization proposed by Murad et al., (2021) that divided each sustainability pillar into micro categories (i.e: for environmental sustainability: *Environmental training*, *hazardous waste*, etc.) and similarly for social sustainability and economic sustainability.

In the words of Ahmad et al., (2019b) some categories (that for this study are referred to as clusters) were further divided and measured accordingly, for example *Raw Materials* can be found in terms *Primary materials* or *Secondary packaging materials*, were as micro categories as *Solid waste* were reported on a general basis. But since the studied contributions don't have the same division for their sustainability categories, afterwards, more micro categories were added as they were found in the studied contributions and didn't fit into the previously proposed ones. For example, Song & Moon, (2019) groups *Energy* and *Raw Materials* below a category called "resources" where as in Ayabaca & Vila, (2020) *Raw Materials* is a separated category. Therefore, the final division to study the sustainability clusters and micro categories proposed by each paper is illustrated in Figure 6.

It is worth noting that some micro categories might contain other micro categories within itself, for example in the economic dimension the most studied indicators are relating to the *Operating cost* which was found to contained within it other very studied indicators such as *Labor cost* which Leong et al., (2020) states that is highly dependent on "employee qualifications, experience and expertise." This is highly relevant since, even though the environmental sustainability pillar is the most studied one, it can be said that the economic dimension is the most relevant as a goal for companies is the economic one. (Zarte et al., 2019).

Moreover, talking about the environmental category and across all sustainability pillars, in each analysis was found as the most studied the category of *Greenhouse emissions*, and in terms of indicators, 31 out of 40 proposed the same one, even though it can be found across the literature with different names such as *Global warming potential* (Huedo et al., 2016; Rahla et al., 2019; Ruiz-Mercado et al., 2012a), *Carbon Emissions* (Bhanot et al., 2016b; Zhu et al., 2022) or *Greenhouse Emissions (GHG)* (Lamjahdi et al., 2021b; Munasinghe et al., 2017; Tan et al., 2015a; Watanabe et al., 2016). The extensive research about this indicator can be explained due to it being a globally important factor from the climate change perspective, but since it has been found that installing devices to reduce pollutant emissions is a high investment/maintenance, small and medium size companies would not engage in the efforts to tackle it. (Thirupathi et al., 2019).

Finally, regarding the social pillar Health & Safety was highly present in this contribution sample. But opposite to *Greenhouse Emissions,* there is no consensus when referring to the actual indicators, because it focuses on factors that can impact health which depending on the type of sector may vary, for example the following indicators were found: Noise exposure (Swarnakar, Singh, & Tiwari, 2021a), Amount of money for non-compliance of regulations (Kocmanova et al., 2017), Medical health checkups (Kumar et al., 2022), Biological, chemical, physical, ergonomic, safety hazard exposure risk (Mesa et al., 2019), Employee health and safety provision (self-perception) (Sureeyatanapas et al., 2015).

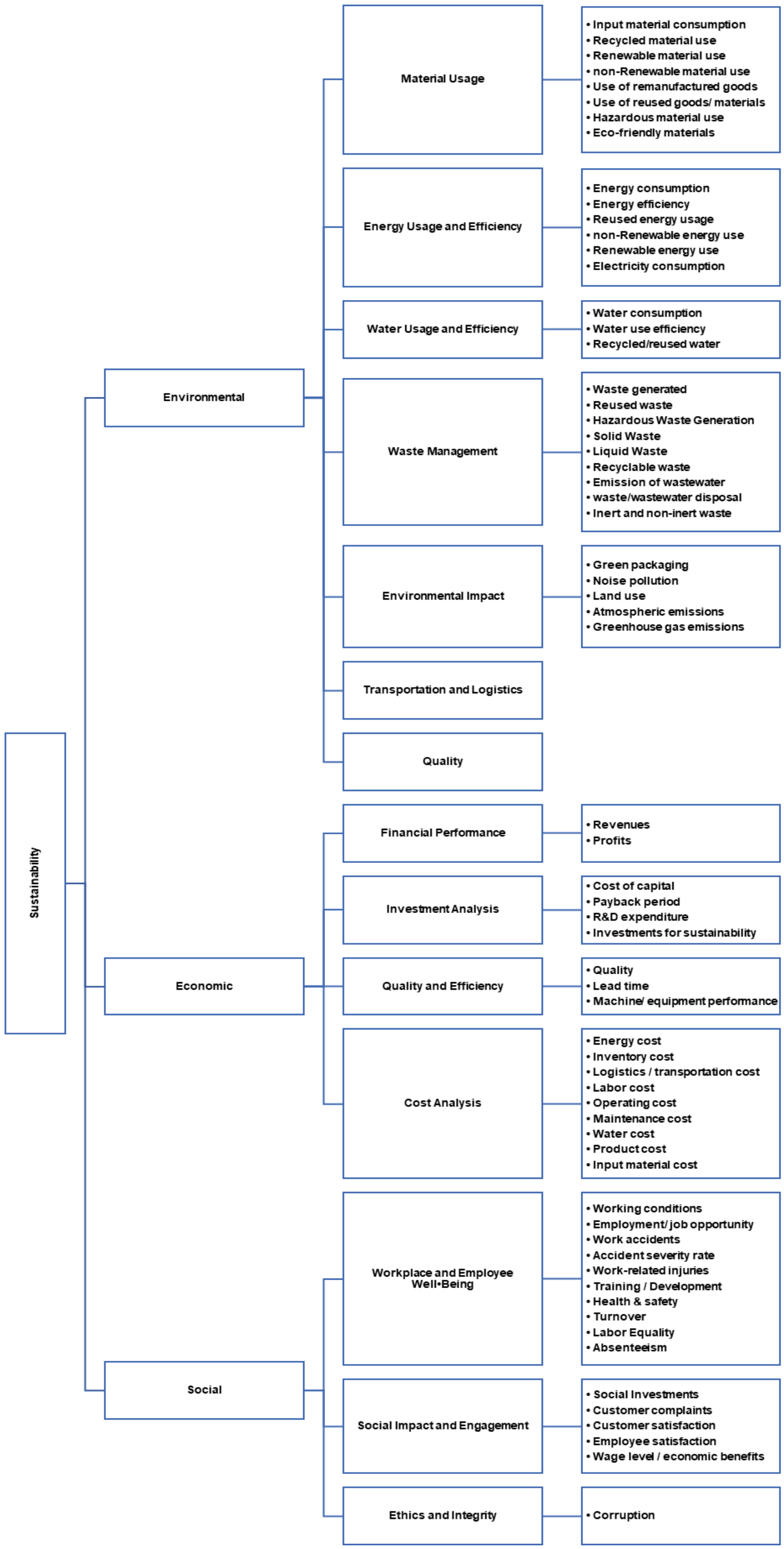

Figure 6. Sustainability pillars division.

1.3.1. Analysis step 1: Sustainability indicators studied

In this part, we signaled which micro category was studied in the research carried out in each article but was not necessarily assigned or proposed a specific indicator to measure it.

1.3.1.1. Environmental Indicators studied per publication

		Material Usage								Energy Consumption and Efficiency						Water Usage and Efficiency			Waste Management									Environmental Impact						
Manufacturing process	Reference	Input Material Consumption	Recycled Material use	Renewable material use	non-Renewable material use	use of Remanufactured goods	use of Reused goods/materials	Hazardous material use	Eco-friendly materials	Energy Consumption	Energy Efficiency	Reused energy usage	non-Renewable Energy use	Renewable Energy use	Electricity Consumption	Water consumption	Water use efficiency	Recycled/Reused water	Waste Generated	Reused waste	Hazardous Waste generation	Solid Waste	Liquid waste	Recyclable waste	Emission of wastewater	Waste/wastewater disposal	Inert and non-inert waste	Green Packaging	Noise pollution	Land use	Atmospheric emissions	Greenhouse Gas Emissions	Transportation and Logistics	Quality
Design	(Leong et al., 2020)	✓																														✓		
Design	(Pask et al., 2017)									✓											✓													
Design	(Thorenz et al., 2018); (Lucato et al., 2018)	✓								✓																								✓
Design	(Assad et al., 2019)	✓								✓	✓																							
Design	(Rahla et al., 2019)																					✓	✓								✓	✓		
Design	(P. P. Singh & Madan, 2016)												✓		✓							✓										✓		
Design	(Huedo et al., 2016)									✓						✓					✓											✓		
Design	(Michałowski & Michalak, 2021)												✓	✓					✓												✓	✓		
Design	(Linke et al., 2014)	✓								✓	✓						✓		✓															
Design	(Mangili & Prata, 2020)	✓								✓	✓						✓		✓													✓		

Design	(Ayabaca & Vila, 2020)	✓	✓							✓									✓							✓						✓		
Design	(Taddese et al., 2021)	✓								✓				✓					✓												✓	✓	✓	
Design	(Machado et al., 2019)	✓	✓	✓					✓		✓																				✓			✓
Design	(Santolaya et al., 2019)	✓														✓	✓					✓	✓								✓	✓	✓	
Design	(Mortazavi & Ivanov, 2019)									✓					✓				✓		✓	✓	✓		✓				✓			✓		
Design	(Mani et al., 2014)									✓			✓		✓	✓			✓			✓			✓						✓	✓		
Design	(Hegab et al., 2018)	✓								✓	✓								✓			✓	✓						✓		✓	✓		✓
Design	(Watanabe et al., 2016)		✓				✓			✓							✓	✓	✓						✓			✓			✓	✓		
Design	(Saavalainen et al., 2017)	✓		✓					✓	✓	✓								✓		✓	✓	✓								✓	✓		
Design	(Smith et al., 2019)	✓		✓				✓			✓			✓		✓					✓	✓	✓		✓						✓	✓		
Design	(S. Kim & Moon, 2017)	✓			✓					✓	✓					✓	✓		✓		✓	✓	✓					✓			✓	✓		
Design	(König et al., 2022)	✓				✓	✓		✓		✓			✓	✓	✓	✓	✓	✓	✓		✓	✓		✓						✓	✓		✓
Distributio n and Logistics	(Barbosa et al., 2023)									✓																						✓	✓	
Distributio n and Logistics	(Li & Mathiyazhagan, 2016)	✓																	✓						✓	✓					✓	✓		
General	(Hsu et al., 2017)	✓							✓	✓						✓		✓	✓	✓					✓	✓					✓	✓		
General	(Kubule & Blumberga, 2019)									✓																						✓		
General	(Edtmayr et al., 2016)																		✓															✓
General	(Voces et al., 2012)																		✓														✓	
General	(Mengistu & Panizzolo, 2023b)	✓	✓							✓	✓																							
General	(Hu & Chong, 2021)	✓								✓									✓												✓			

General	(Chang & Cheng, 2019)	✓						✓																					✓			✓		
General	(Nagarajan et al., 2018)	✓								✓	✓								✓															
General	(Peruzzini & Pellicciari, 2016)									✓	✓					✓																✓		
General	(Munasinghe et al., 2017)	✓								✓																		✓				✓	✓	
General	(Helleno et al., 2017)								✓						✓		✓		✓							✓								
General	(Naderi et al., 2017)	✓								✓									✓						✓	9					✓			
General	(Favi et al., 2022)	✓											✓		✓	✓															✓	✓		
General	(Kibira et al., 2018)	✓								✓	✓											✓									✓	✓		
General	(Kocmanova et al., 2015)													✓		✓			✓		✓										✓	✓		
General	(Zarte et al., 2019a)	✓								✓						✓			✓											✓	✓	✓		
General	(Moslehi & Arababadi, 2016)	✓									✓					✓									✓					✓	✓	✓		
General	(Lanz et al., 2014)	✓								✓						✓			✓												✓	✓	✓	
General	(Seuring et al., 2003)	✓								✓						✓			✓									✓				✓	✓	
General	(K. Singh & Sultan, 2018)	✓								✓			✓			✓						✓								✓	✓	✓		
General	(Kocmanova et al., 2017)	✓	✓							✓						✓			✓		✓										✓	✓		
General	(Amrina & Vilsi, 2015)	✓								✓			✓			✓			✓										✓	✓	✓			
General	(Mikko et al., 2013)	✓							✓	✓	✓																	✓			✓	✓	✓	
General	(Saygili et al., 2023)		✓	✓						✓	✓							✓						✓							✓	✓	✓	
General	(Shabir et al., 2023)										✓						✓		✓			✓			✓					✓	✓	✓	✓	
General	(Contini & Peruzzini, 2022)	✓	✓							✓											✓								✓	✓	✓	✓	✓	
General	(Nagel & Tomiyama, 2004)	✓							✓	✓									✓			✓						✓			✓	✓	✓	
General	(Chaim et al., 2018)	✓								✓						✓			✓		✓	✓	✓							✓	✓	✓		
General	(Ingwersen et al., 2016)	✓								✓			✓	✓	✓	✓							✓							✓	✓	✓		

General	(Kaldas et al., 2020)	✓						✓		✓	✓			✓			✓	✓	✓					✓							✓	✓		
General	(Latif et al., 2017)									✓	✓	✓	✓	✓	✓	✓			✓							✓					✓	✓		
General	(Hsu et al., 2017)	✓								✓	✓					✓	✓				✓	✓	✓							✓	✓	✓		
General	(Kluczek, 2017)	✓									✓		✓						✓		✓	✓	✓			✓	✓			✓	✓	✓		
General	(S. Singh et al., 2014)	✓	✓				✓	✓			✓					✓			✓		✓				✓					✓	✓	✓		
General	(Joung et al., 2013)	✓	✓	✓		✓	✓			✓			✓	✓					✓											✓	✓	✓		
General	(Ahmad et al., 2019)	✓						✓		✓			✓		✓	✓					✓	✓	✓		✓			✓			✓	✓		
General	(Ruiz-Mercado et al., 2012)	✓	✓	✓				✓		✓	✓					✓	✓				✓	✓	✓								✓	✓		
General	(Paju et al., 2010)	✓								✓			✓	✓	✓	✓			✓			✓	✓				✓				✓	✓	✓	
General	(Gani, Bhanot, et al., 2022)	✓	✓						✓	✓	✓		✓	✓		✓	✓	✓				✓			✓					✓	✓	✓		
General	(Swarnakar, Singh, Antony, et al., 2021)	✓	✓	✓			✓			✓					✓	✓			✓		✓	✓	✓		✓	✓						✓		✓
General	(G. Kim et al., 2022)	✓	✓	✓						✓	✓	✓	✓				✓	✓	✓		✓	✓		✓	✓					✓	✓	✓		
General	(Sharma, 2021)	✓		✓				✓	✓	✓			✓	✓		✓	✓		✓			✓	✓		✓				✓		✓	✓	✓	
General	(Taddese et al., 2020)	✓	✓	✓		✓	✓			✓	✓			✓		✓		✓	✓			✓	✓		✓					✓	✓	✓		
General	(Cagno et al., 2019)	✓					✓	✓		✓		✓		✓		✓		✓	✓		✓	✓	✓	✓	✓	✓					✓	✓		
General	(Sherif et al., 2022)	✓	✓	✓						✓	✓		✓	✓			✓		✓		✓	✓			✓	✓	✓	✓			✓	✓	✓	
General	(Barni et al., 2022)	✓	✓	✓						✓			✓	✓	✓	✓		✓	✓	✓	✓			✓	✓	✓				✓	✓	✓		
General	(Gani et al., 2021)	✓	✓			✓		✓		✓	✓		✓	✓		✓		✓	✓		✓	✓	✓			✓				✓	✓	✓		
General	(Sangwan et al., 2019)	✓	✓					✓		✓			✓	✓		✓		✓		✓	✓	✓	✓					✓	✓	✓	✓	✓	✓	
General	(Gharfalkar et al., 2018)	✓	✓						✓	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				✓	✓	✓		
General	(Mengistu & Panizzolo, 2023a)	✓	✓	✓				✓		✓	✓			✓	✓		✓	✓	✓		✓	✓		✓	✓			✓		✓	✓	✓		
General	(Helman et al., 2023)	✓	✓	✓		✓		✓	✓	✓	✓			✓	✓		✓		✓		✓			✓	✓					✓	✓	✓	✓	
General	(Cagno et al., 2023)	✓				✓	✓			✓	✓	✓	✓	✓				✓	✓		✓	✓	✓	✓	✓	✓					✓	✓	✓	
General	(Gani et al., 2020)	✓	✓			✓	✓			✓	✓		✓	✓		✓		✓	✓		✓	✓	✓		✓			✓		✓	✓	✓		
General	(Labuschagne et al., 2005)	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				✓		✓	✓			✓	✓	✓	✓		

Maintenance	(Franciosi et al., 2020)	✓	✓	✓				✓		✓	✓					✓			✓		✓				✓	✓			✓	✓	✓	✓		
Operation	(Chaubey & Gupta, 2022)	✓													✓																			
Operation	(Ming et al., 2021)										✓																				✓			
Operation	(Firmino et al., 2022)	✓								✓																						✓		
Operation	(Marie et al., 2022)															✓			✓										✓					
Operation	(Karkalos et al., 2021)	✓								✓						✓																		
Operation	(Cerdancova et al., 2021); (Bhanot et al., 2016)									✓	✓																					✓		
Operation	(Moktadir et al., 2020)																					✓				✓						✓		
Operation	(Erbis et al., 2016)	✓											✓																			✓		
Operation	(Bhanot et al., 2016a)	✓									✓																					✓		
Operation	(Dorn et al., 2016)												✓		✓																	✓		
Operation	(Guzmán et al., 2022)	✓									✓						✓															✓		
Operation	(Lamjahdi et al., 2021)									✓						✓										✓						✓		
Operation	(Susanty et al., 2019)								✓												✓					✓				✓				
Operation	(Chien et al., 2016)									✓	✓																				✓	✓		
Operation	(Zhu et al., 2022)	✓								✓							✓														✓	✓		
Operation	(Saxena et al., 2020)	✓								✓						✓															✓	✓		
Operation	(Sriyanto et al., 2019)	✓									✓								✓							✓								✓
Operation	(Li et al., 2023)	✓								✓				✓								✓			✓							✓		
Operation	(Kumar et al., 2022)		✓				✓			✓											✓				✓						✓			
Operation	(Hashim et al., 2021)		✓				✓							✓		✓			✓						✓									
Operation	(Garraín et al., 2020)	✓														✓					✓									✓	✓	✓		
Operation	(Mesa et al., 2019)	✓																	✓			✓	✓						✓		✓			
Operation	(Sharathkumar Reddy et al., 2017)	✓								✓			✓			✓													✓		✓			

Operation	(Garraín et al., 2021)									✓						✓						✓	✓								✓	✓	✓		
Operation	(Swarnakar, Singh, & Tiwari, 2021)	✓								✓						✓			✓						✓						✓			✓
Operation	(Murad et al., 2021)										✓						✓		✓		✓					✓					✓	✓		
Operation	(Roy et al., 2020)	✓								✓						✓			✓						✓						✓	✓		
Operation	(Song & Moon, 2019)			✓	✓					✓	✓								✓												✓	✓		
Operation	(Valdivia & Castillejo, 2021)	✓						✓		✓						✓	✓	✓	✓													✓	✓	
Operation	(Hartini et al., 2020)	✓	✓				✓			✓	✓			✓							✓										✓	✓		
Operation	(Patalas-Maliszewska & Łosyk, 2020)	✓					✓	✓		✓											✓	✓									✓	✓		✓
Operation	(Trianni et al., 2019)							✓						✓				✓	✓		✓			✓	✓					✓	✓			
Operation	(Thirupathi et al., 2019)	✓	✓			✓				✓				✓							✓	✓			✓							✓		
Operation	(Sureeyatanapas et al., 2015)		✓							✓	✓				✓						✓	✓			✓					✓	✓			
Operation	(Kluczek & Włosiński, 2013)	✓	✓							✓									✓			✓	✓						✓		✓		✓	
Operation	(Ojo et al., 2020)	✓								✓						✓					✓	✓	✓			✓			✓	✓	✓			
Operation	(Pinto et al., 2020)	✓	✓	✓			✓	✓	✓	✓						✓						✓			✓							✓		
Operation	(Hussain et al., 2017)	✓							✓	✓			✓		✓				✓			✓	✓								✓	✓	✓	
Operation	(Harik et al., 2015)	✓	✓					✓	✓	✓						✓			✓							✓				✓		✓	✓	
Operation	(Swarnakar et al., 2022)	✓	✓			✓	✓			✓	✓				✓				✓						✓						✓	✓	✓	
Operation	(Petrillo et al., 2016)	✓	✓	✓					✓	✓	✓					✓			✓			✓	✓				✓	✓				✓		
Operation	(Tan et al., 2015)	✓	✓	✓			✓			✓	✓		✓				✓	✓				✓			✓			✓				✓		
Operation	(Zarte et al., 2019b)	✓	✓	✓	✓					✓			✓	✓		✓		✓	✓		✓				✓						✓	✓		
Operation	(Gani, James, et al., 2022)	✓	✓	✓		✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓				✓	✓	✓		

Table 1. Environmental Indicators studied per publication

In **Table 1**, the pillar of environmental sustainability is divided into the clusters: *Material usage, Energy consumption and efficiency, Water usage and efficiency, Waste management* and *Environmental impact*. With two micro categories that don't belong to any of the previous clusters, which are: *Transportations and logistics* and *Quality*. Of all the pillars, the environmental one has the most contributions overall, because as previously mentioned, it is the pillar most associated with the manufacturing industry. In fact, is also the one with the larger number of micro categories.

From each cluster the most studied micro categories were:

For *Material Usage*: *Input material consumption*.
For *Energy consumption and efficiency*: *Energy consumption.*
For *Water usage and efficiency*: *Water consumption.*
For *Waste management*: *Waste generated.*
And for *Environmental impact*: *Greenhouse gas emissions.*

It can also be worth mentioning that the paper that studies the most micro categories from the division is Gani et al., (2022)

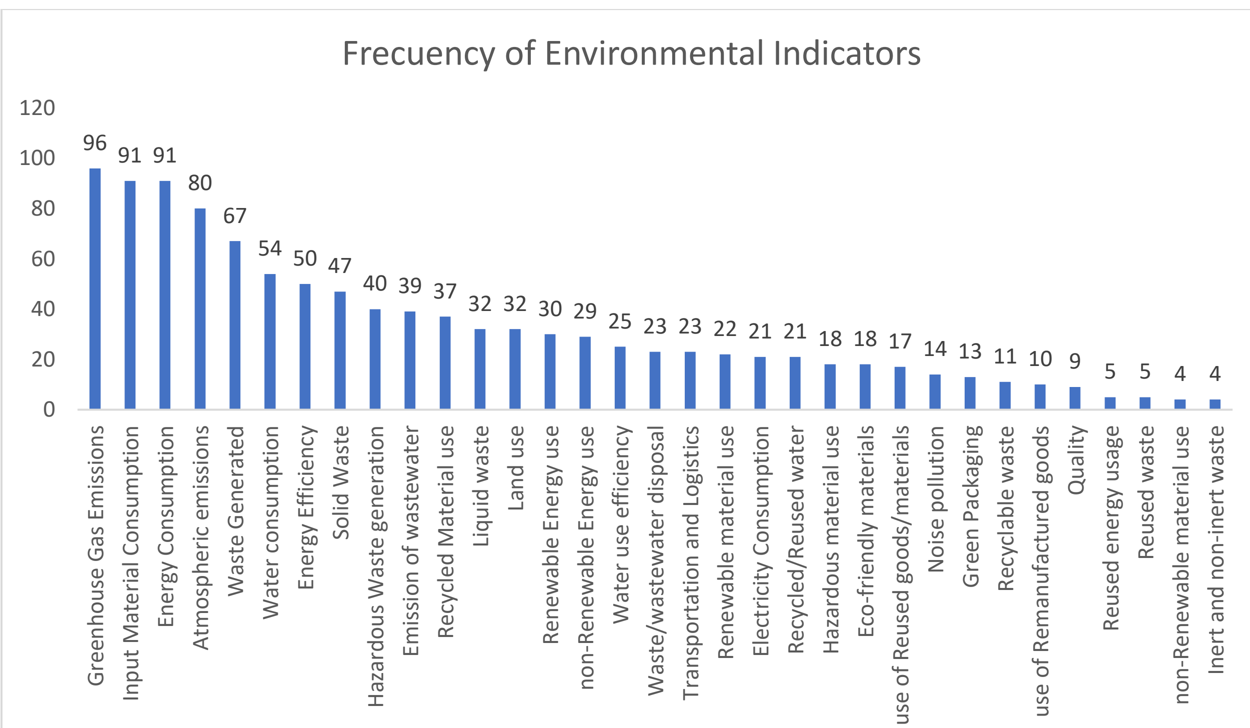

Figure 7. Sustainability indicators: Frequency of environmental indicators

In **Figure 5**, we can observe that the three most studied environmental micro categories were *Greenhouse Gas Emissions, Input Material consumption* and *Energy consumption*.

The reason for *Greenhouse Gas Emissions* to be the most present across all contributions may be because there is a more global consideration on air emissions such as CO_2, than to solid or water waste in the major political forums. (Ahmad et al., 2019b).

Meanwhile, the three that were the least studied were *Reused Waste*, *Non/renewable material use*, *Inert and non/inert waste*.

1.3.1.2. Social indicators studied per publication

		Workplace and Employee Well-Being											Social Impact and Engagement					Ethics and Integrity
Manufacturing process	Reference	Working conditions	Employement/ job opportunity	Work Accidents	Accident Severity Rate	work-related injuries	Training/Development	Health & Safety	Noise pollution	Turnover	Labor equality	Absenteeism	Social investments	Customer complaints	Customer satisfaction	Employee satisfaction	Wage Level/Economic Benefits	Corruption
Design	(Pask et al., 2017)		✓															
Design	(Machado et al., 2019)						✓	✓										
Design	(Ayabaca & Vila, 2020)	✓					✓									✓		
Design	(Lucato et al., 2018)			✓			✓		✓									
Design	(Hegab et al., 2018)	✓		✓				✓										
Design	(Leong et al., 2020)	✓						✓				✓					✓	
Design	(Watanabe et al., 2016)			✓			✓					✓		✓		✓		
Design	(Taddese et al., 2021)		✓	✓			✓				✓				✓		✓	
Distribution and Logistics	(Barbosa et al., 2023)	✓																
Distribution and Logistics	(Li & Mathiyazhagan, 2016)						✓			✓				✓	✓			
General	(Helman et al., 2023); (Latif et al., 2017); (Nagel & Tomiyama, 2004)							✓										
Operation	(Kubule & Blumberga, 2019)		✓															
General	(Peruzzini & Pellicciari, 2016); (Mikko et al., 2013); (Ruiz-Mercado et al., 2012)	✓						✓										
Operation	(Voces et al., 2012)	✓															✓	
General	(Paju et al., 2010)		✓											✓				
General	(Chang & Cheng, 2019)		✓				✓	✓										
General	(Moslehi & Arababadi, 2016)			✓	✓			✓										
Operation	(Seuring et al., 2003)	✓					✓	✓										

General	(Zarte et al., 2019a)						✓	✓					✓		✓			
Operation	(K. Singh & Sultan, 2018)						✓	✓							✓	✓		
General	(Naderi et al., 2017)		✓				✓	✓						✓				
General	(S. Singh et al., 2014)	✓					✓			✓					✓			
General	(Chaim et al., 2018)						✓	✓					✓		✓	✓		
General	(Helleno et al., 2017)			✓					✓	✓		✓					✓	
General	(Kocmanova et al., 2015)						✓			✓	✓		✓				✓	
Operation	(Amrina & Vilsi, 2015)	✓		✓			✓	✓			✓							
General	(Joung et al., 2013)	✓					✓	✓							✓	✓		
General	(Hsu et al., 2017)							✓		✓	✓			✓	✓	✓		
General	(Saygili et al., 2023)		✓				✓	✓			✓				✓		✓	✓
General	(Kaldas et al., 2020)	✓		✓		✓	✓	✓			✓		✓					
General	(Lanz et al., 2014)		✓	✓			✓	✓			✓		✓					✓
General	(Taddese et al., 2020)		✓	✓			✓				✓		✓	✓			✓	✓
General	(Kocmanova et al., 2017)		✓				✓	✓		✓	✓		✓				✓	✓
General	(Mengistu & Panizzolo, 2023b)	✓					✓	✓		✓		✓		✓	✓	✓	✓	
General	(Mengistu & Panizzolo, 2023a)		✓			✓		✓		✓		✓			✓	✓	✓	✓
General	(Sharma, 2021)		✓	✓			✓	✓		✓	✓	✓			✓	✓		
General	(Swarnakar, Singh, Antony, et al., 2021)			✓			✓	✓	✓	✓	✓	✓				✓	✓	
General	(Gani et al., 2020)	✓	✓	✓		✓		✓			✓	✓	✓	✓				
General	(Labuschagne et al., 2005)	✓	✓	✓	✓	✓	✓	✓					✓			✓		
General	(Cagno et al., 2023)		✓	✓	✓	✓	✓	✓			✓	✓			✓	✓		
General	(Contini & Peruzzini, 2022)			✓	✓	✓	✓	✓	✓	✓	✓					✓	✓	✓
General	(Sangwan et al., 2019)		✓	✓		✓	✓	✓			✓	✓	✓		✓	✓	✓	
General	(Cagno et al., 2019)		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
General	(Ahmad et al., 2019)	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓
Maintenance	(Franciosi et al., 2020)	✓	✓	✓		✓	✓	✓			✓					✓		
Operation	(Erbis et al., 2016)							✓										
Operation	(Saxena et al., 2020)	✓						✓										
Operation	(Mesa et al., 2019)	✓		✓														
Operation	(Marie et al., 2022)						✓	✓	✓									
Operation	(Hashim et al., 2021)	✓								✓					✓			
Operation	(Moktadir et al., 2020)							✓							✓	✓		
Operation	(Hartini et al., 2020)			✓				✓									✓	
Operation	(Susanty et al., 2019)		✓					✓								✓		
Operation	(Zarte et al., 2019b)	✓					✓										✓	
Operation	(Kluczek & Włosiński, 2013)	✓					✓	✓										
Operation	(Li et al., 2023)		✓	✓			✓				✓							
Operation	(Song & Moon, 2019)		✓					✓							✓	✓		
Operation	(Sharathkumar Reddy et al., 2017)			✓			✓	✓			✓							
Operation	(Bhanot et al., 2016a)	✓					✓	✓								✓		
Operation	(Tan et al., 2015)						✓	✓				✓		✓				
Operation	(Lamjahdi et al., 2021)					✓	✓	✓					✓			✓		
Operation	(Swarnakar, Singh, & Tiwari, 2021)		✓	✓			✓				✓					✓		

Operation	(Ojo et al., 2020)			✓			✓	✓					✓			✓		
Operation	(Patalas-Maliszewska & Łosyk, 2020)		✓				✓	✓		✓					✓			
Operation	(Thirupathi et al., 2019)						✓			✓			✓		✓	✓		
Operation	(Bhanot et al., 2016)	✓					✓	✓								✓	✓	
Operation	(Harik et al., 2015)	✓						✓			✓		✓				✓	
Operation	(Swarnakar et al., 2022)			✓			✓			✓	✓	✓				✓		
Operation	(Kumar et al., 2022)	✓	✓	✓			✓	✓							✓	✓		
Operation	(Murad et al., 2021)			✓			✓	✓		✓		✓			✓		✓	
Operation	(Trianni et al., 2019)	✓	✓				✓	✓			✓		✓					✓
Operation	(Sureeyatanapas et al., 2015)			✓			✓	✓		✓			✓	✓			✓	
Operation	(Pinto et al., 2020)		✓	✓			✓				✓	✓	✓	✓		✓		

Table 2. Social indicators studied per publication

In **Table 2**, the pillar of social sustainability is divided into clusters: *Workplace and employee wellbeing, Social impact and engagement,* and *Ethics and integrity.*

From each cluster the most studied micro categories were:

For *Workplace and employee wellbeing: Health & Safety*.
For *Social impact and engagement*: *Employee satisfaction*
And for *Ethics and integrity*: *Corruption.*

It can also be worth mentioning that the paper that studies the most micro categories from the division are Ahmad et al., (2019b) and Cagno et al., (2019).

To summarize the information presented in the table the following graph was developed:

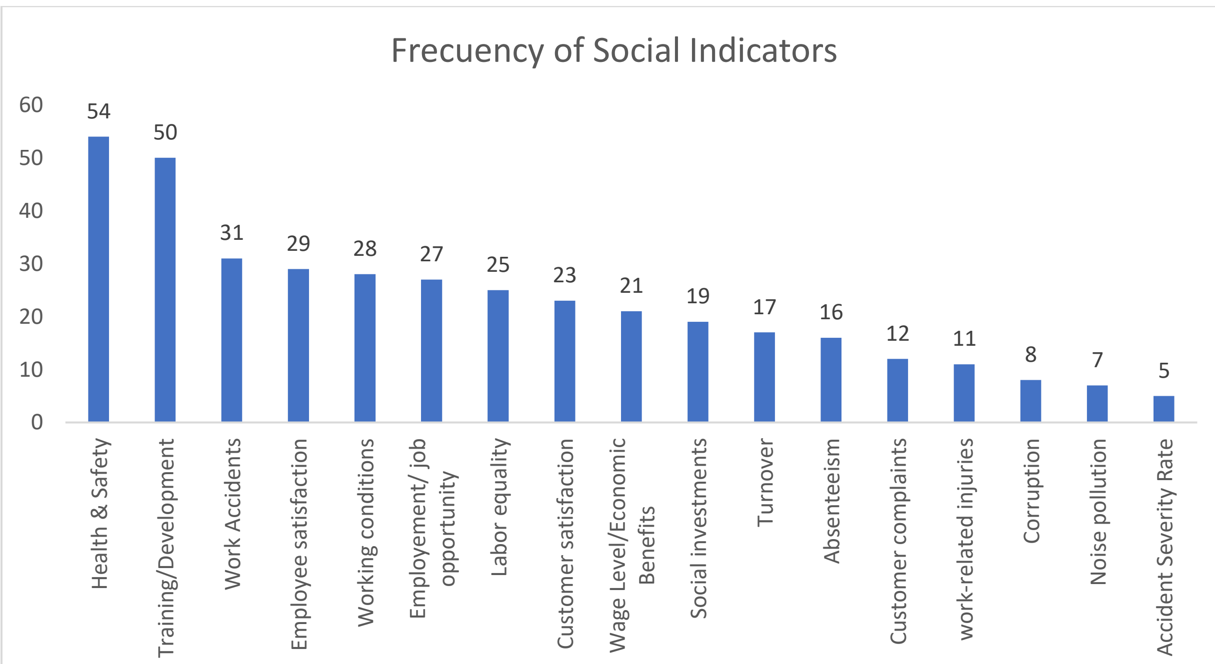

Figure 8. Sustainability indicators: Frequency of social indicators

Lastly in **Figure 7**, we can observe that the three most studied economic indicators were *Health & Safety, Training/Development* and *Work accidents*.

Again, Health & Safety is a micro category that can include within it others such as work accidents or working conditions, this explains why it has a higher number of contributions that talk about it.

On the other hand, the three that were the least studied were *Corruption, Noise pollution* and *Accident severity rate.*

1.3.1.3. Economic Indicators studied per publication.

		Financial performance		Investment analysis			Quality and efficiency			Cost analysis									
Manufacturing process	Reference	Revenues	Profit	Cost of Capital	Payback period	R&D expenditure	Investments for sustainability	Quality	Lead Time	Energy Cost	Inventory cost	Logistics/Transportation cost	Labor Cost	Operating cost	Machine/Equipment Performace	Maintenance cost	Water cost	Product cost	Input material cost
Design	(Rahla et al., 2019)																		✓
Design	(Taddese et al., 2021)						✓					✓							
Design	(Ayabaca & Vila, 2020)												✓	✓					
Design	(Lucato et al., 2018)												✓		✓				
Design	(Linke et al., 2014)							✓					✓						
Design	(Mangili & Prata, 2020)				✓	✓							✓						
Design	(Hegab et al., 2018)													✓	✓				✓
Design	(Huedo et al., 2016)						✓			✓						✓			
Design	(König et al., 2022)						✓	✓		✓				✓					
Design	(Leong et al., 2020)		✓			✓	✓						✓	✓					
Design	(Mortazavi & Ivanov, 2019)									✓			✓	✓			✓		✓
Design	(Pask et al., 2017)						✓	✓		✓				✓	✓				
Design	(Watanabe et al., 2016)			✓						✓			✓	✓					✓
Design	(Smith et al., 2019)	✓		✓	✓					✓				✓				✓	✓
Design	(S. Kim & Moon, 2017)		✓	✓			✓			✓		✓		✓					✓
Design	(Santolaya et al., 2019)	✓		✓						✓			✓	✓	✓			✓	✓
Distribution and Logistics	(Barbosa et al., 2023)								✓										
Distribution and Logistics	(Li & Mathiyazhagan, 2016)			✓									✓						
General	(Gani et al., 2021); (Taddese et al., 2020); (Kluczek, 2017)						✓												
Operation	(Ingwersen et al., 2016)									✓									✓

General	(Mikko et al., 2013)		✓			✓													
Operation	(Voces et al., 2012)						✓			✓									
General	(Helman et al., 2023)	✓	✓			✓													
Operation	(Kubule & Blumberga, 2019)	✓					✓			✓									
General	(Zarte et al., 2019a); (Labuschagne et al., 2005)		✓	✓			✓												
Operation	(K. Singh & Sultan, 2018)									✓							✓	✓	
General	(Kocmanova et al., 2017)			✓			✓			✓									
General	(Moslehi & Arababadi, 2016)						✓							✓		✓			
Operation	(Seuring et al., 2003)			✓		✓		✓											
Operation	(Favi et al., 2022)									✓				✓		✓			✓
General	(Barni et al., 2022)									✓			✓	✓		✓			
General	(Sharma, 2021)	✓					✓						✓	✓					
General	(Swarnakar, Singh, Antony, et al., 2021)							✓				✓	✓	✓					
General	(Chang & Cheng, 2019)		✓				✓	✓	✓										
General	(Helleno et al., 2017)										✓		✓	✓				✓	
Operation	(Amrina & Vilsi, 2015)										✓	✓	✓						✓
General	(S. Singh et al., 2014)			✓				✓				✓			✓				
General	(Gani et al., 2020)						✓	✓					✓	✓	✓				
General	(Kocmanova et al., 2015)	✓	✓	✓									✓	✓					
General	(Paju et al., 2010)						✓			✓			✓					✓	✓
General	(Kaldas et al., 2020)	✓		✓		✓					✓	✓	✓						
General	(Nagarajan et al., 2018)			✓						✓			✓	✓	✓	✓			✓
General	(Naderi et al., 2017)									✓		✓	✓		✓	✓	✓		✓
General	(Mengistu & Panizzolo, 2023b)	✓	✓			✓		✓	✓				✓				✓		✓
General	(Ruiz-Mercado et al., 2012)	✓		✓	✓					✓			✓	✓			✓	✓	
General	(Cagno et al., 2019)	✓	✓			✓	✓	✓					✓	✓	✓	✓			
General	(Sangwan et al., 2019)		✓	✓		✓	✓					✓	✓	✓		✓	✓		
General	(Hsu et al., 2017)	✓	✓	✓		✓		✓	✓			✓		✓	✓				
General	(Contini & Peruzzini, 2022)					✓	✓	✓	✓	✓		✓	✓			✓	✓		✓
General	(Joung et al., 2013)					✓				✓	✓	✓	✓	✓		✓	✓	✓	✓
General	(Mengistu & Panizzolo, 2023a)	✓	✓			✓		✓	✓	✓	✓		✓	✓		✓			✓
General	(Cagno et al., 2023)	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			
General	(Ahmad et al., 2019)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓
Maintenance	(Franciosi et al., 2020)					✓	✓			✓						✓			

Operation	(Roy et al., 2020)						✓												
Operation	(Erbis et al., 2016)													✓					
Operation	(Moktadir et al., 2020)	✓	✓																
Operation	(Sriyanto et al., 2019)							✓			✓								
Operation	(Zarte et al., 2019b)													✓					✓
Operation	(Harik et al., 2015)					✓	✓												
Operation	(Kluczek & Włosiński, 2013)						✓									✓			
Operation	(Li et al., 2023)					✓	✓						✓						
Operation	(Swarnakar et al., 2022)							✓					✓	✓					
Operation	(Karkalos et al., 2021)							✓						✓		✓			
Operation	(Susanty et al., 2019)							✓							✓	✓			
Operation	(Bhanot et al., 2016a)							✓							✓			✓	
Operation	(Kumar et al., 2022)		✓					✓		✓				✓					
Operation	(Marie et al., 2022)							✓		✓	✓								✓
Operation	(Swarnakar, Singh, & Tiwari, 2021)							✓			✓			✓	✓				
Operation	(Pinto et al., 2020)		✓			✓								✓	✓				
Operation	(Patalas-Maliszewska & Łosyk, 2020)		✓				✓							✓	✓				
Operation	(Sureeyatanapas et al., 2015)		✓				✓						✓			✓			
Operation	(Murad et al., 2021)						✓			✓			✓				✓		✓
Operation	(Hartini et al., 2020)		✓					✓			✓	✓		✓					
Operation	(Thirupathi et al., 2019)	✓	✓			✓	✓	✓											
Operation	(Mesa et al., 2019)						✓			✓			✓					✓	✓
Operation	(Bhanot et al., 2016)									✓				✓	✓		✓		✓
Operation	(Hashim et al., 2021)		✓			✓	✓	✓						✓		✓			
Operation	(Lamjahdi et al., 2021)		✓				✓	✓				✓	✓	✓					✓
Operation	(Song & Moon, 2019)	✓		✓		✓				✓	✓	✓			✓				
Operation	(Trianni et al., 2019)					✓		✓	✓	✓	✓				✓			✓	

Table 3. Economic Indicators studied per publication

In **Table 3**, the pillar of economic sustainability is divided into clusters: *Financial performance, Investment analysis, Quality and efficiency* and *Cost analysis.*

From each cluster the most studied micro categories were:

For *Financial performance: Profit*.
For *Investment analysis*: *Investments for sustainability.*
For *Quality and efficiency*: *Quality.*
And for *Cost analysis*: *Operating cost.*

It can also be worth mentioning that the paper that studies the most micro categories from the division is (Ahmad et al., 2019b).

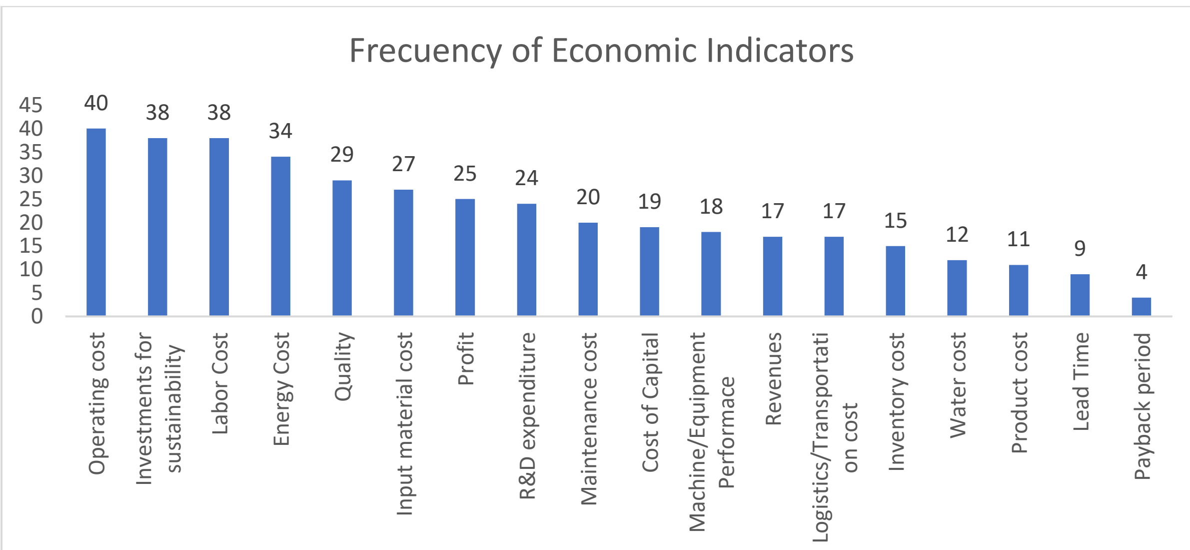

Figure 9. Sustainability indicators: Frequency of economic indicators

In **Figure 7**, we can observe that the three most studied economic indicators were *Operating cost, Investments for sustainability* and *Labor Cost*.

Indeed, *Operating cost* being the most studied micro category can be explained because this topic is known to group inside other micro categories such as *Labor cost* or *Energy cost.* This highlights the need for more standardized language for assessing economic sustainability in the sector. (Armstrong et al., 2014).

On the other hand, the three that were the least studied were *Product cost, Lead Time* and *Payback period.*

1.3.2. Analysis step 2: Sustainability indicators proposed

In this part, we identified which indicator category was studied in the research carried out in each article and the proposed indicator to effectively measure it.

1.3.2.1. Proposed Environmental indicators per publication.

		Material Usage								Energy Consumption and Efficiency						Water Usage and Efficiency			Waste Management								Environmental Impact						
Manufacturing process	Reference	Input Material Consumption	Recycled Material use	Renewable material use	non-Renewable material use	use of Remanufactured goods	use of Reused goods/materials	Hazardous material use	Eco-friendly materials	Energy Consumption	Energy Efficiency	Reused energy usage	non-Renewable Energy use	Renewable Energy use	Electricity Consumption	Water consumption	Water use efficiency	Recycled/Reused water	Waste Generated	Reused waste	Hazardous Waste generation	Solid Waste	Liquid waste	Recyclable waste	Emission of wastewater	Waste/wastewater disposal	Green Packaging	Noise pollution	Land use	Atmospheric emissions	Greenhouse Gas Emissions	Transportation and Logistics	Quality
General	(Helman et al., 2023)	Product size [m or m3] Product weight [kg]		Number of renewable parts [pcs. or units per product]			Number of reused parts assembled [pcs. or units per product]		Material carbon footprint [ton of CO2 or CO2e]	Energy usage [kWh/unit]	Energy usage [kWh/unit]						Reduced water consumption of a product [m3 / unit]		Amount of waste [kg/unit]			Water polluted [mg/m3]		Waste recycled/reused [kg]	Material water footprint [1/kg]							Use of low-emission transport [%]	
General	(Shabir et al., 2023)										Energy efficiency [kWh/m3 of produced milk]								Waste [kg]			Solid waste [kg]									Carbon footprint [kg CO2 eq / kg product]		
General	(Cagno et al., 2023)	Reduction of raw materials used [unit of mass]	Recycled material [%]			Remanufactured products [#]	Reused goods [unit of mass]			Energy use [unit of energy]		Reused energy [unit of energy]	Non-renewable energy use for production [unit of	Renewable energy use for production [unit of energy]				Recycled water use [unit of volume]			Hazardous waste [unit of mass]	Hazardous solid waste [unit of mass]	Hazardous liquid waste [unit of volume]	Waste recycled [unit of mass]		Manufacturing waste management [qualitative]				Toxic emissions [unit of volume]	CO2 [unit of volume]	Transportation [quantity of volume]	
Operation	(Guzmán et al., 2022)	Material Consumption [g/unit]									Energy efficiency [Mj/kg prod]						Water efficiency [L/kg prod]														CO2 [kg CO2/kg prod]		
Operation	(Zhu et al., 2022)	Raw material usage [g/process]								Energy usage [Wh/day]							Process water usage [gal/process]														Carbon emission coefficient [CO2e/kg/kWh		

Operation	General	Operation	General	Operation	Operation	Operation	Operation	Operation
(Lamjahdi et al., 2021)	(Swarnakar, Singh, Antony, et al., 2021)	(Garraín et al., 2021)	(Barni et al., 2022)	(Favi et al., 2022)	(Gani, James, et al., 2022)	(Chaubey & Gupta, 2022)	(Kumar et al., 2022)	(Firmino et al., 2022)
	Raw Material Consumption [kg/unit]		total material input [kg]	Lubricant cons. Kg	Raw materials [Weight/year]	Wire consumption [g/min]		Material consumption[kg] [liters]
	Reuse/Recycle Raw Material Ratio		Percentage of total recycled input materials				Recycling and reuse of product, raw material, consumables	
			Percentage of renewable materials used		Consumption of renewable Material [Weight/year]			
					Percentage of product/component recovered			
	Reuse/Recycle Raw Material Ratio				Share of recycled/reused input materials in		Recycling and reuse of product, raw material, consumables	
Total energy consumption		Resource use (energy and fossils) [MJ]	Total Energy Consumption [MJ]		Total Energy consumption [kW or MW]			Consumption [kWh]
							Energy consumption units [kWh/kg or kWh/unit]	Consumption/sec [kWh/s]
			Percentage of non-renewable energy consumption [%]	Natural gas cons. M3	non-Renewable energy use [%]			
			Percentage of renewable energy consumption [%]		Renewable energy use [%]			
	Electricity Consumption [w/unit]		Total electricity consumption [MJ]	Electricity consumption [kWh]]	Electricity consumption [kW or MW]	Electricity consumption [kWh]		
Total water consumption		Water scarcity [m3 water world eq]	Total water intake [ML]	water consumption [litre]	Total amount of water consumption [liters/year]			
					Water intensity [L/unit]			
			Percentage of water reused/recycled by the organization		Amount of water reused/recycled [kl/year]			
			Total waste [kg]		Waste per produced unit			
			Total waste reused [kg]					
	Toxic Discharge to Water		Percentage of hazardous waste diverted from disposal		Total amount of hazardous waste generated [kgs/yr.]		Usage of hazardous materials/components /products [Nos]	
	Net Solid Waste Generation	Terrestrial eutrophication [molc N eq]			Total amount of solid waste generated [weight/year]			
		Acidification [molc H+ eq]			Amount of Liquid waste discharging into water [liters/year]			
			Waste recycled [%]		Percentage of waste recovered			
			Total water discharge [ML]		Total Wastewater Discharge [m3 /ton of production]		Reduction in wastes – air emission, water [%]	
Disposal of waste	Waste Segregation percentage				Amount of Liquid waste discharging into water [liters/year]			
		Land use [Pt]						
		Ozone depletion [kg CFC-11 eq]	total emissions [kg]	Air emissions [kg CFC11 eq]	Total Air emissions [Weight or Volume/year]		Reduction in wastes – air emission, water [%]	
Amount of GHG generated	Net CO2 Emission Impact	Climate change [kg CO2 eq]	Percentage of greenhouse gases (GHG) total GHG	total emissions [kg CO2 eq]	Total amount of GHG generated [Weight or Volume/Year]			CC [kg CO2-eq]
	Scrap Rate							

Design	Design	Operation	Operation	Design	Operation	Operation	Operation	Operation
(Rahla et al., 2019)	(Smith et al., 2019)	(Thirupathi et al., 2019)	(Trianni et al., 2019)	(Mangili & Prata, 2020)	(Garraín et al., 2020)	(Cerdancova et al., 2021)	(Valdivia & Castillejo, 2021)	(Ming et al., 2021)
	Mass intensity			Total molar flow rate of raw materials/Total molar flow rate of	Mineral, fossil & ren resour depletion [kg Sb eq]		Mat. Intensit [mass/product output]	
	Renewability-material index							
	Mass of hazardous materials input [kg]		Dangerous inputs [kg and/or cubic metres of				Proportion of Hazardous material	
	Total energy consumption			Total energy demand [GJ]				
	Specific energy intensity [MJ/kg]			Total mass flow rate of natural gas/Total molar flow rate of MAN [kg/kmol]		Specific electricity consumption [MWh/km]	Energy intensity [energy/product output]	Energy efficiency per volume (EEV) [KJ/mm3]
						Specific natural gas consumption [m3/km]		
	Renewability-energy index		Renewable energy [Degree or percentage					
	Total water consumption [m3]				Water resource depletion [m3 water eq]		Total water consumption [volume]	
				Total volumetric flow rate of make - up water/Total molar flow rate of MAN [m3/kmol]			Water intensity [volume/product output]	
			Recycled water [Degree or percentage of using recycled water/total water				Recycled water usage [%]	
			Land pollution [kg and/or cubic metres of	Total volumetric flow rate of effluent/Total			Waste generation intensity [mass/time]	
	Toxic release intensity [TRI]		Dangerous outputs [kg and/or cubic					
Terrestrial ecotoxicity potential [kg (1,4-DB	specific solid waste mass [kg]							
Marine aquatic ecotoxicity potential	Environmental hazard, water hazard [m3/kg]							
			Recyclable wastes [Degree or percentage					
	Aquatic acidification potential [H+eq/unit]		Water pollution [kg of particles]					
			Land use [Squared metres of land used		Land use [kg C deficit]			
Ozone depletion potential [kg (CFC-11 eq)]	Stratospheric ozone-depletion potential [CFC-11 eq]		Air pollution [kg of gases]		Ozone depletion [kg CFC-11 eq]			exhaust emissions characteristics (EEC) [ug/m3]
Global warming potential [kg (CO2	Global Warming potential GWP	Mass fraction of greenhouse gases		Total mass flow rate of CO2 emitted/Total	Climate change [kg CO2 eq]	Specific summary CO2 emissions [CO2	CO2 emission intensity [volume or	

General	General	General	Operation	Design	Operation	General	General	Operation
(Helleno et al., 2017)	(Hsu et al., 2017)	(Munasinghe et al., 2017)	(Sharathkumar Reddy et al., 2017)	(Lucato et al., 2018)	(Mesa et al., 2019)	(Ahmad et al., 2019)	(Sangwan et al., 2019)	(Zarte et al., 2019b)
		Embodied energy × amount of fertilizer used	Material consumption	Soluble oil consumption [Parts/10 L]	Mass of raw material/consumables consumed [kg]	Overall materials	Total raw material used	Total weight orvolume ofmaterials [kg, m3, pc]
							Fraction of recycled material used	Weight or volume of recycled input materials [kg, m3, pc]
								Weight or volume of renewable materials [kg, m3, pc]
								Weight or volume of non-renewable materials [kg, m3, pc]
						Chemicals for cleaning and washing	Hazardous material used	
Green Production Rate [%]								
			Energy Consumption			Overall energy	Total amount of energy used	Total energy consumption [kWh]
		Energy Consumption [MJ/kg of tea]		Electric energy consumption [Parts/kwh]				
			Fuel consumption			Fuel/Natural gas	Fossil fuel used	Consumption of conventional energies [kWh]
							Fraction of renewable energy used	Consumption of renewable energies [kWh]
Electric Power Consumption [w/unit]								
			Water utilization			Overall water	Water used	Total volume of water withdrawn [m3]
Water Consumption [L/unit]								
							Fraction of water recycled	Volume of recycled water [m3]
Waste with Traceable Treatment [%]					Mass of raw material/consumable waste [kg]			Total weight of waste [kg]
							Fraction of water reused	
						Hazardous Waste	Amount of hazardous solid waste	
					Mass of solid waste [kg]		Amount of total solid waste	
					Volume of liquid effluent [l]	Suspended solids, Oils, pH,	Amount of total liquid waste	
						Overall wastewater		Total volume of water discharge [m3]
Waste Segregation [%]								
		Embodied energy in a 200 g polysac × amount of fertilizer				Primary/Secondary packaging materials	Weight of packaging Fraction of reclaimed packaging	
			Noise pollution		Level of noise generated [dB]		Noise emissions	
							Land used	
					Mass of CO2, CH4, NOx [kg]	Overall emissions [kg]	NOx emissions Particulate matter (PM)	Indirect GHG emission [t CO2eq]
		GHG Emissions [kg CO2e/kg of tea]				CO2 CO SOx NOx N20 H2S H2 emission [kg]	Carbon dioxide (CO2) emission	Direct GHG emission [t CO2eq]
		Embodied energy from diesel × distance travelled					Total energy used in distribution	
				Scrap generation [parts/kg]				

Operation	Distribution and Logistics	Operation	Operation	Design	Design	General	General	Design
(Bhanot et al., 2016)	(Li & Mathiyazhagan, 2016)	(Chien et al., 2016)	(Ingwersen et al., 2016)	(P. P. Singh & Madan, 2016)	(Pask et al., 2017)	(Kocmanova et al., 2017)	(Naderi et al., 2017)	(S. Kim & Moon, 2017)
	Resource consumption rates		Metal depletion kg Fe-eq			Total consumption of materials / Added value. [t/CZK]	Total consumption of Material for the production of a part	Virgin material use
						Percentage content of used recycled materials from total		
								Depletion of non-renewable energy resources
Basic energy		Total energy consumption area [KWH]	Cumulative energy demand, non-renewable [MJ]			Total energy sources.	Total installed power [KW]	Energy use
Energy consumption/component [kWh / component]		Total energy efficiency [NTD/year]						Waste energy emission
			Fossil fuel depletion [kg oil-eq]	Quantity of fuel consumed [m3]				
						Total of renewable energy / Total energy sources		
				Electrical energy consumed [kWh]				
			Water consumption/depletion [m3]			Total annual consumption of water / Added value. [m³/rok/CZK]		Quantity of water used per day
								Quantity of water used per unit of production
	Quality of air, soil and water					Total annual production of waste / Added value. [t/CZK]	Total amount of Waste produced in the manufacture of a part	
					Toxicity [ppm]	Total annual production of hazardous waste /		Hazardous substances
				Solid waste indicator [kg]				Solid waste emission
			Freshwater eutrophication [kg N-eq, kg P-eq]					Fluid emission
	Quality of air, soil and water						Total amount of Wastewater Produced during the	
	Protection of quality and supply of fresh water resources							
								Packaging material use
			Land occupation/transformation [m2 yr]					
	Quality of air, soil and water	Emissions of the exhaust System of the clean room	Particulate matter [kg PM2.5eq, kg PM10eq]			Total emissions to air / Added value [t/CZK] (solid particulate	Amount of Emissions discharged into the Atmosphere [kg]	Gaseous emission
Carbon emissions/component [kg CO2]	Embedded or embodied carbon	Total CO2 emission reduction [kg-CO2/year]	Global climate [kg CO2-eq]	Carbon emissions due to electric energy usage [kg of CO2]		Total greenhouse gas emissions / Added value [t/Kc]		Greenhouse gases

Operation	Operation	General	Operation	Operation	General	Operation	Design	Design
(Harik et al., 2015)	(Sureeyatanapas et al., 2015)	(Edtmayr et al., 2016)	(Dorn et al., 2016)	(Bhanot et al., 2016a)	(Moslehi & Arababadi, 2016)	(Erbis et al., 2016)	(Watanabe et al., 2016)	(Huedo et al., 2016)
Source reduction adoption				Coolant Consumption (C.C./comp) [ltr/comp]	Resource Scarcity	Primary material intensity over product life [thousand kg]		
Recycled Material	Percentage of reprocessing, derived from the weight of						Reused/Recycled Materials used in Products	
							Reused/Recycled Materials used in Products	
Harmful substancescontent								
Conscious raw material selection								
Energy usage regulations and standards							Total Energy Consumption	Primary energy consumption [Mj, kWh/m2]
	Rate of steam consumption relative to a tonne of cane processedper year [t/t]			Energy Consumption [kWh/component]	Energy Returned per Energy Invested			
			Specific Fuel Consumption [kWh/t]			Total non-renewable energy used [million kW h]		
	Rate of electricity consumption relative to a tonne of		Specific Electricity Consumption [kWh/t]					
Water consumption					Water Consumption			Water consumption [l/m2]
							Water intensity	
							Water Reused	
Residuals intensity		Total waste [kg per time period]					Waste Material Discarded	
	Rate of hazardous waste disposed of relative to a tonne of							Hazardous waste [kg/m]
	Rate of non-hazardous waste disposed of relative to							
	Rate of water discharged into the environment relative				Fresh Water Ecotoxicity		Waste Water Discharged	
Waste treatment methods								
							Packaging Materials Discarded	
Land use	Rate of areas of sugar manufacturing sites relative to a tonne				Land Use			
	Concentration of total suspended particulate [mg/m3]				Respiratory Inorganics		Air quality	
			Specific net CO2 emissions [kg/t of product]	Carbon Emissions [kg CO2]	GHG emissions through the life cycle [t CO2e/GWh]	Total CO2 emission avoided [million kg]	Greenhouse Gas Emissions	Global Warming Potential [kg Eq CO2/m]
Inventory tracking techniques								
		Cumulated scrap rate [%]						

Distribution and Logistics	General	Operation	Design	Operation	Operation	General
(Barbosa et al., 2023)	(Ruiz-Mercado et al., 2012)	(Voces et al., 2012)	(Mani et al., 2014)	(Tan et al., 2015)	(Amrina & Vilsi, 2015)	(Kocmanova et al., 2015)
	Total material consumption [kg/h]			Materials saved from implemented initiatives [kg/kg]	Material consumption	
				Reused/recycled materials used in products [kg/Unit]		
				Reused/recycled materials used in products [kg/Unit]		
	Mass of hazardous material input [kg/h]					
Energy Consumption [kWh]	Total energy consumption [kJ/h]		Total energy usage (MWh)	Waste energy emission [kWh]	Energy consumption	
	Energy intensity			Energy intensity		
			Total gas & oil (MWh)	Vehicle fuel consumption saved from implemented	Fuel consumption	
						Total consumption of renewable energy /Added value
			Total electricity [MWh]			
			Total water usage (1000 m3)		Water utilization	Total annual consumption of water / Added value [m³/year/EUR]
	Water intensity			Water intensity [m3/unit]		
				Water reused [m3]		
		Total waste [t/€]	Total waste-at-cost (ton)		Nonproduct output	Total annual production of waste / Added value [t/EUR]
						Total annual production of hazardous waste /
	Total solid waste mass		Total waste-to-landfill (ton)	Solid waste produced [kg]		
	Ecotoxicity to aquatic life potential					
			Total discharged water (1000 m3)	Waste water discharged [m3]		
				Packaging materials discarded [kg/unit]		
					Noise pollution	
					Land utilization	
	Stratospheric Ozone depletion potential [kg CFC-11/h]		Total VOC emissions (ton)		Air emission	Total emissions to air / Added value [t/EUR]
CO2 emissions from the production processes at the	Global Warming Potential [kg CO2/h]		Total CO2 (ton)	Greenhouse gas emissions [kgCO2e]		Total greenhouse gas emissions / Added value [t/EUR]
CO2 emissions from the product and materials transport						

Table 4. Proposed Environmental indicators per publication

To summarize the information presented in the table above the following graph was developed:

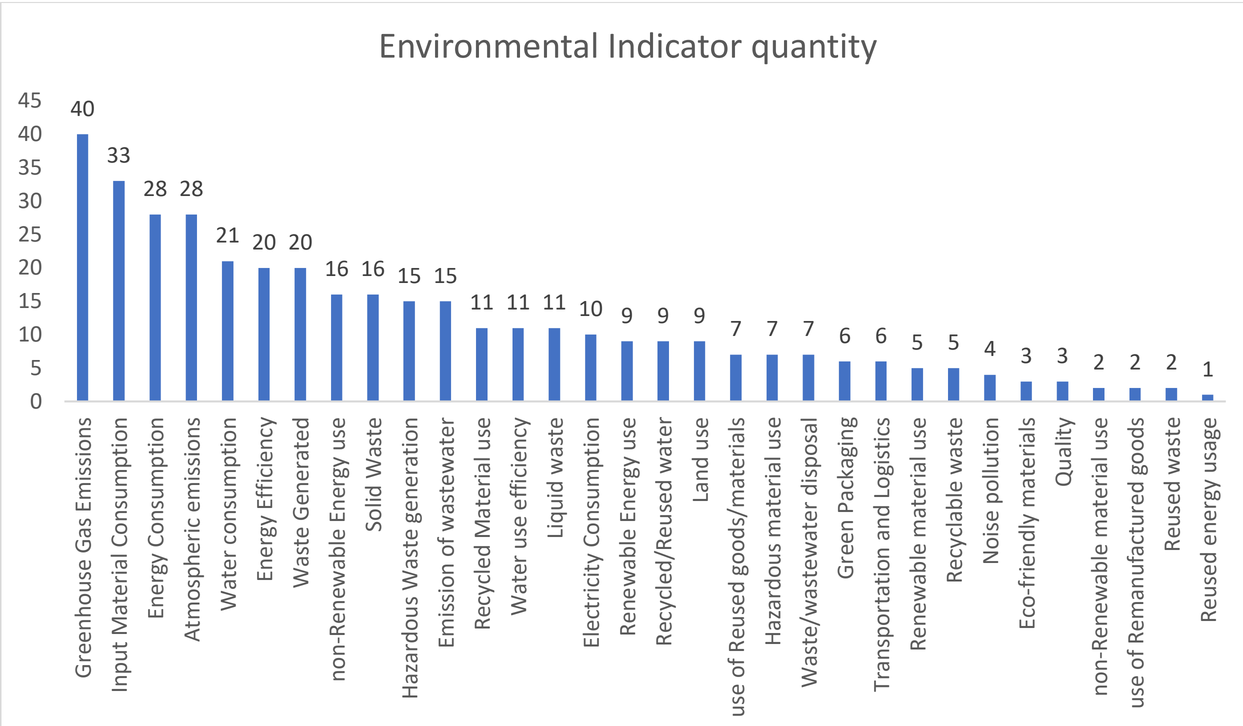

Figure 10. Sustainability indicators: Environmental indicator quantity

From **Figure 10**, we can report that in 40 of the contributions, an indicator was proposed for the category *Greenhouse Gas Emissions*, being the category with the highest number of indicators proposed, followed by *Input Material Consumption*, *Energy consumption* and *Atmospheric emissions*. This is in line with the results obtained in the Analysis 3.2.1.1. being the same macro categories the most studied across the included contributions.

For *Greenhouse Gas Emissions*, one of the aspects that this analysis found was that for this category, the proposed indicators might be called different, but they refer to the same measurement. For example, *Global warming potential* (Huedo et al., 2016; Rahla et al., 2019; Ruiz-Mercado et al., 2012a), *Carbon Emissions* (Bhanot et al., 2016b; Zhu et al., 2022) or *Greenhouse Emissions (GHG)* (Lamjahdi et al., 2021b; Munasinghe et al., 2017; Tan et al., 2015a; Watanabe et al., 2016), they're all assessed in terms of *kg* CO_2.

According to Huedo et al., (2016), the use of the indicator of *Global warming potential* is directly associated the emissions of all greenhouse gases such as Sulphur Oxides, Nitrogen Oxides, Methane etc. and is proposed as the most representative for evaluating the environmental sustainability of buildings. On the other hand, for Bhanot et al., (2016b) the indicator proposed is *Carbon Emissions*, associated with carbon emissions caused by the production of carbide inserts for the cutting operations, cutting fluids, raw materials of the manufacturing operation and chips, as well as for the electricity used by the CNC machine. By directly comparing the scope of these 2 proposals, we can observe how for the first one the focus is contained in the site of operation, while for the second one it is also considered the carbon impacts of the manufacturing of different consumables used in the operation, as well as the source of the energy used.

Related to *Greenhouse Gas Emissions* we can also find *Atmospheric Emissions* but in this micro category we find different types of indicators such as Air pollution [kg of gases] (Trianni et al., 2019a), Mass of CO2, CH4, NOx [kg] (Mesa et al., 2019), Concentration of total suspended particulate [mg/m3] (Sureeyatanapas et al., 2015), but a recurring one found in 5 articles was Ozone depletion [kg CFC-11 eq] (Garraín et al., 2020, 2021), or Stratospheric ozone-depletion potential [CFC-11 eq] (Rahla et al., 2019; Ruiz-Mercado et al., 2012; Smith et al., 2019).

Some authors propose the use of atmospheric emissions indicators to measure the overall impact of the operation such as Ozone depletion [kg CFC-11 eq] (Garraín et al., 2020, 2021). On the other hand, some authors propose a more specific indicator to measure the direct output emissions of an operation like Mass of CO2, CH4, NOx [kg] (Mesa et al., 2019). It is important to note the difference in application for both cases, the first one is used in a Life Cycle Assessment while the second one is an evaluation of indicators specific to the manufacturing stage.

For *Input Material Consumption* something similar was found: the most commonly proposed indicator (even though it had different names) was in terms of *Total Material Consumption [kg]* or *Raw material consumption [kg/unit]* (Amrina & Vilsi, 2015; Barni et al., 2022; Firmino et al., 2022; Guzmán et al., 2022; Kocmanova et al., 2015; Mesa et al., 2019; Naderi et al., 2017; Ruiz-Mercado et al., 2012; Sharathkumar Reddy et al., 2017; Swarnakar et al., 2021; Zhu et al., 2022).One resonant aspect worth mentioning is the use of the indicator: Virgin material use (Kim & Moon, 2017), since it can be important in certain types of industries, for example, in those that use recycled materials i.e plastics.

It is relevant to highlight the different advantages that can emerge from using an absolute measure (*Total Material Consumption [kg]*) versus a specific measure (*Raw material consumption [kg/unit]*). The absolute measure is generally simpler to implement and to follow its evolution, and it is particularly useful for operations that do not suffer from changes over time. The value obtained is generally unique for the whole plant and is directly linked to the amount of output generated, which can also make it useful for seasonality analysis of the operation but can also render it harder to benchmark monthly, especially if no historical data is available. Meanwhile, the specific measurement offers a more detailed understanding of the process and can be implemented for each type of product or service offered. If used ad hoc, we can have more visibility on the complexity of each product, helping the company identify strengths and weaknesses in terms of sustainability for the different processes used. It is also important to mention that the 2 types of measurement are, by no means, mutually exclusive and the same logic can be applied to any indicator studied in this research where the 2 types of measurement were proposed.

The above happened similarly also for *Energy consumption* were the indicator was fairly standard called simply *Energy consumption* or *Energy usage* measured in *[kWh*] (Amrina & Vilsi, 2015; Barbosa et al., 2023; Barni et al., 2022a; Cagno et al., 2023a; Chien et al., 2016; Firmino et al., 2022; Gani et al., 2022a; Garraín et al., 2021; Helman et al., 2023; Huedo et al., 2016; Lamjahdi et al., 2021b; Mani et al., 2014; Ruiz-Mercado et al., 2012a; Sangwan et al., 2019a; Sharathkumar Reddy et al., 2017; Smith et al., 2019; Watanabe et al., 2016; Zarte et al., 2019b; Zhu et al., 2022). And for *Energy efficiency*, there can mainly be found three indicators, *Energy consumption* [kWh/kg or kWh/unit] (Bhanot et al., 2016a, 2016b; Cerdancova et al., 2021; Kumar et al., 2022; Lucato et al., 2018; Munasinghe et al., 2017) , *Energy intensity [energy/product output]* (Ruiz-Mercado et al., 2012b; Smith et al., 2019; Tan et al., 2015a; Valdivia & Castillejo, 2021) and *Energy efficiency* (Chien et al., 2016; Guzmán et al., 2022; Ming et al., 2021; Shabir et al., 2023).

Furthermore, there are many sources of energy a company can use like electricity, steam, natural gas, fuel, cogeneration, geothermal, renewable energy such as wind, solar, hydropower among others. But regardless of the energy type chosen, it is of high importance to measure both the total energy consumption and the specific energy consumption to keep under control the process and gain insights on the physics behind them used to generate value. As stated by Kumar et al., (2022) "Energy consumption is the key important metrics for industries."

For Water Consumption, the widely used indicator refers to the *Total Water Consumption*, (Amrina & Vilsi, 2015; Barni et al., 2022a; Favi et al., 2022a; Gani et al., 2022b; Harik et al., 2015; Huedo et al., 2016; Ingwersen et al., 2016; Kocmanova et al., 2015, 2017; Lamjahdi et al., 2021b; Mani et al., 2014; Moslehi & Arababadi, 2016; Sangwan et al., 2019a; Sharathkumar Reddy et al., 2017; Smith et al., 2019; Song & Moon, 2019; Valdivia &

Castillejo, 2021; Zarte et al., 2019b) what varies among them is the time frame evaluated (day/month/year). Typically, for the different time frames we have different output purposes. For the short term such as day, we have a more detailed behavior of the process allowing the company to focus on correcting deviations on the consumption rate. For the month time frame companies can directly associate a cost for the utilities bill, while for the year time frame companies present them as sustainability goals or results.

Regarding *Waste generated*, the most mentioned indicator is *Total waste [kg]* (Barni et al., 2022a; Edtmayr et al., 2016; Naderi et al., 2017a; Shabir et al., 2023a; Zarte et al., 2019b) among the other indicators found is worth mentioning *Waste generated intensity [mass/time]* (Harik et al., 2015; Valdivia & Castillejo, 2021). The importance of waste is determined by the type of waste and the type of industry where the analysis is being performed. For example, it is of great importance for Shabir et al., (2023a) and is a top priority, studied in a comprehensive way since their research is done in a food processing system. While for Valdivia & Castillejo, (2021), the generation of waste is an extra characteristic to be looked at when evaluating a company's sustainability.

Referring *to Non-Renewable Energy Use* the indicators can be found in general terms *Non-renewable energy use for production [unit of energy]* (Barni et al., 2022a; Cagno et al., 2023a; Erbis et al., 2016; Gani et al., 2022a) or more specific ones such as *Natural gas consumption [m3/km]* (Ahmad et al., 2019b; Cerdancova et al., 2021; Favi et al., 2022a) or *Fossil fuel depletion [kg oil-eq]* (Ingwersen et al., 2016; Sangwan et al., 2019).

Continuing with *Solid Waste* this is also a micro category measured mainly in general terms as *Amount of total solid waste* (Gani et al., 2022a; Mesa et al., 2019; Ruiz-Mercado et al., 2012a; Sangwan et al., 2019a; Shabir et al., 2023b; Singh & Madan, 2016; Song & Moon, 2019; Tan et al., 2015a). Even though the proposed indicator is the same, some differences can be found relating to how they are approached depending on the context where they are. For Mesa et al., (2019) this indicator is directly measured as the loss of raw material during manufacturing to further control and improve it. While for Ruiz-Mercado et al., (2012a) the focus is on totaling amounts of different types of waste and then assessing the environmental and economic impact of handling them.

Following *Solid waste*, we can find *Hazardous Waste Generation,* which can be considered one of its subdivisions. This micro category is also measured mainly in terms of mass: *Hazardous waste [unit of mass]* (Ahmad et al., 2019b; Cagno et al., 2023b; Gani et al., 2022a; Huedo et al., 2016; Kocmanova et al., 2015, 2017; Sangwan et al., 2019a) but also in terms of *Toxic release intensity [TRI]* (Pask et al., 2017; Smith et al., 2019; Swarnakar, Singh, & Tiwari, 2021b). Naturally, depending on the context each company belongs to, they are prone to different types of pollutants and wastes according to their operations. We mainly find differences in the indicators proposed and how they were implemented following their specific conditions. The severity of the environmental impact is dictated by the type of waste generated, which in effect renders this indicator either of extreme or very low importance.

For *Emission of wastewater,* it was found that it is measured quite standardly in terms of *Total volume of water discharge [m3]* (Barni et al., 2022a; Gani et al., 2022a; Mani et al., 2014; Naderi et al., 2017a; Sureeyatanapas et al., 2015; Tan et al., 2015a; Watanabe et al., 2016; Zarte et al., 2019b)

Regarding *Recycled Material use* it is worth highlighting that the indicators proposed agree that it should be measured in a ratio: *Percentage of total recycled input materials* (Barni et al., 2022a; Cagno et al., 2023b; Harik et al., 2015; Kocmanova et al., 2017; Sureeyatanapas et al., 2015; Swarnakar, Singh, & Tiwari, 2021a; Tan et al., 2015a; Watanabe et al., 2016; Zarte et al., 2019a). For Swarnakar, Singh, Antony, et al., (2021b) and (Barni et al., 2022a), the focus was on providing as much information and analysis as possible for manufacturing industries where recycling is particularly relevant and feasible. While for Watanabe et al., (2016) the focus was to evaluate the performance of a new industrial business model, mentioning the use of the *Recycled Material use*, but not necessarily on providing tools to improve it.

For *Water Use Efficiency*, all contributions that proposed an indicator talk about *Water intensity [volume/product output]* (Gani et al., 2022a; Guzmán et al., 2022; Helleno et al., 2017; Mangili & Prata, 2020; Ruiz-Mercado et al., 2012a; Song & Moon, 2019; Tan et al., 2015; Valdivia & Castillejo, 2021; Watanabe et al., 2016; Zhu et al., 2022).

Instead, for *Liquid Waste*, two sources measure it generally as *Amount of Liquid waste discharging into water [liters/year]* (Gani et al., 2022a; Sangwan et al., 2019a), and other specific indicators are proposed such as *Marine aquatic ecotoxicity potential [kg (1,4-DB eq)]* (Rahla et al., 2019) or *Freshwater eutrophication [kg N-eq, kg P-eq]* (Ingwersen et al., 2016). Here, the main difference between them is in what the indicator is measuring, for the first one, the output is being measured in absolute terms (quantity/time). While for the second one it is measured the total net effect of the output, disregarding the quantity. It is important for companies to correctly choose what to measure since it can have different implications and action plans related to which one is being communicated.

Electricity consumption was another indicator where all the contributions talking about it measured it in the same terms: *Electricity consumption [kWh]]* (Barni et al., 2022a; Chaubey

& Gupta, 2022; Dorn et al., 2016; Favi et al., 2022b; Gani et al., 2022a; Helleno et al., 2017; Mani et al., 2014; Singh & Madan, 2016; Sureeyatanapas et al., 2015; Swarnakar, Singh, & Tiwari, 2021a). Differences arise between them when analyzing the source of the electricity, which is when they also start to propose the differentiation of indicators as seen in *Renewable Energy use* and *non-Renewable Energy use.*

This was similarly found for *Renewable Energy use* since it is measured by all contributions in terms of percentage: *Total of renewable energy / Total energy sources.* (Barni et al., 2022a; Cagno et al., 2023b; Gani et al., 2022a; Kocmanova et al., 2015, 2017; Sangwan et al., 2019a; Smith et al., 2019; Trianni et al., 2019a; Zarte et al., 2019a)

The same also for *Recycled/Reused Water* were the commonly used indicator was *Recycled water usage [%]* (Barni et al., 2022b; Gani et al., 2022a; Sangwan et al., 2019a; Tan et al., 2015b; Trianni et al., 2019a; Valdivia & Castillejo, 2021; Watanabe et al., 2016)

Likewise for *Land use* as well, where the shared indicator was *Land use [Squared metres of land used for the plant]* (Amrina & Vilsi, 2015; Garraín et al., 2020, 2021; Harik et al., 2015; Ingwersen et al., 2016; Moslehi & Arababadi, 2016; Sangwan et al., 2019; Trianni et al., 2019b).

Instead, for *Use of Reused goods/materials*, there are different type of indicators, *Reused goods [unit of mass]* (Cagno et al., 2023b), *Number of reused parts assembled [pcs. or units per product]* (Helman et al., 2023) or *Reuse/Recycle Raw Material Ratio* (Swarnakar, Singh, & Tiwari, 2021a). Meanwhile, *Hazardous Material Use* was mainly measured in terms of *Mass of hazardous materials input [kg]* (Ruiz-Mercado et al., 2012a; Sangwan et al., 2019; Smith et al., 2019; Valdivia & Castillejo, 2021).

Moreover, for *Waste/wastewater disposal*, two of the sources share the *Waste Segregation [%] indicator*. (Helleno et al., 2017; Swarnakar et al., 2021a). Whereas in *Green Packaging* two main indicators can be found *Packaging material use*(Song & Moon, 2019) or *Packaging Materials Discarded* (Tan et al., 2015a; Watanabe et al., 2016).

In contrast, *Transportation and Logistics*, which is a subcategory that does not belong to any of the clusters, has 5 different indicators proposed: *Use of low-emission transport [%]* (Helman et al., 2023), *Transportation [quantity of volume]* (Cagno et al., 2023), *Total energy used in distribution* (Sangwan et al., 2019), *Embodied energy from diesel × distance travelled* (Munasinghe et al., 2017), *Inventory tracking techniques* (Harik et al., 2015), *CO2 emissions from the product and materials transport activities, measured [kgCO2eq]* (Barbosa et al., 2023).

Regarding *Renewable material use* the indicators that we can highlight for it are: *Percentage of renewable materials used* (Barni et al., 2022) and *Weight or volume of renewable materials* (Zarte et al., 2019b) [kg, m3, pc]. Meanwhile when speaking about Recyclable waste it was shown to be measured in two ways: *Waste recycled [%]* (Barni et al., 2022a; Gani et al., 2022a; Trianni et al., 2019a) or *Waste recycled [unit of mass*] (Cagno et al., 2023b; Helman et al., 2023).

Furthermore, *Noise pollution* which is studied in both the environmental and social pillar, in this case is measured in terms of *Level of noise generated [dB]* (Amrina & Vilsi, 2015; Mesa et al., 2019; Sangwan et al., 2019; Sharathkumar Reddy et al., 2017). This indicator can have an impact in both a social and environmental aspect, most research's categorized it as a social indicator.

In reference to *Eco-friendly materials*, we have three different indicators: *Material carbon footprint [ton of CO2 or CO2e]* (Helman et al., 2023), *Green Production Rate [%]* (Helleno et al., 2017), and *Conscious raw material selection* (Harik et al., 2015). In contrast to *Quality* (the other micro category that doesn't belong to a cluster) that all three contributions agree on the same indicator *Scrap generation [parts/kg]* (Edtmayr et al., 2016; Lucato et al., 2018; Swarnakar, Singh, & Tiwari, 2021a)

Finally, the categories with the least number of indicators proposed were *non-Renewable material use* where two indicators can be found: *Weight or volume of non-renewable materials [kg, m3, pc]* (Zarte et al., 2019b) and *Depletion of non-renewable energy resources* (S. Kim & Moon, 2017). *Use of Remanufactured goods*, where there are *Remanufactured products [#]* (Cagno et al., 2023) and *Percentage of product/component recovered* (Gani, James, et al., 2022). *Reused waste* with *Total waste reused [kg]* (Barni et al., 2022) and *Fraction of water reused* (Sangwan et al., 2019) and lastly *Reused energy usage* with the namesake indicator *Reused energy [unit of energy]* (Cagno et al., 2023).

1.3.2.2. Proposed Social indicators per publication

		Workplace and Employee Well-Being										Social Impact and Engagement					Ethics and Integrity
Manufacturing process	Reference	Working conditions	Employement/ job opportunity	Work Accidents	Work-related injuries	Training/Development	Health & Safety	Noise pollution	Turnover	Labor equality	Absenteeism	Social investments	Customer complaints	Customer satisfaction	Employee satisfaction	Wage Level/Economic Benefits	Corruption
Design	(Lucato et al., 2018)			Lost hours due to accidents [Parts/h × 10]		Training hours [h/part × 10−4]		Noise level [(dB standard/dB actual) × 10]									
Design	(Pask et al., 2017)		Employment Opportunity														
Design	(Watanabe et al., 2016)			Labour Accidents Rate		Labour Training in sustainability					Work Days Lost		Customer Complaints		Job Satisfaction		
Distribution and Logistics	(Li & Mathiyazhagan, 2016)					Education, public awareness and training			Employee turnover rates and costs				The rate of complaints and how they were addressed	Customer satisfaction [through surveys or feedback and complaints]			
General	(Cagno et al., 2023)		Job creation [#]	Accidents [#]	Injuries [#] Fatalities [#]	Safety training [#, qualitative]				Gender discrimination [qualitative or # or %)	Absenteeism [unit of time]			Customer satisfaction [qualitative]			

Operation	Operation	General	General	General	General	General	General	General	General
(Voces et al., 2012)	(Amrina & Vilsi, 2015)	(Kocmanova et al., 2015)	(Kocmanova et al., 2017)	(Naderi et al., 2017)	(Helleno et al., 2017)	(Hsu et al., 2017)	(Ahmad et al., 2019)	(Sangwan et al., 2019)	(Swarnakar, Singh, Antony, et
	Employee involvement						Workload		
			Number of employees from the region / Average recorded number of	Nº of workers on each machine			Local employment or employment creation	Number of jobs created	
	Accident rate				Accident Rate [accident]		Work accidents	Number of work-related accidents/incidents	Accident rate
							Work related injuries	Fraction of worker with work-related disease	
	Training and education	- Education and training expenditures / Added value [%]	Education and training expenditures / Added value	Nº of training hours required for the job			Training and career development	Total hours of employee training	Training opportunity to employees
	Occupational health and safety		Total amount of money for non-compliance of regulations related to	Nº of hours of training in safety and health			Workers' health and safety	Reported customer health and safety issues	Time weighted average to record noise exposure
					Noise Level [dB]		Noise in factory		
		Number of terminated employments / Average number of employees [%]	Number of terminated employments / Total number of employees in		Turnover [%]	Reduction of employee turnover rate			Employee turnover ratio
	Gender equity	Number of women / Average number of employees [%]	Total number of women / Total number of employees in given to period.				Equal opportunity or no discrimination	Gender ratio Female to male salary ratio	Gender ratio
					Absenteeism [%]		Lost workdays	Average sick leave per employee	Absenteeism ratio
		Monetary support of local community and gifts to municipalities /	Total amount of money of charitable work in support of local communities /				Contributions to economic development	Investment in employee health and safety Investment in employee training	
				Nº of customer complaints, and claims or questions		Reduction of the number of customer complaints			
						Enhancement of customer satisfaction degree	Consumer satisfaction	Customer satisfaction	
						Enhancement of degree of employee work satisfaction	Workers' satisfaction	Employee satisfaction	Employee satisfaction rate
Unitary average wage		Wage costs / Average number of employees[EUR/ Number]	Wage costs / Added value		Benefits/Commission/Profit [%]		Wage or salary	Fraction of income difference relative to industry	Staff incentives /commission/ benefits
			Share of final judgements for corruption * 100 / Total members Cg. [%]				Anti-corruption programs		

Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation
(Sureeyatanapas et al., 2015)	(Erbis et al., 2016)	(Bhanot et al., 2016)	(Sharathkumar Reddy et al., 2017)	(Mesa et al., 2019)	(Zarte et al., 2019b)	(Thirupathi et al., 2019)	(Trianni et al., 2019)	(Lamjahdi et al., 2021)	(Kumar et al., 2022)
				Biological, chemical, physical, ergonomic, safety hazard exposure	Time of employees working at risky workplaces [h]		Work conditions Number of accidents due to working condition		Fresh air index [Number]
							Employment Number of new employees per year		Employment generation [Nos]
Rate of work-related accidents relative to the total workinghours in			Accident rate						Numer of accidents [#]
								Injury rate	
Employee training and education provision [Qualitative			Training and education		Time of training for employees [h]	Employee knowledge level [Number]	HR development [Number of training hours/employee]	Ratio of training hours	Skill enhancement/development initiatives [Level]
Employee health and safety provision [Qualitative evaluation (10	CNT exposure [μg m−3]		Occupational health and safety	Biological, chemical, physical, ergonomic, safety hazard exposure			Healthcare [Degree or percentage of health service level or Budget]	Occupational Health & Safety	Medical health checkup and safety [Nos]
Annual employee turnover rate [%]									
			Gender equity				Discrimination [Degree or percentage of discrimination]		
Rate of expenditure on external social development per tonne of sugar							Societal investment [Degree or percentage of annual budget to	Investments in community development activities	
The number of customer complaints and product returns peryear [Number]									
						Customer satisfaction [%]			Customer satisfaction [Rating score]
		Job satisfaction level [salary, incentives and workload]						Level of employee satisfaction	Employee satisfaction survey [%]
Internal fairness on employee wages and benefits [Qualitative		Job satisfaction level [salary, incentives and workload]							
							Fight against corruption [Degree or percentage]		

Operation	(Harik et al., 2015)	Employee ergonomic consideration					International safety and workerrights standards			Male/female ratio		Investment in local community				Average salary	
Operation	(Tan et al., 2015)					Average hours of sustainability training	Personal protective and safety equipment				Lost workdays [Days]		Customer complaints [1]				

Table 5. Proposed Social indicators per publication

To summarize the information presented in the table above the following graph was developed:

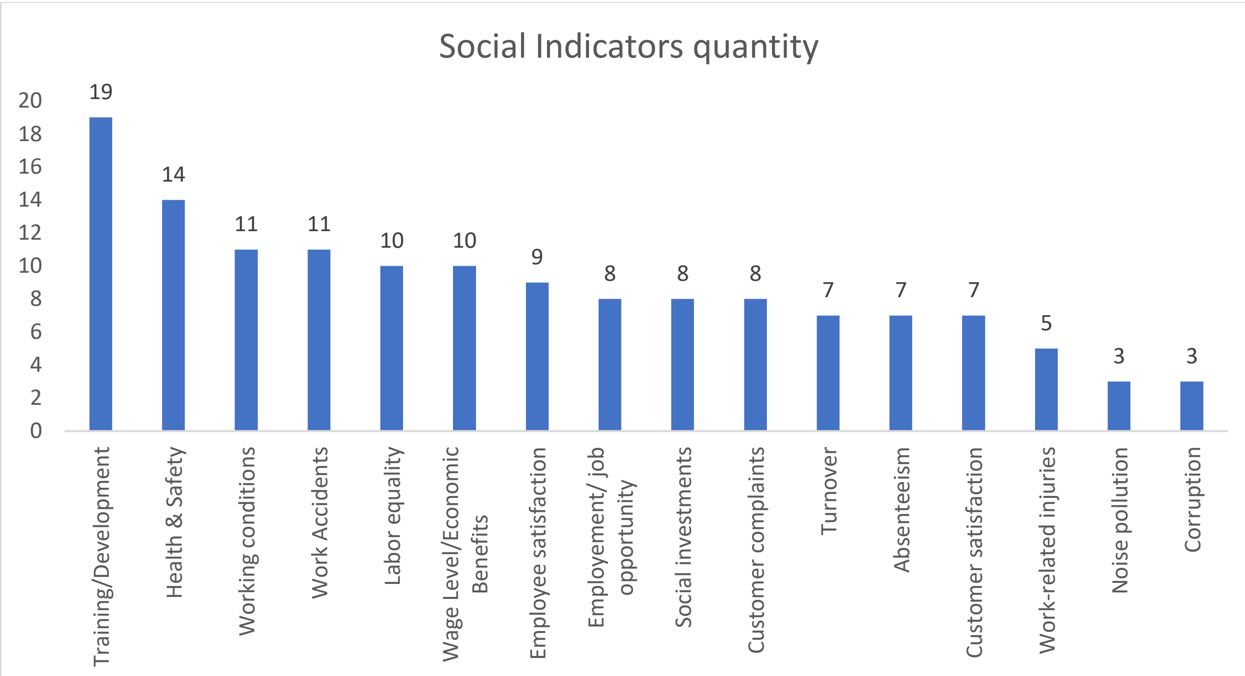

Figure 11. Sustainability indicators: Social indicator quantity

In **Figure 9**, we can observe that in 19 of the contributions, an indicator was proposed for the category *Training/Development*, being the category with the highest number of indicators proposed, followed by *Health & Safety* and *Working conditions*. It's worth highlighting that against the Analysis 3.2.1.2. This time the micro category *Health & Safety* occupies second place.

For *Training/Development* some of the proposed KPIs were in terms of time *Average hours of sustainability training* (Naderi et al., 2017a; Tan et al., 2015a; Trianni et al., 2019a; Watanabe et al., 2016 or in qualitative terms *Safety training [#, qualitative]* (Cagno et al., 2023b; Kumar et al., 2022; Sureeyatanapas et al., 2015). For this indicator, no specific training program or tool was mentioned. Nevertheless, it can be inferred given the frequency of appearance and usage of this indicator that it is given a high importance for sustainability, but the implementation and control of it is fairly simple. As seen in **Table 5**, all publications that appear in this category refer to the number of hours of training for employees, some more specific than others. For example, for Watanabe et al., (2016) the proposed indicator is *Labour Training in sustainability*, while for Naderi et al., (2017a) a more general *Nº of training hours required for the job* is used.

For *Health & Safety* different indicators were found but is worth highlighting *Biological, chemical, physical, ergonomic, safety hazard exposure risk* [1-5 scale] (Mesa et al., 2019), *Medical health checkup and safety* [Nos] (Kumar et al., 2022), and *Nº of hours of training in safety and health* [h] (Naderi et al., 2017). Since many things can negatively affect a worker's health and safety, we find a wide range of different indicators in this category. Some propose measure of reported cases as seen in Sangwan et al., (2019a) *Reported customer health and safety issues*. Others take a different approach by measuring the number of health and safety checks performed to employees *Medical health checkup and safety [Nos]* (Kumar et al., 2022). Others, such as Ahmad et al., (2019b) follow a general approach by proposing *Workers' health and safety*. Risks are naturally bound to the specific activities performed by companies, and an extensive analysis of the risks is needed to correctly assess a companies sustainability.

Similarly for *Working conditions* where there are indicators as *Workload* (Ahmad et al., 2019), *Fresh air index [Number]* (Kumar et al., 2022), and *Time of employees working at risky workplaces [h]* (Zarte et al., 2019b). We find in these publications that special attention is given to the working environment in order to reduce accidents, maintain a worker's health and increase productivity.

In contrast for *Work Accidents* a main indicator was found *Number of accidents [#]* (Ahmad et al., 2019b; Amrina & Vilsi, 2015; Cagno et al., 2023b; Helleno et al., 2017; Kumar et al., 2022; Sharathkumar Reddy et al., 2017; Swarnakar, Singh, & Tiwari, 2021a; Watanabe et al., 2016). This indicator is relevant to the company's operations as it "directly affect the productivity of the manufacturing process"(Helleno et al., 2017). All publications proposed the same general indicator to track work accidents, although several categories of accidents and incidents exist, none made the distinction and kept the general indicator as a comprehensive measure of workplace safety.

The micro category *Labor equality* was found to be mainly referring to *Number of women / Average number of employees [%]* (Amrina & Vilsi, 2015; Cagno et al., 2023b; Harik et al., 2015; Kocmanova et al., 2015, 2017; Sangwan et al., 2019a; Sharathkumar Reddy et al., 2017; Swarnakar, Singh, & Tiwari, 2021a). Meanwhile for *Wage Level/Economic Benefits* different indicators were found such as *Staff incentives /commission/ benefits* (Swarnakar, Singh, Antony, et al., 2021), *Job satisfaction level [salary, incentives and workload*] (Bhanot et al., 2016) and *Average salary* (Harik et al., 2015). Different approaches can be observed between them, but the general idea is for the company to keep an eye on providing equal opportunities for all their employees. This can be done in many different ways, the most recurrent one being first on employee gender ratio and job satisfaction.

A main indicator was found for *Employee satisfaction*, which was *Level of employee satisfaction* (Ahmad et al., 2019b; Bhanot et al., 2016c; Kumar et al., 2022; Lamjahdi et al., 2021a; Sangwan et al., 2019b; Swarnakar, Singh, Antony, et al., 2021; Watanabe et al., 2016). *Similarly for Employement/ job opportunity* were the main indicator was *Number of jobs created* (Cagno et al., 2023b; Kumar et al., 2022; Sangwan et al., 2019a; Trianni et al., 2019b). Talent retention can be particularly important in contexts where the workers' skill highly influences the output of the company. As part of this idea, many authors propose the *Employee satisfaction* as an indicator to keep track of, as well as to guarantee long-term operations.

Pertaining *Social investments,* it was found to be measured in terms of *Societal investment [Degree or percentage of annual budget to investment in society]* (Ahmad et al., 2019b; Harik et al., 2015; Lamjahdi et al., 2021b; Trianni et al., 2019a). The presence of this indicator is to track and foster the continuous investment in social well-being, either directly with the employees or with local communities. This approach aligns with the broader goal of promoting workplace safety and corporate responsibility, emphasizing the nature of sustainable and socially responsible business practices.

The same for *Customer complaints* where the main indicator was *Nº of customer complaints, and claims or* questions (Naderi et al., 2017a; Sureeyatanapas et al., 2015; Tan et al., 2015a; Watanabe et al., 2016). This happened also for *Turnover* which was measure in *Annual employee turnover rate [%]* (Helleno et al., 2017; Hsu et al., 2017; Kocmanova et al., 2015, 2017; Li & Mathiyazhagan, 2016; Sureeyatanapas et al., 2015; Swarnakar, Singh, & Tiwari, 2021a).

Moreover, *Absenteeism* was measured either in *Lost workdays [Days]* (Cagno et al., 2023b; Tan et al., 2015a; Watanabe et al., 2016) or *Absenteeism ratio* (Helleno et al., 2017; Sangwan et al., 2019a; Swarnakar, Singh, Antony, et al., 2021b). Tracking absenteeism in a company is crucial to manage productivity, control costs, and monitor employee well-being. It ensures compliance with leave policies and labor laws while revealing trends or underlying issues. Addressing absenteeism can improve employee engagement, safety, and overall workplace satisfaction.

For *Customer satisfaction* the main indicator was *Customer satisfaction [%]* (Ahmad et al., 2019b; Kumar et al., 2022; Sangwan et al., 2019a; Thirupathi et al., 2019). They all suggest to keep track of the customer in a comprehensive way, taking care of clients to ensure future operations.

Finally, the categories with the least number of indicators proposed were *Work-related injuries* measured in *Injuries [#]* (Ahmad et al., 2019a; Cagno et al., 2023b; Lamjahdi et al., 2021b, *Noise pollution* with *Noise Level [dB]* (Ahmad et al., 2019b; Helleno et al., 2017; Lucato et al., 2018) and *Corruption* that proposes *Fight against corruption [Degree or percentage]* (Ahmad et al., 2019a; Kocmanova et al., 2017; Trianni et al., 2019a) .

1.3.2.3. Proposed Economic Indicators per publication

		Financial performance		Investment analysis			Quality and efficiency			Cost analysis									
Manufacturing process	Reference	**Revenues**	**Profit**	**Cost of Capital**	**Payback period**	**R&D expenditure**	**Investments for sustainability**	**Quality**	**Lead Time**	**Machine/Equipment Performace**	**Energy Cost**	**Inventory cost**	**Logistics/Transportation cost**	**Labor Cost**	**Operating cost**	**Maintenance cost**	**Water cost**	**Product cost**	**Input material cost**
General	(Helman et al., 2023)							Amount of scrap [%]											
General	(Cagno et al., 2023)	Total revenues [unit of currency]	Total profit [unit of currency]			R&D investment [unit of currency]	Energy efficiency investment [unit of currency] Safety investment [unit of currency] Environmnet investment [unit of currency]		Lead time [unit of time]		Bill of energy [unit of energy]	Inventory cost [unit of currency]	Supply cost [unit of currency] Distribution cost [unit of currency]	Labor cost [unit of currency]	Production cost [unit of currency]	Maintenance cost [unit of currency]			
Operation	(Kumar et al., 2022)		Profit growth year on year [%]					Reduction in part rejection [PPM or percentage]			Energy consumption units [kWh/kg or kWh/unit]				Reduction in manufacturing [cost/part]				
Operation	(Favi et al., 2022)														Operating costs [k€]				
General	(Swarnakar, Singh, Antony, et al., 2021)							Acceptance rate of product					Transportation efficiency ratio	Labor cost	Operational cost				

General	Operation	Design	Design	Operation	Operation	Design	Operation
(Sangwan et al., 2019)	(Zarte et al., 2019b)	(Rahla et al., 2019)	(Smith et al., 2019)	(Thirupathi et al., 2019)	(Trianni et al., 2019)	(Mangili & Prata, 2020)	(Lamjahdi et al., 2021)
			Revenue from eco-products [$]				
Profit gained				Gross proft – operating expenses [INR]			Net profit
Capital employed Return on investment			Net present value [$]				
			Payback period [time]			Payback period [years]	
Technology and innovation cost Investment in new services and products					Product development cost [Percentage of annual budget to R&D]		Investments in innovation and R&D
				Defect per unit [ppm]	Product quality Rate of customer complaints [units/unit time]		Quality of products and services
					Response [Days]		
					Enterprise productivity [Units/hour]		
			Total energy cost [$]		Energy price [$/barrel]		
					Material handling equipment [Number of material handling equipment]		
Transportation cost							Rate of one time delivery
							Labour cost
Operational cost	Operation costs [€]		Manufacturing cost [$]				Operational and capital costs
Maintenance and improvement cost							
Water cost fraction							
			Total product cost [$]		Product costs [$/unit]		
	Costs spending on local suppliers [€]	Concrete binder cost [€]	Specific raw material cost [$]				Material cost

General	General	Design	General	General	Operation	Design	Operation	General
(Kocmanova et al., 2017)	(Naderi et al., 2017)	(S. Kim & Moon, 2017)	(Helleno et al., 2017)	(Hsu et al., 2017)	(Sharathkumar Reddy et al., 2017)	(Lucato et al., 2018)	(Mesa et al., 2019)	(Ahmad et al., 2019)
				Growth of marginal revenue				Revenues
		Profit earned by organization		Growth of capital recovery rate				Profit
ROA		Return on investment		Return on investment				Fixed asset depreciation
								Payback period
								Research & Development
Total investments for environmental protection / Added value		Eco-friendly investment					Machinery/Tooling cost [USD]	Investments
								Defective products
	Total processing time [h]			Improvement of manufacturing processes		Cycle time [Parts/h]		
Total consumption of renewable energy /Added value. [GJ/CZK]	Cost of the Power of Energy consumed for each section [€/KWh)]	Fuel price volatility					Energy cost [USD]	
			Stock Cost [US$]		Inventory cost			Warehousing and logistics
	Cost of removal of Packaging [€/Kg]	Transportation cost						Warehousing and logistics
	Cost per hour of the RR.HH. staff [€/h]		Salary Level		Labor Cost	Labour cost [Parts/US$10.00]	Worker cost [USD]	Labor cost
		Production cost	Operation Cost [US$]					Operation cost
	Cost associated to the maintenance and acquisition of the EPIs [€]							Maintenance cost
	Cost of water consumed for each section of loop z [€/m3]							
			Effective Cos [US$]		Machining cost		Product expected cost [USD]	
	Cost of Material for the production of a part [€/Kg]	Material cost			Material cost		Raw material/consumable cost [USD]	Overall materials cost

Operation	General	Operation	Design	Design	Operation	Distribution and Logistics	Operation	Design
(Bhanot et al., 2016a)	(Moslehi & Arababadi, 2016)	(Erbis et al., 2016)	(Watanabe et al., 2016)	(Huedo et al., 2016)	(Bhanot et al., 2016)	(Li & Mathiyazhagan, 2016)	(Ingwersen et al., 2016)	(Pask et al., 2017)
			Operational and Capital costs			Rate of return and payback periods for capital investments		
	Initial costs [$/kW]			Investment costs [€/m2]				Capital investment [£ (000s)]
Surface Roughness								Quality
Material Removal Rate [cm3/sec]					Material removal rate [cm3 /s]			Production Efficiency [%]
			Energy costs	Energy costs [€/m2]	Basic energy cost		Fossil fuel depletion [$]	
			Labour costs			Employee turnover rates and costs		
	Operational costs [$/kW]	Total production cost [million $]	Operational and Capital costs		Production cost/component			Operating costs [£/hr]
	Maintenance Costs			Maintenance costs [€/m2]				
					Oil and water cost			
Production Cost/component								
			Material cost		Oil and water cost		Metal depletion [$]	

Distribution and Logistics	General	Operation	Operation	Operation	Operation	Operation
(Barbosa et al., 2023)	(Ruiz-Mercado et al., 2012)	(Voces et al., 2012)	(Tan et al., 2015)	(Amrina & Vilsi, 2015)	(Harik et al., 2015)	(Sureeyatanapas et al., 2015)
	Revenues from eco-products					
			Net profit margin			Gross profit margin per year [%]
	ROI		Return on investment			
	Payback period					
			Innovation & R/D investments [$]		R&D	
		Investment rate			Brand-related expenses	Rate of expenditure on environmental improvement and protection per tonne of sugar produced per year [Monetary unit/t]
Supplier lead time						
		Energetic efficiency [M €]	Energy Cost [$]			
				Inventory cost		
				Product delivery		
			Labour costs [$]	Labor Cost		Rate of expenditure on employee training and education pertonne of sugar produced per year [Monetary unit/t]
	Production cost		Operational and capital costs [$]			
						Rate of expenditure on process maintenance and improvementper tonne of sugar produced per year [Monetary unit/t]
	Total water cost					
	Total product cost					
			Material cost [$]	Material cost		

Table 6. Proposed Economic Indicators per publication

To summarize the information in the table above the following graph was developed:

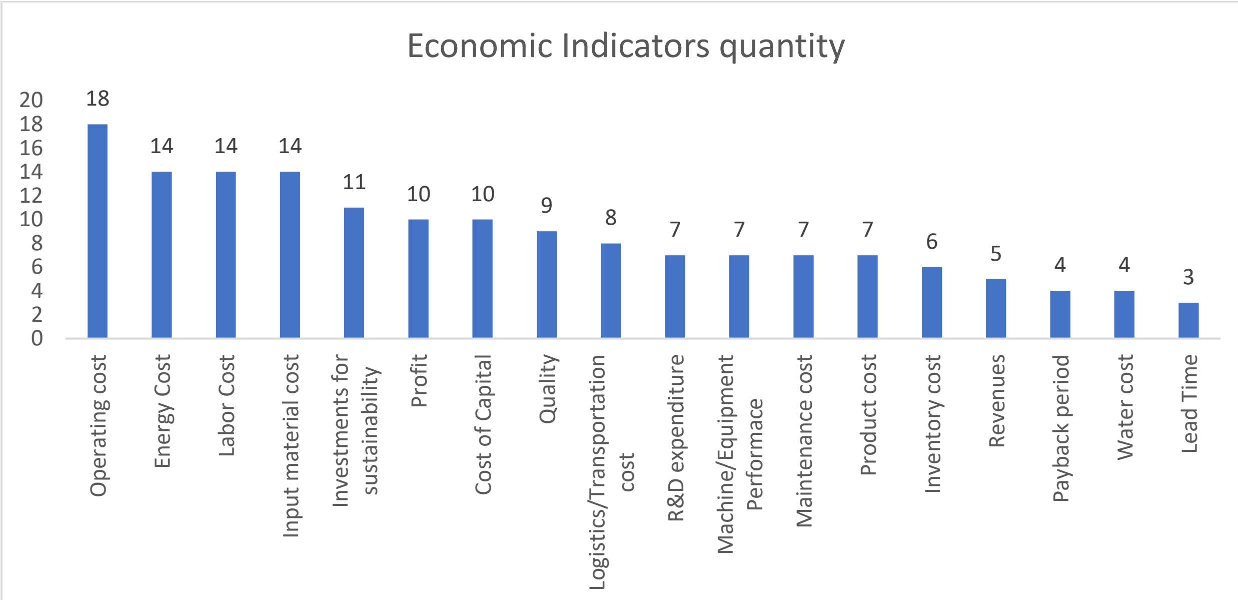

Figure 12. Sustainability indicators: Economic indicator quantity

From **Figure 12**, we can report that in 18 of the contributions, an indicator was proposed for the category *Operating cost*, being the category with the highest number of indicators proposed, followed by *Energy cost, Labor cost* and *Input material cost.* These categories at the same time can be all sub-divisions of *Operating cost.*

For *Operating cost* almost all of the contributions propose an indicator in monetary terms, called *Operation costs [€]* (Ahmad et al., 2019b; Erbis et al., 2016; Favi et al., 2022a; Helleno et al., 2017; Lamjahdi et al., 2021b; Moslehi & Arababadi, 2016; Pask et al., 2017; Sangwan et al., 2019a; Swarnakar, Singh, & Tiwari, 2021a; Tan et al., 2015a; Watanabe et al., 2016; Zarte et al., 2019a) or *Total production cost [million $]* (Bhanot et al., 2016b; Erbis et al., 2016; Kim & Moon, 2017; Ruiz-Mercado et al., 2012a; Smith et al., 2019), The only resonant indicator found is in terms of *Reduction in manufacturing [cost/part]* (Kumar et al., 2022). This indicator has typically always been present in companies as a fundamental key aspect in economic management. It includes different expenses necessary for the day-to-day operations, such as labor, utilities, maintenance, and materials. Monitoring this cost is crucial for cost control, budgeting, and to identify critical areas for improvement. Most proposals measured it as a total absolute value while Kumar et al., (2022) proposed to measure the reduction of it per unit.

For *Energy cost:* there is a general indicator as well, *Total energy cost [$]* (Bhanot et al., 2016a; Huedo et al., 2016; Mesa et al., 2019; Smith et al., 2019; Tan et al., 2015a; Trianni et al., 2019a; Watanabe et al., 2016) with two specific ones *Fuel price volatility* (S. Kim &

Moon, 2017) and *Cost of the Power of Energy consumed for each section [€/KWh)]* (Naderi et al., 2017). The existence and use of this type of indicator underlines the importance of any operation to become more efficient, it serves as a reminder that it not only conserves resources but directly impacts the company's profitability and long-term sustainability.

Similarly for *Labor cost,* a commonly used indicator is used: Labor cost [unit of currency] (Ahmad et al., 2019b; Amrina & Vilsi, 2015; Cagno et al., 2023b; Lamjahdi et al., 2021b; Mesa et al., 2019; Sharathkumar Reddy et al., 2017; Swarnakar, Singh, & Tiwari, 2021a; Tan et al., 2015a; Watanabe et al., 2016), it can be highlighted *Cost per hour of the RR.HH. staff [€/h]* (Naderi et al., 2017), and *Rate of expenditure on employee training and education per ton of sugar produced per year [Monetary unit/t]* (Sureeyatanapas et al., 2015), as specific indicators. In most contexts, labor cost is often one of the highest components of the operating cost. In labor-intensive industries such as clothing or food, it becomes relevant to keep track of the labor cost so that a better workforce allocation and expenses control can be achieved.

Meanwhile for *Input material cost,* the indicator proposed starts to diversify depending on the type of industry that developed the research, hence there is a general indicator Material cost [$] (Ahmad et al., 2019b; Amrina & Vilsi, 2015; Kim & Moon, 2017; Lamjahdi et al., 2021b; Naderi et al., 2017b; Sharathkumar Reddy et al., 2017; Tan et al., 2015a; Watanabe et al., 2016) and industry specific costs like: *Concrete binder cost [€]* (Rahla et al., 2019), *Metal depletion [$]* (Ingwersen et al., 2016), *Oil and water cost (Bhanot et al., 2016)*. It is worth mentioning that, as seen in **Figure 12**, the first four most studied indicators belong to the Cost analysis cluster. Although most researchers treated material cost as a general indicator, some used it as a way to assess sustainability for the design and strategic use for product family manufacturing as seen in Kim & Moon, (2017).

Continuing with *Investments for sustainability*, it was found as *Total investments for environmental protection / Added value* (Kocmanova et al., 2017), *Investment costs [€/m2]* (Huedo et al., 2016) or *Initial costs [$/kW]* (Moslehi & Arababadi, 2016). As for the *Social Investments*, this indicator helps to foster and track all monetary investments aimed at maintaining or improving any aspect of the company's sustainability, including newer machinery, or infrastructure, among others.

Furthermore, *Profit* was found either in terms of *Total profit [unit of currency]* (Cagno et al., 2023a; Kim & Moon, 2017; Sangwan et al., 2019a; Sureeyatanapas et al., 2015) or *Net profit* (Lamjahdi et al., 2021; Tan et al., 2015a; Thirupathi et al., 2019). Whereas *Cost of Capital* which belongs to the Investment analysis cluster, aroused the main indicator of *Return on investment* (Hsu et al., 2017; Kim & Moon, 2017; Li & Mathiyazhagan, 2016; Ruiz-Mercado et al., 2012a; Sangwan et al., 2019a; Tan et al., 2015a). Going forward, for *Revenues* it is worth highlighting the *Revenue from eco-products [$]* (Ruiz-Mercado et al., 2012a; Smith et al., 2019)as well as *Total Revenues* (Cagno et al., 2023b).

Profit and revenue have always been fundamental indicators driving companies forward. Profit incentivizes businesses to manage all costs efficiently and innovate their operations to maximize returns. Revenue reflects market demand and growth potential. Both metrics influence strategic decision-making and investments. The success of companies is often correlated with their ability to strategically manage these 2 indicators, adapting to changing context in markets and economic conditions.

For *Quality*, which was also analyzed in the Environmental division, pertaining to this cluster, a main indicator was found *Product quality Rate of customer complaints [units/unit time]* (Lamjahdi et al., 2021b; Pask et al., 2017; Trianni et al., 2019a) along with specific ones such as *Amount of scrap [%]* (Helman et al., 2023), or *Defect per unit [ppm]* (Thirupathi et al., 2019). Scrap rate is often measured at an economic level. As seen during this SLR, it was proposed 9 times at an economic level versus 3 times at an environmental level. Regardless of at what level it is proposed, the general purpose remains the same: to monitor and control the quality rate of manufacturing.

Going back to Cost analysis, for *Logistics/Transportation cost*, it was found with different indicators such as: *Transportation cost* (Kim & Moon, 2017; Sangwan et al., 2019a) as a general one, but also *Transportation efficiency ratio* (Swarnakar, Singh, Antony, et al., 2021), *Rate of one time delivery* (Lamjahdi et al., 2021) and *Cost of removal of Packaging [€/Kg]* (Naderi et al., 2017). Different aspects of the logistics system were considered. Predominantly, transportation costs were proposed the most with some proposals in a more detail level such as *Rate of one time delivery.*

For *R&D expenditure* consensus was found as it is measured generally as *R&D investment [unit of currency]* (Ahmad et al., 2019b; Cagno et al., 2023b; Harik et al., 2015; Lamjahdi et al., 2021; Sangwan et al., 2019; Tan et al., 2015a). R&D is mentioned 23 times and proposed 7 times, which underlines the importance of it. As seen in Harik et al., (2015), it plays a critical role in leading to the development of more efficient, eco-friendly, and sustainable products and processes. Most proposals were general, as amount of currency dedicated to R&D while others such as Trianni et al., (2019) and Sangwan et al., (2019) propose a more specific measurement of *Product development cost [Percentage of annual budget to R&D]* and *Investment in new services and products* respectively.

In contrast, for *Machine/Equipment Performance*, different indicators were found *Material removal rate [cm3 /s]* (Bhanot et al., 2016a, 2016b) , *Production Efficiency [%]* (Pask et al., 2017), *Cycle time [Parts/h]* (Lucato et al., 2018) or *Total processing time [h]* (Naderi et al., 2017). Differently, in the same cluster for *Maintenance cost* a main indicator was found as Maintenance cost [unit of currency] (Ahmad et al., 2019b; Cagno et al., 2023a; Huedo et al., 2016; Moslehi & Arababadi, 2016; Sangwan et al., 2019a). Regarding *Product cost*, there is an indicator proposed measured in general terms *Total product cost [$]* (Helleno et al., 2017; Mesa et al., 2019; Ruiz-Mercado et al., 2012a; Smith et al., 2019) , and *Product costs [$/unit]* (Bhanot et al., 2016a; Trianni et al., 2019a). And for *Inventory cost*, there is a general indicator *Inventory cost [unit of currency]* (Amrina & Vilsi, 2015; Cagno et al., 2023b; Helleno et al., 2017; Sharathkumar Reddy et al., 2017).

Similarly, as seen before, for the previous indicators we find a difference in scope in the proposals identified. They each serve a different purpose and they depend on at what level was the analysis built. For example, we can identify in Bhanot et al., (2016a), the use of a very process specific indicator *Material removal rate [cm3 /s]* while in Lucato et al., (2018) we find *Cycle time [Parts/h].* It is particularly important for the framework proposal of this research to highlight how for the same category of indicators, we can find such different scopes and detail level in the proposals.

Finally, the categories with the least number of indicators proposed were *Payback period* with *Payback period [years*] (Ahmad et al., 2019b; Mangili & Prata, 2020; Ruiz-Mercado et al., 2012a; Smith et al., 2019), *Water cost*: *Total water cost* (Ruiz-Mercado et al., 2012) and *Lead time: Lead time [unit of time]* (Barbosa et al., 2023; Cagno et al., 2023b; Trianni et al., 2019a). Lastly, it is worth highlighting that in both the analysis Analysis 1 and 2, there is a coherence between the most studied categories and the categories that have the highest quantity of indicators proposed.

4. Discussion and framework proposal

As a result of the SLR, it was found that there is a significant number of indicators used by the manufacturing industry in the extant literature, some are relevant for a specific industry while others are general and can be adapted to a wider range of companies. As a result, this thesis would like to propose a guideline to assess a company in terms of sustainable manufacturing, establishing a framework is important for several reasons:

- Environmental Impact and Resource Efficiency: Sustainability indicators measure and monitor a company's environmental impact, such as input material consumption, carbon emissions, energy consumption, and waste generation. By tracking these indicators, companies can identify areas for improvement and create action plans accordingly to increase their efficiency and thus reduce their ecological footprint. This leads to cost savings, reduced waste generation and minimize natural resources depletion.

- Regulatory Compliance: Industries are often subject to environmental regulations and reporting requirements. Monitoring sustainability indicators can help companies remain compliant with these regulations, avoiding potential legal and financial risks.
- Reputation and Branding: Consumers and stakeholders increasingly value environmentally and socially responsible businesses. Implementing sustainability indicators and demonstrating progress can enhance a company's reputation and attract eco-conscious customers. (Medne & Lapina, 2019).
- Risk Management: Sustainability indicators can help identify potential future risks, either in the short or long term, related to environmental, social, and economic factors. Companies can proactively address them to avoid negative impacts on their operations and profitability.
- Innovation and Competitiveness: Adopting a sustainability mindset encourages companies to innovate and develop new technologies, products, and processes to enhance their competitive advantage by meeting evolving market demands.
- Employee Engagement: By implementing and following social and environmental indicators, companies can demonstrate their commitment with society thus fostering employee engagement and satisfaction.

Moreover, the framework has the need to be adaptable because as Murad et al., (2021) narrates, in the manufacturing industry there is the need for the sustainability assessment to be able to adapt to the need and size of the institutions, so they can be measured on: Corporation level, production process levels and production line and plant levels. For example, across this literature review other proposed frameworks were found but they had some limitations, for example the one from Lucato et al., (2018) considers one manufacturing equipment that has unusual characteristics.

The proposed framework suggests a series of steps:

1. **Identify Key Categories:** Which translates to identifying the areas that are relevant to the specific industry to be measured such as energy consumption, waste management, financial performance, workplace and employee well-being.

2. **Select the indicators:** Identify the specific measurable indicator for each category for example: Hazardous materials used [unit of mass / unit produced] or Energy cost [unit of currency / unit of time]

To facilitate this process, a table was developed and was constructed as follows:

First, we analyzed Tables 4, 5 & 6, which show the proposed indicators for each category. Next, we discarded categories with indicator frequencies within the first quartile. From the remaining categories, we selected an indicator for each one. This choice was based on either the most frequently mentioned indicator or one that could be applied across a broader spectrum of sectors (i.e., not specific to one industry). This approach ensures the framework's versatility for adoption and customization within any manufacturing industry.

Each proposed indicator is accompanied by its corresponding unit of measurement, aiming for generality and adaptability (i.e., Unit of Currency), making it easier to adjust the framework to different countries or industry sectors as needed.

			Proposed indicators	
Environmental	**Material Usage**	Input Material Consumption	Raw Materials Consumption Rate [unit of mass / unit produced]	Consumables Utilization Rate [unit of mass / unit produced]
		Recycled Material Use	Percentage of Recycled Materials used [100* mass of recycled raw material / total mass of raw materials used]	
		Use Of Reused Goods/Materials	Reused/recycled materials used [unit of mass / Unit produced]	
		Hazardous Material Use	Hazardous materials used [unit of mass / unit produced]	
	Energy Consumption and Efficiency	Energy Consumption	Total Energy consumption [unit of energy / month]	
		Energy Efficiency	Energy consumption rate [unit of energy / unit produced]	
		Non-Renewable Energy Use	Total non-renewable energy use [unit of energy / month]	
		Renewable Energy Use	Total Renewable Energy use [unit of energy / month]	
		Electricity Consumption	Total Electric Energy Consumption [unit of energy / month]	
	Water Usage and Efficiency	Water Consumption	Total water consumption rate [unit of volume / unit of time]	

		Water Use Efficiency	Water consumption efficiency [unit of volume / unit produced]	
		Recycled/Reused Water	Percentage of recyced/reused water [%]	
	Waste Management	Waste Generated	Total waste generated [unit of mass / month]	
		Hazardous Waste Generation	Total hazardous waste [unit of mass / month]	
		Solid Waste	total solid waste [unit of mass / unit of time]	
		Liquid Waste	total liquid waste [unit of volume / month]	
		Waste/Wastewater Disposal	Waste segregation [total mass of waste segregated / total mass of waste produced]	
	Environmental impact	Land Use	Total land use [unit of area]	
		Atmospheric Emissions	Total Air emissions [kg CFC11 eq / unit of time]	
		Greenhouse Gas Emissions	Greenhouse Gas Emissions [t CO2eq / unit of time]	
	Transportation And Logistics	Transportation And Logistics	Total energy used in distribution [unit of energy / month]	Total carbon emissions from transportation [kg CO2-eq / month]
Economic	**Financial performance**	Revenues	Revenues [unit of currency]	
		Profit	Profit [unit of currency]	
	Investment analysis	Cost of Capital	Capital costs [unit of currency]	
		R&D expenditure	Research and Development expenditure [unit of currency / unit of time]	
	Quality and efficiency	Investments for sustainability	Sustainability related investments [unit of currency / unit of time]	
		Quality	Scrap rate [%]	
	Cost analysis	Machine/Equipment Performace	Production efficiency [%]	
		Energy Cost	Energy cost [unit of currency / unit of time]	
		Inventory cost	Inventory cost [unit of currency / unit of time]	
		Logistics/Transportation cost	Logistics/Transportation cost [unit of currency / unit of time]	
		Labor Cost	Labor cost [unit of currency / unit of time]	
		Operating cost	Operating cost [unit of currency / unit of time]	

		Maintenance cost	Maintenance cost [unit of currency / unit of time]	
		Product cost	Total product cost [unit of currency / unit produced]	
		Input material cost	Total input material cost [unit of currency / unit produced]	
Social	**Workplace and Employee Well-Being**	Working conditions	Biological, chemical, physical, ergonomic, safety hazard exposure risk [1-5 scale]	
		Employement/ job opportunity	Employment growth [number]	
		Work Accidents	Accident rate [number of accidents / year]	
		Training/Development	Employee Skill Enhancement [%]	
		Health & Safety	Employee health and safety provision [Qualitative evaluation]	
		Turnover	Employee Turnover [%]	
		Labor equality	Gender ratio [%]	
		Absenteeism	Lost workdays [days]	
	Social Impact and Engagement	Social investments	Investment in local communities [unit of currency / unit of time]	
		Customer complaints	Customer complaints [number / unit of time]	
		Customer satisfaction	Customer satisfaction [qualitative]	
		Employee satisfaction	Employee satisfaction survey [%]	
		Wage Level/Economic Benefits	Average Salary [unit of currency]	

Table 7. Proposed framework of indicators

It is worth noting that in two of the categories, two indicators were chosen. First within *Input Material Consumption.* Because there was a need to differentiate two types of input materials; the two indicators are: *Raw Materials Consumption Rate* [unit of mass / unit produced]. This one refers to the materials that go in the production of the final product and the second indicator *Consumables Utilization Rate* [unit of mass / unit produced] refers to the materials used in the production of the final product but does not necessarily go in it. For example, a lubricant, this material is needed for the final product but does not go in it.

The second indicator is *Transportation and Logistics.* Because it was necessary to differentiate between *Total energy used in distribution* [unit of energy / month] and *Total carbon emissions from* transportation [kg CO2-eq / month]. That are both important to evaluate sustainability.

Continuing with the steps for the sustainability assessment framework:

3. **Collecting the data and setting baseline:** Refers to establishing the data collection mechanisms such as sensors, software systems or manual data collection to monitor the performance of each indicator, determining the baseline values for each indicator.
4. **Set targets and integrate with operations:** Define achievable targets for each indicator and incorporate each one into daily operations. This might also entail providing training to employees and all parties involved.
5. **Data analysis and interpretation**: Analyze the collected data to evaluate the performance keeping in mind the targets set in the last point. This will help identify trends and improvement areas.
6. **Implement improvements:** From the data gathered in the previous step, act and improve technologies and practices.
7. **Reporting:** Present reports to stakeholders about the progress, challenges and achievements regarding sustainability.

It is hoped that by using this framework within the manufacturing industry, companies can better assess themselves in terms of sustainability, to reduce environmental impact, meet customer demands and lastly, to contribute to the worlds effort towards a more sustainable society.

5. Conclusion and future research directions

This thesis operates a systematic literature review of the state-of-the art of sustainability Indicators used in the manufacturing industry, with the goal of identifying the most relevant indicators in order to provide a framework that companies within the industry can use when looking to measure themselves in terms of sustainability.

First, the sources were divided by the manufacturing stage they refer to, and it turned out that most of them were not specific to a manufacturing stage, being "General" the category for most papers. Afterwards, to identify the currently used indicators two tables were developed. The first one reunited the articles that studied a certain sustainability category, this allowed us to identify the most used or studied topics. These were *Greenhouse Gas Emissions, Input Material consumption* and *Energy consumption*. The second table takes into consideration contributions that besides studying one of the categories, uses or proposes an actual indicator to effectively measure that category. This table allowed us to identify exactly how companies within the manufacturing industry were assessing themselves in terms of sustainability. Moreover, by comparing these two tables we're able to conclude that the micro categories most studied are coherent with the ones with the larger number of proposed indicators.

From this analysis a framework was proposed to collect the most studied/used sustainability indicators, with a sequence of general steps to follow in order to facilitate the process of sustainability assessment for manufacturing companies, this framework includes the most studied sustainability categories with an indicator and their units of measurement. This was proposed as general as possible so it can be adapted to any type of company wanting to leverage on it, since nowadays companies need to be transparent about their sustainable practices (Mengistu & Panizzolo, 2023).

The theoretical purpose of the framework is to gather and organize the indicators found in extant literature. To compare what has been proposed and highlight the widely studied sustainability indicators and also noting the niche indicators that don't have a lot of research. This provides a comprehensive view that can be used as a starting point for future research.

On the other hand, the practical implication of the framework is to provide a guideline for manufacturing companies that want to assess themselves in terms of sustainability but don't have a clear understanding of where to begin, or which indicators are the most relevant for them to use. Since the proposed framework is general and adaptable, these companies can adjust it to their specific context or needs.

To conclude, in line with the key points emerged from this review, in future research it is suggested:

- To evaluate the proposed framework performing a case study, to understand its usability and possible improvements.
- To include articles found in other databases for academic research besides SCOPUS.
- To study the indicators at manufacturing stage level, i.e: in the design stage or maintenance stage.
- Since the number of publications on this topic keeps growing, it will be necessary to update this framework as new proposals arise.

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