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Review

Sustainability Outcomes of Green Processes in Relation to Industry 4.0 in Manufacturing: Systematic Review

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Abstract: Green processes are very important for the implementation of green technologies in production to achieve positive sustainability outcomes in the Industry 4.0 era. The scope of the paper is to review how conventional green processes as a part of Industry 4.0 provide sustainability outcomes in manufacturing. The paper is based on the methodology of systematic literature review through the content analysis of literary resources. Twenty-nine studies were included in our content analysis. The results show the main focus of current literature related to Industry 4.0, sustainability outcomes and green processes. The authors present a conceptual Sustainability Green Industry 4.0 (SGI 4.0) framework that helps to structure and evaluate conventional green processes in relation to Industry 4.0 and sustainability. The study summarizes which technologies (big data, cyber-physical systems, Industrial Internet of Things and smart systems) and green processes (logistics, manufacturing and product design) are important for achieving a higher level of sustainability. The authors found that the most often common sustainability outcomes are energy saving, emission reduction, resource optimalization, cost reduction, productivity and efficiency and higher economic performance, human resources development, social welfare and workplace safety. The study suggests implications for practice, knowledge and future research.

Keywords: green processes; green technologies; green manufacturing; sustainability; Industry 4.0

1. Introduction

The concept of green technologies and processes was introduced in the 1960s, as a part of the environmental movement in the industrialized countries. The use of such technologies and processes is seen by researchers in homes, industry, energy and products. The use of green technologies allows enterprises and factories to introduce the green processes into production which reduce the impact of the production processes on the environment. The scope of the green processes (operations) ranges from product development to product lifecycle management, including the environmental practices such as ecodesign, clean production, recycling and reuse, with a focus on minimizing costs associated with production, distribution, use and disposal of products [1]. Green technology generally refers to the terms of technology, industrial processes, steps and products that are able to reduce environmental pollution and the use of raw materials as the natural energy sources [2]. Following Chen [3], "green" and "green image" represent a set of brand perception in the mind of the consumer, which is associated with environmental commitments and environmental concerns. In this way, it refers to corporate social responsibility. For reasons of environmental responsibility, enterprises try to reuse, refurbish and recycle used products to reduce the negative impact on the environment [4].

The green processes are currently a great challenge and an opportunity for new industries, bringing a competitive advantage in the field of the environment [5]. The enterprises should use ecological and technological innovation of the processes, products and image to improve their financial performance [6]. Green production differs from the conventional production in its emphasis on the natural effect of environmental guidelines, which actually reduce costs, increase profitability [7] and make the organizations more competitive. The concept of green processes and technologies gained popularity, especially following the introduction of the Kyoto Protocol, the Copenhagen and Paris conferences on the climate change. The main source of pollution is industrial production. Cherrafi et al. [8] found that adoption of environmental practices significantly improved the performance of the green supply chain.

In connection with the impact of the industrial and manufacturing enterprises on the environment, the green technologies and processes are linked to Industry 4.0. They are an important source of solutions for the future, as they bring the concept of the triple bottom line (economic, environmental, and social), i.e., the elements of sustainability and environmental protection, into the production [9]. The manufacturing organizations are able to implement environmental practices as a precautionary measure with a focus on environmental efficiency, which can limit its potential competitive priority despite a positive impact on quality, cost, supply and flexibility [10]. Cyber-Physical Systems (CPS), big data analysis, cloud manufacturing, additive manufacturing, and artificial intelligence systems within Industry 4.0 enable the automatic solution of environmentally sustainable manufacturing processes [11].

Regarding the growing emphasis on the environmental benefits of technology, this review paper discusses the link between conventional green processes and Industry 4.0 technologies. The review should provide an overview of the studies, dealing with sustainability outcomes and green processes in relation to Industry 4.0.

2. Theoretical Background

This section outlines the existing reviews available in literature and concepts related to terms green processes, green economy, green technologies, Industry 4.0, sustainability and others.

2.1. Review Papers in Literature

A systematic literary review discussing sustainability outcomes of green processes in relation to Industry 4.0 in manufacturing has not been carried out so far. The closest to such aim is a study which aimed to analyze various research approaches to Industry 4.0 in relation to sustainability [12]. However, the study does not deal with the distinction of green processes and their sustainability outcomes. On the other hand, Ghobakhloo [9] elaborated on relationships among various sustainability functions of Industry 4.0 to understand the opportunities of the digital revolution for sustainability.

Couckuyt and Van Looy [13] carried out a comprehensive overview of application domains and research topics of green business process management. Furthermore, Couckuyt and Van Looy [14] also conducted a systematic elaboration of studies of green business process management with regard to capabilities, disciplines and environmental problems. However, a comprehensive review covering the interconnection of green processes, Industry 4.0 and sustainability in manufacturing is lacking. In the literature, authors have dealt with the issue of green processes mainly with a focus on various technologies, processes, fields and areas. These are mainly review papers dealing with green processes for electronic waste recycling [15], green food processing techniques [16], green supply chain processes [17], logistics processes [18], processes using supercritical fluid carbon dioxide [19], electrical discharge machining [20] and green chemical process and synthesis [21]. Green chemistry has a special position in this area. There are seven principles applied in this area: waste prevention, atom economy, safer syntheses, safer products, safer auxiliaries, energy efficiency, renewable feedstock, derivative reduction, catalysis, degradability, pollution prevention, accident prevention

[22]. Sustainability outcomes of green processes were structured by Mendoza-Fong et al. [23] into three categories: operating, commercial and economic benefits.

A comprehensive review of the literature from 1994 to 2010 related to green and low carbon technology innovation research is provided by Shi and Lai [24]. Similarly, the authors Schiederig et al. [25] deal with the issue of green innovation in technology; in addition to sustainability, they also consider the social field. Some authors discuss different green technologies, such as low-carbon iron making technology [26], green fertilizer technology adoption [27], green cement technology [28], harvesting green energy [29], scale inhibitors for oilfield scale handling [30], natural fiber in the automotive industry [31], metal additive manufacturing processes [32], green biodiesel [33], energy efficient CO_2 technologies for iron and steel manufacturing [34], oil extraction using subcritical water technology and biodiesel production [35].

Similarly, there are review papers focused on Industry 4.0. The major focus of such review papers is on different technologies [36–38], trends and perspectives [39,40], the fields such as Industry 4.0 in economics [41], management [42] and the construction industry [43].

2.2. Main Concepts and Terms

Green technologies are defined as technology which is environmentally friendly [44] and results in economic and social sustainability [45]. Shaikh [46] in his review classifies green technology as performing green processes, into water treatment, sewerage treatment, solid waste treatment, air purification, environmental remediation, energy conservation, renewable energy, capture and storage technology, green building practices, sustainable transportation, clean industries, hydrogen and fuel cells, agricultural technology (eco-farming, biomass plants, water pollution, soil erosion mitigating, fertilizers, etc.) Green processes are defined as new or modified processes, systems and products that reduce the negative impact on the environment [47]. The goal of modern green processes is to design and commercialize industrial processes that are sustainable and economically feasible [48]. Xie [6] adds that the goal of green processes is to reduce energy consumption during production processes or during processes that convert waste into utility value. Green process innovation improves existing business processes and brings new ones—reducing negative impacts on the environment [49]. These newly created processes have a positive effect on the company’s financial performance [50] and improve the company’s image [47].

Singh and Kumar [51] in their monograph describe various green technologies and their influence on environmental sustainability. For example, solar photovoltaics, transportation (biodiesel, biofuels), synthetic flocculants, pollutants detection, waste management, vermitechnology, nanocellulosic fibers, drug delivery, phytotechnologies, bioremediation of arsenic, etc. Purohit and Malvi [52] describe the use of green technologies to address sustainability. In industry, they consider the use of renewable and alternative energy sources, the application of the 3R rule (reduce, reuse, recycle; minimizing the use of water and other resources, the use of alternative production processes, the use of telecommuniting, digitization and hybrid cars) to be the most important. In South Korea, in terms of development, they report a trend from individual technologies such as solar and fuel cells, LEDs (light-emitting diode), Internet of Things (IoT) of addressing the overall issue of climate change [53].

Innovation and technology are seen as the triggers in the transition to a green economy. The commercialization of academic knowledge, including the patenting and licensing of inventions, i.e., green technologies, is both a driving force for economic growth, and a necessary element of world sustainability [54]. With the development of information technology, an information layer for data collection, storage and analysis is emerging [55]. The term “big data” is understood as a set of methods and means for processing structured and unstructured data [56]. As data grow, there is enormous pressure on current information systems in the areas of integrity, speed and storage [57]. Xie [6] adds that businesses use high-volume data analysis to better understand customer needs and consider their data to be their primary business asset [58]. From the point of view of information systems, it is the use of large-volume data for statistical modeling of various data sets, monitoring of consumption, demand, etc. [58–60].

In their research, Chu et al. [61] present six concepts that represent the main problems of the 21st century in relation to green technologies, namely: energy saving, energy consumption, green production, green products and sustainable production. Saving and consuming energy is considered one of the challenges of Industry 4.0, defined by Zhong et al. [62] as a combination of embedded manufacturing processes and intelligent manufacturing processes that fundamentally transform the industry value chains and business models. The article understands Industry 4.0 as a revolutionary industrial concept of the production process in manufacturing, focused on new technologies that interconnect machines and equipment with digital data into automatic, intelligent systems. The definition was created on the basis of an analysis of a number of opinions and research [63–70], where we could rank it among the most important authors, such as Ghafoorpoor who focused mainly on production, or Zambon [71] who mentions mentions the main contribution to coordination; Mehrpouya [72] sees the benefits of industry 4.0 in maintaining long-term competitiveness, or, for example, automation as mentioned by Lie [73]. Vrchota and Pech [74] state that the main technologies of Industry 4.0 include use of sensors, data collections and analysis, information technology (IT) and mobile terminals, cloud storage, information systems and learning software, autonomous robots, machine-to-machine (M2M) communication, sharing and using data with suppliers and customers, use of virtual (and extended) reality, simulation, and digital twins, additive manufacturing. Green technologies are generally accepted as sustainable techniques for the use of natural resources. Industry 4.0 aims to maximize productivity and minimize waste, so green technologies are seen as a key component of Industry 4.0 [75]. Industry 4.0 technologies such as 3D printing, robots, IoT and big data reduce the amount of business resources required [76]. Thanks to these technologies, it is possible to expect a shortening of innovation cycles, but with regard to general environmental objectives [77]. The combination of the terms Industry 4.0 and green process can also be seen in reverse logistics, i.e., product management at the end of the product life cycle [78,79], or lean manufacturing [76,80].

One of the partial building blocks of Industry 4.0 is related to the radio frequency identification (RFID). It is a technology of automatic identification and data collection. The tag itself consists of three elements, namely a chip with an antenna, a reader enabling two-way communication and also the middleware, which connects RFID hardware with the user environment [62]. Arshad et al. [81] raise concerns about active RFID in relation to energy consumption, as active RFID requires batteries as a power source. In terms of green manufacturing, therefore, they propose, for example, the reduction of the RFID network using nodes and sophisticated routing mechanisms or the use of selective scanning, where only the data needed to evaluate a specific situation are collected. Xu et al. [82] add energy saving as a critical goal of the implementation of the Internet of Things.

The principle of green production is to produce the same product with fewer resources and energy. In both cases, there is a saving of funds, so the prevention of waste is both ecologically and financially effective [83]. It is rapid depletion of resources, increasing energy intensity, increasing customer awareness and compliance with environmental regulations that results in a paradigm shift and a boom in green production [84]. Paul et al. [4] define green manufacturing as a general term for sustainable manufacturing technologies such as photovoltaics, wind turbines, bioreactors, biofiltration or desalination. Maruthi and Rashmi [85] understand green manufacturing as a philosophy rather than a standard or process, a production method that minimizes waste and pollution through product and process design, with sustainability as the main goal of green production. According to Govindan et al. [86], the most common reasons for the transition of production towards a green economy include financial savings, corporate image, environment and compliance with legislation.

The concept of the green economy has become increasingly attractive to policy makers over the last ten years. The green economy includes many different concepts and its links to sustainable development are not always clear. The products on offer are increasingly influenced not only by quality and price, but also by environmental and social factors, including sustainability of the technologies used in the production and processing of raw materials. In this context, together with the uncertain recovery of world economies, many organizations focus on the green economy and green growth [87,88]. The European Commission developed a Sustainable Growth Plan to support competitive and green economies. The European Commission considers reducing the use of resources and increasing their efficiency to be key mechanisms for tackling environmental problems and strengthening European competitiveness. The plan of the European Commission is largely in line with the wording of the OECD (Organization for Economic Co-operation and Development) strategy for the ecological growth, emphasizing innovation as a means of decoupling growth from natural capital depletion [89,90]. Explaining the term "green economy" is not easy, as the industries currently classified as green are used as a benchmark for the economies that aspire to such classification [91]. Gasparator et al. [92] define the green economy as an economic system that results in improved human well-being, social justice, significantly reducing environmental risks and deficiencies. Wilis [93] adds that the conservation of biodiversity and ecosystem services are the most important pillars of the efforts to move towards a green economy. Green growth—the green economy is seen as a path to sustainable development, i.e., the path to economic prosperity, reduced poverty and environmental progress [94]. Cudlinova et al. [95] prefer to use the term "bioeconomy" to bring economics and ecology together to achieve sustainability. The enterprises seeking to optimize their environmental and social responsibility must necessarily focus on waste reduction techniques in production processes [91].

The enterprises seeking to optimize their environmental and social responsibility must necessarily focus on waste reduction techniques in production processes [96]. Furthermore, it should be emphasized that reducing waste sources is also a huge social challenge requiring the social mobilization and environmental awareness of the citizens [97]. Extending the life of materials, promoting recycling and reducing the negative impact on the environment in connection with waste reduction are the main goals of the concept of circular economy [98]. The circular economy (CE) is understood as a regenerative economy, in which inputs, waste and emissions are minimized, while repairs, reuse, refurbishment and recycling are the essence of the circular economy [99]. According to Kirchherr et al. [100], the main goal of circular economics is to separate economic growth from resource consumption. Korhonen et al. [101] add that the circular economy limits economic growth to the extent that nature tolerates it. However, there are also negative impacts related to the investment in renewable energy technologies and the additional costs of renewable energy systems—the total cost to the industry [102].

The above terms are defined by the term "sustainable development". This is the most important principle of economic, environmental and social development, seeking to meet the needs of the present without compromising the ability of the future generations to meet their own needs [103]. The concept of sustainable development is characterized by three pillars—environmental, social and economic. Within this framework, the environmental and social aspects of sustainability are integrated. The starting point is that environmental degradation spills over into the social pillar. The economic aspect can be an end in itself or a means to fulfil social goals [104]. The energy needed to produce products for which sustainability impact assessments can always be a driver of economic growth [105]. However, it is the role of management to respond to these three pillar challenges, namely sustainability management tools such as transparency, accountability to stakeholders or achieving long-term prosperity [106,107].

According to Searcy [108], the motivation of the enterprises to participate in sustainable development is a better reputation and image of the organization, cost savings, the motivation of employees, reduced risk and increased competitiveness. Dyllick and Hockerts [109] discuss an issue of the tendency of enterprises to focus on the short-term results. The obsession with short-term profit runs counter to the long-term nature of sustainability. At the first glance, the adoption of the principles of corporate sustainability is reflected in the internal documents of an organization, the inclusion of the sustainability measures is reflected in the evaluation of employee performance and training. At the value level of the organization, the principles of corporate sustainability are spread, and the employees are convinced towards more responsible and ethical values. The basic level of corporate sustainability is then characterized by the dependence of human and ecological systems [110]. The level of maturity of corporate sustainability strategies is useful in relation to the corporate strategy for the enterprise both in the planning process and in the implementation process. If these strategies are taken into account at the same time, it is possible that a sustainability strategy is a path to a general business strategy [111].

3. Materials and Methods

The paper is based on the methodology of systematic literature review with a focus on Industry 4.0, green processes and sustainability outcomes. Through the analysis of literary sources, the relevant publications are assessed and analyzed in order to find possible gaps in research. Within this review, a reception of scientific publications from prestigious databases is discussed. This review focuses on combining all three concepts and creating a comprehensive overview of the studies that bring them together. The above literature review showed that the current literature contains many reviews focusing on the green processes, in most cases in relation to sustainability, but none relates them to Industry 4.0. To close this gap, this paper presents a conceptual framework that helps to structure and evaluate conventional green processes in relation to Industry 4.0 and sustainability.

An overview of the literature is an essential part of any research work. We use a systematic review methodology that strives to comprehensively identify, appraise and synthesize all the relevant studies on a given research questions. The systematic review is based on the following seven stages [112]:

1. Clearly define the research questions or hypotheses.
2. Determine the databases, search terms and types of relevant studies.
3. Carry out a comprehensive literature search.
4. Screen the results of the search (selection and exclusion criteria).
5. Critically appraise the included studies.
6. Synthesize the studies.
7. Disseminate the findings of the review.

3.1. Objectives and Research Questions

The scope of the paper is to review how conventional green technologies as a part of Industry 4.0 provide sustainability outcomes in manufacturing. As part of the research, the authors formulated the most important research questions, discussed through the analysis of database resources. Their secondary objective is to develop a conceptual framework for the classification of the Industry 4.0, green processes and sustainability relationship. There are the following research questions:

1. How to classify Industry 4.0 technologies that provide sustainability outcomes of green processes in manufacturing?
2. Which conventional green processes produce sustainability outcomes as part of Industry 4.0 in manufacturing?
3. What are the sustainability outcomes of the conventional green processes in the context of Industry 4.0 in manufacturing?

3.2. Information Sources

After creating a literature review, based on the goal and research questions, relevant sources of publications related to the areas of green processes, sustainability and Industry 4.0 were identified. Due to the scope, the Web of Science (WoS) and Scopus databases were chosen, which contain renowned publications by Taylor and Francis, Springer, MDPI, IEEE, Elsevier, Emerald, etc. These databases contain the most extensive collection of citation sources, thousands of peer-reviewed journals in science, technology, medicine and social sciences.

3.3. Topics and Keywords

Based on an initial survey of the Web of Science and Scopus databases, occurrences of the basic topics "Industry 4.0", "sustainability" and "green processes" were identified. Due to the large number of publications on Sustainability and the overall effort to find an intersection of the search results (no publications dealing with Industry 4.0 were written before 2010), the period 2010–2020 was chosen for all the topics. The total number of publications in the databases is shown in Table 1.

Table 1. Results of topics search (30.3.2020).

Topic	Industry 4.0	Green Processes	Sustainability
Web of Science	5,035	1,436	122,097
Scopus	9,387	1,890	167,629

The development of the total number of Scopus and Web of Science publications is shown in Figure 1. It is clear that there is an international increase in the number of publications for all the topics. For sustainability, the number of publications tripled between 2010 and 2020. Industry 4.0 increased from single units to thousands. In the case of green processes, the number of publications almost doubled during the period under review.

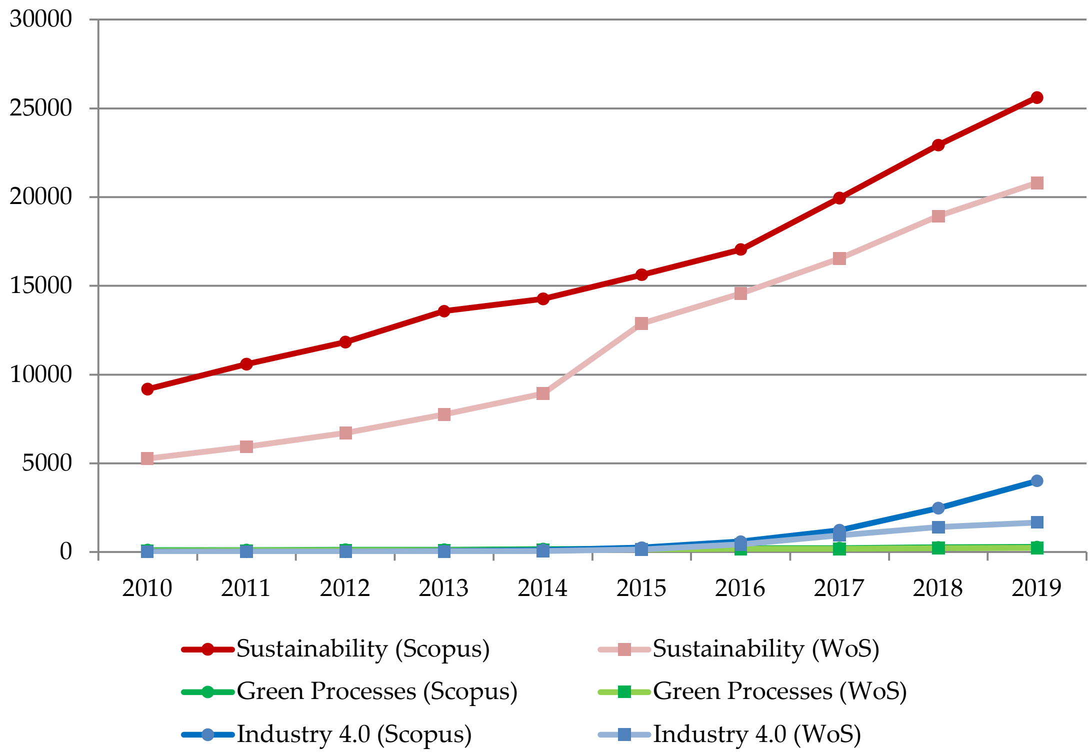

Figure 1. The development of the total number of Scopus and Web of Science publications.

Based on a search in the Web of Science databases, the key keywords were identified for the topics: "Industry 4.0", "sustainability" and "green processes". To ensure the scientific quality of the review, the modified eligibility methodology was used to synthesize the results. The acronym PICO (Problem, Intervention, Comparison, Outcome) is often used to identify four critical parts of a well-built research question [113]. This methodology consists of context (participants or problem), intervention, comparison (facultative, we do not use it), outcomes. The necessary formal step in all searches is to determine any alternative terms or synonyms for the identified concepts in the PICO logic grid [114].

The results are shown in Table 2, including the arrangement according to the PICO logic grid. Due to the number of publications, only publications 2010–2020 were selected for analysis. The software for constructing and visualizing bibliometric networks VOSviewer was used to find out keywords [115,116]. The software used the cluster method and helped create a search algorithm strategy.

Table 2. PICO logic grid.

	Context (How?)	Interventions (Which?)	Outcomes (What?)
Topic	Industry 4.0	Green Processes	Sustainability
Synonyms	Fourth industrial revolution	Environmental processes	Ecological
	Smart factory	Eco/ecological processes	Environmental
	Smart production	Clean processes	Social
	Smart manufacturing	Low carbon processes	Economical
Keywords	Internet of things	Nanoparticles	Management
	Cyber physical system	Synthesis	Governance
	Big Data	Biomass	Energy
	Internet	Extraction	Climate-change
	System	Ionic liquids	Development
	Management	Oxidation	Innovation
	Technology	Reduction	Life-cycle assessment
	Innovation	Optimization	Policy
	Smart manufacturing	Kinetics	Indicators
	Digitization	Chemistry	Conservation
	Smart Factory	Conversion	Consumption
	Supply Chain	Derivatives	Ecosystem services
	Simulation	Adsorption	Environment
	Cloud computing	Fabrication	Biodiversity
	Architecture	Catalysis	Corporate social responsibility
	Automation	Separation	

3.4. Search Strategy

Systematic search strategies are developed and adapted for use across the Web of Science and Scopus databases, combining various terms and free texts for keywords related to the topics. International databases were searched from the beginning to March 2020. The surveys were conducted in January 2020 and subsequently repeated in March 2020. The search strategy is shown in Table 3 below.

Table 3. Search strategy (30 March 2020).

Searches	Terms/Thesaurus
1 Industry 4.0	(“Industry 4 *” OR “Fourth industrial revolution” OR “Smart”) AND (“factory” OR “production” OR “manufactur*” OR “assembl*” OR “fabricat*”)
2 Green processes	(“process *” OR “technolog *” OR “operation *”) AND (“Green” OR “Environmental” or “Eco” or “Ecological” or “Clean” or “low carbon”)
3 Sustainability	(“Sustainab *”)
Query	1 AND 2 AND 3

The total number of publications found is shown in Table 4. It is clear from the results that a total of 1171 publications were obtained, further subjected to data extraction and screening based on selection and exclusion criteria and filters.

Table 4. Number of papers Web of Science (WoS) and Scopus bibliographic databases.

	Article	Other	Total
WOS	239	180	419
SCOPUS	302	450	752

3.5. Selection and Exclusion Criteria, Filters

To further refine the results, the authors defined parameters for further filtering of records. Duplicates of both databases, records published before 2010, records in a language other than English, records of other types of publications and records with incomplete bibliographic data information (see below) were removed from the records. Books, chapters, doctoral theses, white papers, editorial notes, etc. were excluded after all sources had been found to ensure that the research comes from academic sources.

Records were filtered based on applied criteria:

1. Not duplicated;
2. Published from 2010 to April 2020;
3. Written in English;
4. Type of publication: journal paper (not review, white paper, book, etc.);
5. Publications with completed information (authors, year, journal name, etc.).

To ensure that all documents are consistently and objectively evaluated, the criteria for pre-screening and eligibility evaluation of the overall overview are defined, including the evaluation procedure. The evaluation procedure is further described in Subsection 3.4.

Publications were included if the following criteria applied (title, keywords criteria):

1. Having more main topics as its core subject;
2. Focusing on the Industry 4.0;
3. Focusing on green processes;
4. Focusing on sustainability;
5. Focusing on the interconnection of the main topics;
6. The paper is not a review (paper is not focused only on challenges or future perspectives).

Publications were excluded if the following criteria applied (abstract criteria):

1. Discussing only the specification and theoretical description of a particular definition, methodology or review, for example, "Industry 4.0" or "sustainability" or "green processess";
2. Discussing the application of topics in areas other than industry and manufacturing (for example, agriculture, physics, construction);
3. Application of topics in smart cities or houses (for example "smart city New York");
4. Chemistry studies focused on the chemical processes, reactions or production of chemicals (for example, "Nanotubes with Lutetium Chloride");
5. Energy studies focused on methods or processes of energy production in plants or plant design (for example, "application of technology in biorefineries", "solar plant innovations");
6. Dealing with the topic sustainability without specific outcomes (for example, sustainability of a region vs. sustainability of clean transportation).

3.6. Data Extraction and Screening

The result of search queries revealed a total of 1171 publications (the process is described in Figure 1). All citations and the abstracts identified by the search strategy were uploaded to the Endnote software database. The authors ensured coverage of various aspects of green processes, sustainability and Industry 4.0. At the same time, the authors performed record filtering based on the defined filtering criteria.

Then, the objective screening (title, keywords) was performed for each collected contribution based on the selection criteria. The abstract of the paper was also used in controversial situations. All the works that were originally marked as "potentially eligible (records after filtering)" were examined independently by two team members, using the defined selection criteria.

The presence of a combination of key topics was found for the publications to be evaluated on a scale of 1–3 (1—low relevance, 2—medium relevance, 3—high relevance). Publications with low ratings were excluded.

In the next phase, the abstracts of the remaining papers are reviewed in terms of eligibility using defined exclusion criteria. If necessary, complete papers were analyzed to examine the publications, specify their original evaluation and possibly add them to the search database. Publications were included if the exclusion criteria were met. Meetings of the publishing team were held to compare the selection of the papers included. Any disagreements between the two team members were resolved by discussion to reach an informed consensus. The publications with inaccessible papers via full-text review were also excluded from the final selection.

The flow diagram in Figure 3 demonstrates the preferred reporting items for systematic reviews and meta-analyses [117,118] flow of articles from search to final selection. In the last phase, the full text of each of the remaining papers was found to have the number of main keywords in the text (except for the abstract and reference section): Industry 4.0 (or fourth industrial revolution, I4), sustainability and green processes. In this last phase of the elimination, the total number of articles decreased to 29 publications for the synthesis. The excluded studies are briefly described in Section 4.5. The full report of PRISMA checklist is included in Appendix A

3.7. Synthesis and Assesment of Bias

To ensure the content analysis, each paper collected was reviewed and evaluated by at least two members of the research team. At the same time, the publications were assessed with regard to their indirect quality via journal ranking and bias with author or journal. Systematically selected articles were assessed for quality based on the Critical Review Form (CRF) of the Critical Appraisal Skills Program (CASP) methodology [119].

3.8. Content Analysis

Content analysis is used to identify and summarize literature trends and evaluate structure and text. Gaur and Kumar [120] recommend four stages of content analysis: data collection, coding, analysis and interpretation of content. By exhausting the selection and exclusion criteria derived from data extraction and screening, the researchers identified the relevant text bodies for content analysis. The content analysis is focused on the methodology and findings of included studies. Coding schemes are developed in consultation with experts and based on the review objectives. For this purpose, an Excel spreadsheed was created and a code frame was developed. We identified the following dimensions of content analysis classification including:

1. Methodology (type of research, method of analysis etc.);
2. Industry 4.0 variables (technologies);
3. Green context (processes and their importance for sustainability);
4. Sustainability outcomes (key findings).

3.9. Data Analysis

Data were analyzed using qualitative methods and processed using VOSviewer software. The analysis is performed in order to find out the differences and common characteristics of publications. The analysis used the method of qualitative data clustering for close examination of the collected data to understand its contextual meanings (Industry 4.0, green processes and sustainability classification) and discover the studies' sustainability outcomes. The main contributions and results of the studies were processed through narrative synthesis of the obtained classifications into a comprehensive framework.

4. Results

The final selection of synthesis of studies consists of a sample of a total of 29 papers from WOS and Scopus, which discuss the sustainability outcomes, Industry 4.0 and green processes and technologies. The studies were further subjected to synthesis and content analysis.

4.1. Year of Publication

The selected sample of publications includes only scientific papers that have been published in the last three years (Figure 2). This situation occurred probably because the combination of Industry 4.0, sustainability and green processes has been a relatively recent and new interest of scientists. Publications dealing with Industry 4.0 have appeared in the last 5 years and were initially focused mainly on the use of various technologies. Later, researchers discovered their impact on the environment, the economy and society.

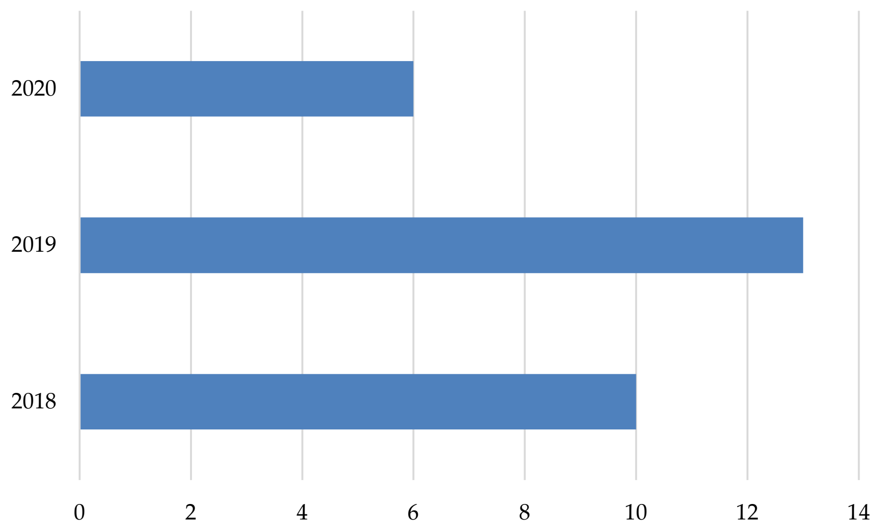

Figure 2. Included studies according to year of publication.

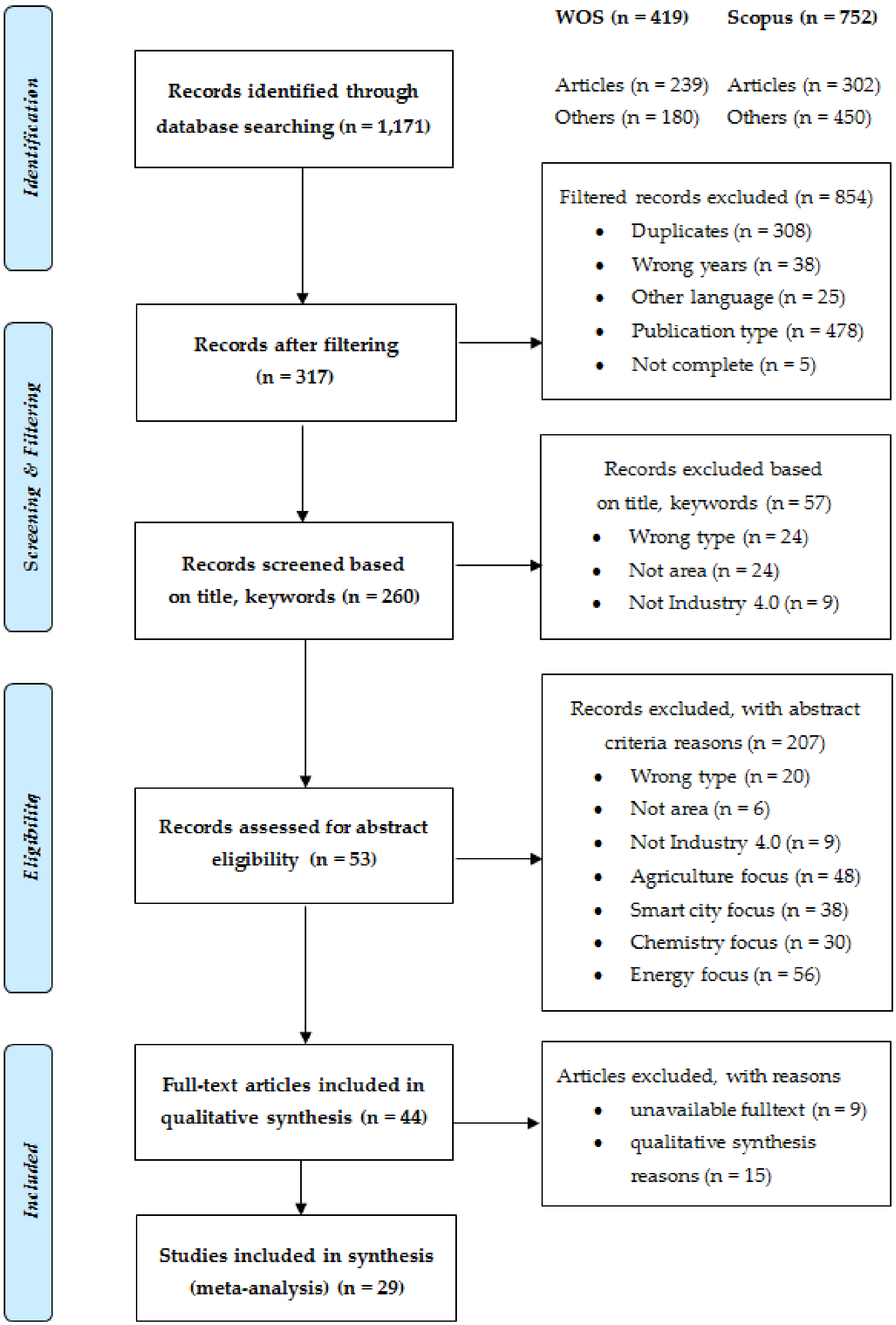

Figure 3. Flow diagram with preferred reporting items for systematic reviews and meta-analyses based on PRISMA [117] and QUORUM [118] flowcharts.

4.2. Contribution by Publishers and Journals

The contributions made by various publishers are shown in Figure 4. MDPI and Elsevier have the highest number of papers. Most papers were published in the journal *Sustainability, Social Sciences, International Journal of Production Research* and *Journal of Cleaner Production*.

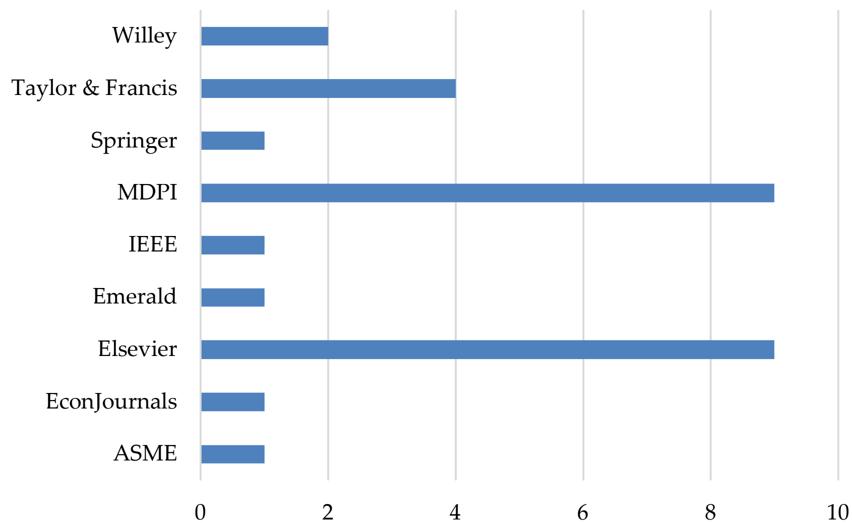

Figure 4. Included studies according to publisher.

4.3. Quality of Included Studies

The sample consists of 29 publications, of which 25 are contained in the Web of Science database and 4 in the database Scopus. The quality of publications was determined on the basis of predefined criteria: the position of the journal in the subject category (Web of Science database) and the number of citations (times cited). An overview of the representation of publications in quartiles of the Web of Science database subject categories is given in Figure 5a. Most of the papers were published in journals with a high impact factor situated in the upper quartiles (Q1, Q2) of the subject category. Due to the novelty of the articles, a third of the publications have been less cited so far (Figure 5b). On the other hand, the best publication has already been cited 78 times. Collected data include 29 studies and meet CASP requirements based on quality, ethical methodology and appropriate content suitable for analysis.

4.4. Type of Research

The methodology characteristics of the included studies are used for classification of papers into groups. We divided the papers into groups based on their methodology: questionnaire survey, experiment, simulation and case study. Publications based on questionnaire surveys and case studies were the most represented (Figure 6).

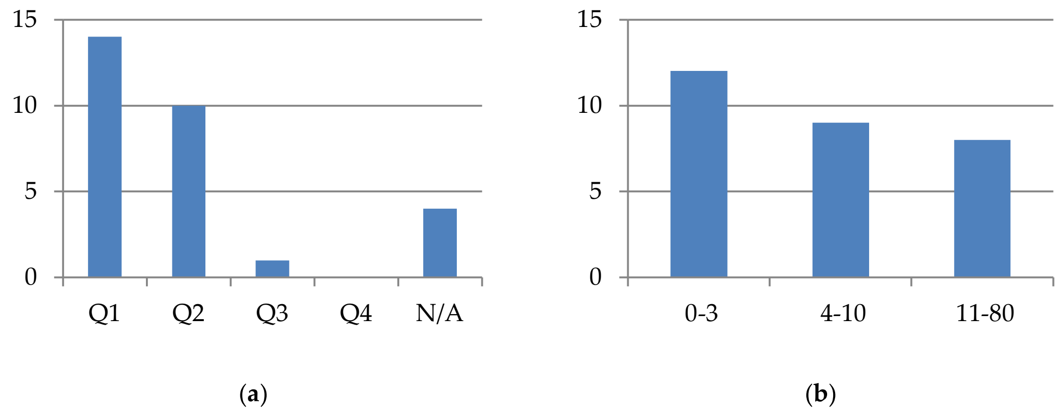

Figure 5. Included studies according to quality characteristics: (**a**) quartile in Web of Science category; (**b**) times cited (number of citations).

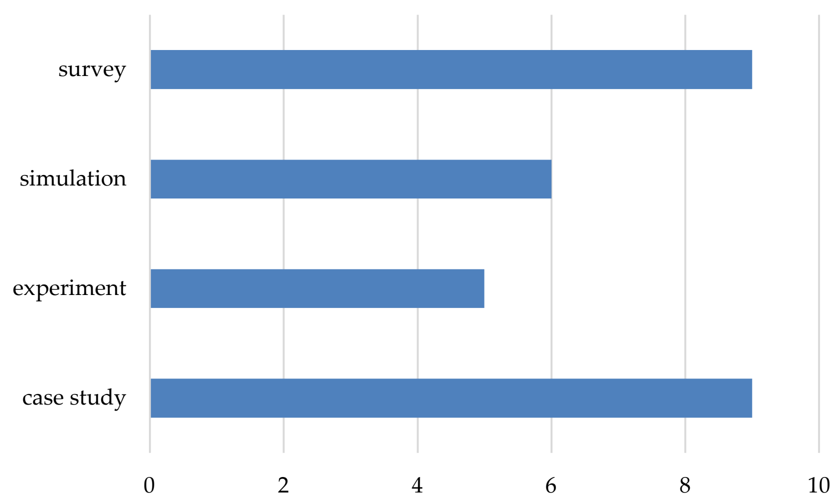

Figure 6. Included studies according to type of research.

4.5. Excluded Studies

In the last phase, a total of 15 publications were excluded from the final selection of publications for synthesis and review. Of these, 14 papers were eliminated due to the fact that they do not explicitly discuss Industry 4.0 in the full text (this concept is not mentioned in the paper at all), however, the technologies used may be related to the concept.

These include Cabot et al. [121], dealing with the design of the methodology of interconnected objects—intelligent packaging systems for the food industry. Similarly, the study of He et al. [122], presenting a thin self-propelled system that is suitable for mass production using sensors within IoT, was excluded. This technology can be used for portable electronics wearables. Similarly, Van der Velden et al. [123] take environmental aspects into account in the clothing industry at the product design stage (ecodesign), which allows for up to 25% lower environmental impacts. Park et al. [124] describe a service sector platform for the small and medium-sized enterprises (SMEs) to use IoT-based energy-efficient devices. Later, Park et al. [125] recommend a platform based on the

Industrial Interent of Things (IIoT), big data and CPS to small and medium-sized enterprises to reduce costs. IoT technology is also mentioned in Rajabion et al. [126], dealing with the development of an intelligent transportation system for farmers. Blockchain technology was used by Manupati et al. [127] in monitoring supply chain performance and optimizing sustainability outcomes.

Similarly, other studies were excluded. Similarly, some studies focused on the use of robots, nanotechnologies, sensors, blockchain and mobile applications. Therefore, studies using mobile platforms [128], automatic robot in the intelligent manufacturing process [129], robot-based reconfigurable fixture [130], smart partial least squares structural equation modeling (PLS-SEM) in the cement industry [131] or nanotechnology in the bioecoomy sector in Poland [132] were excluded. In addition, a publication focusing only on the optimization of the tree-echelon cold supply chain under cap and trade regulation in Industry 4.0 was excluded [133]. An interesting publication, although not primarily focused on Industry 4.0, deals with the bio-manufacture of buildings using a special fungal architecture exhibiting sensing and computing characteristics [134]. Similarly, Iuorio et al. [135] dealt with the influence of prefab structures on sustainability.

4.6. Keyword Analysis

VOSviewer software [115,116] was used to classify the most important keywords. The analysis was based on 263 keywords, from which the 14 most used keywords are used for the cluster analysis. The most commonly used keyword with the highest number of occurences in all selected papers was "Industry 4.0" (9.1%), followed by "sustainability" (4.2%), "system" (4.2%), "big data" (3.0%), "future" (2.7%). Other important keywords were "smart", "performance", "challenges", "green", "research", "management", "supply chain management" and "framework". These are the keywords most commonly used in the papers focused on Industry 4.0, sustainability and green processes. For the sake of completeness, in addition to the analysis of the keywords listed in the papers, the keywords appearing in the title of the paper were also analyzed (a total of 109 keywords). The terms "Industry 4.0" (16.5%), "sustainability" (13.8%) and "manufacturing" (11%) are reported as those with the most frequencies. The result of the cluster analysis of the keywords (settings: 14 keywords; method: association strength; threshold/minimum number of occurrences: 4) revealed three clusters, which are characterized by the terms "Industry 4.0", "sustainability" and "green". The results of the cluster analysis are shown in Figure 7.

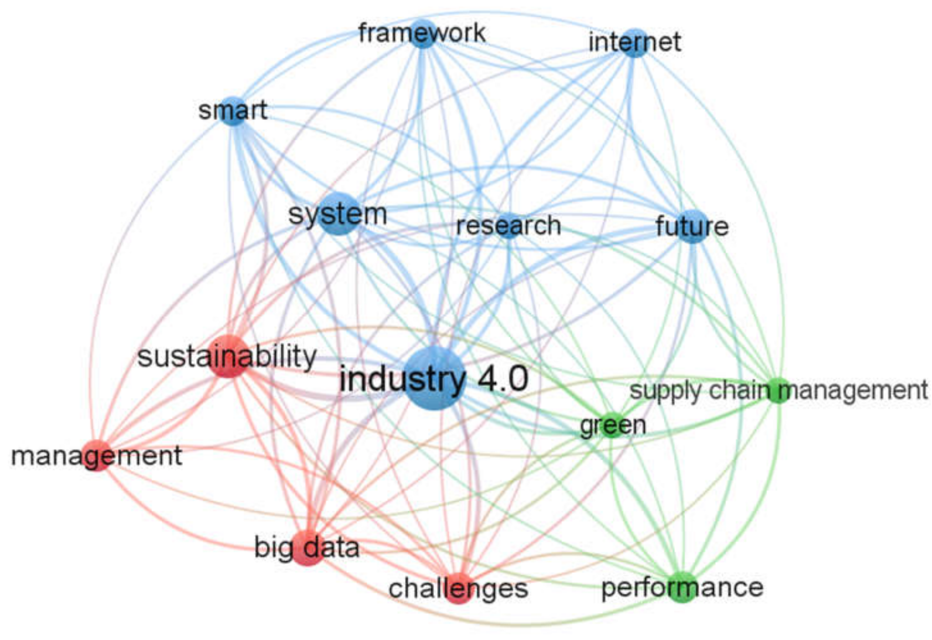

Figure 7. Results of keyword cluster analysis.

Obviously, the associations based on the total link strength in the first cluster of Industry 4.0 connected the keywords “Industry 4.0”, “smart”, “Internet”, “future”, “system”, “framework” and “research”. The cluster corresponds to the concept of Industry 4.0 with its focus on the future and new technologies. The second cluster is the Sustainability area using the keywords “sustainability”, “management”, “challenges” and “big data”. With the exception of “big data”, referring more to Industry 4.0, the keywords of sustainability papers often focus on “challenges” and the concepts of managing sustainable development. The last cluster, called Green, is made up of the terms “green”, “performance” and “supply chain management”. The combination of these words demonstrates one of the important environmental processes referred to as the green supply chain. The focus of such papers is mainly on the performance of the process. Based on the cluster analysis, the papers are arranged into the above-mentioned three clusters and further processed and analyzed in this way.

4.7. Industry 4.0 Variables Analysis

In relation to Industry 4.0 technologies, the content of the publications was analyzed, and new keywords were created, including a total of 15 different Industry 4.0 technologies from the papers. The results show that most of the papers deal with “big data”, “IIoT”, “cyber-physical systems”, “sensors” and “smart systems”. In addition, the term “Industry 4.0” is left in the analysis, as the general focus of the paper is on more technologies. These data are further classified through the cluster analysis into four areas that occur together in the papers and form the following clusters:

- A: Industry 4.0 and Smart Systems Implementation
- B: Use of Big Data in Information Systems and Smart Factories
- C: Cyber-Physical Systems and Interconnection of Real and Digital World
- D: IIoT and Sensors in Robotics and Communication

The clusters describe the current trends in Industry 4.0 publications in conjunction with sustainability and green processes. Such four areas are used to classify the publications in the reports. The designations A, B, C and D in Table 5 indicate the predominant focus of the publication on one of the four areas of Industry 4.0.

Table 5. Classification of Industry 4.0 technologies.

A: Industry 4.0 and Smart Systems Implementation	
Industry 4.0	Braccini and Margherita [136], Dev et al. [137], Chiarini et al. [138], Kamble et al. [139], Moktadir et al. [140], Muller et al. [141], Saudi et al. [142]
Smart systems	Kamble et al. [139], Moktadir et al. [140], Muller et al. [141], Munodawafa and Johl [143], Thomas et al. [144]
Aditive manufacturing	Dev et al. [137], Chiarini et al. [138], Moktadir et al. [140], Nascimento et al. [145], Stock et al. [146]
B: Use of Big Data in Information Systems and Smart Factories	
Big data	Gupta et al. [147], Chiarini et al. [138], Jena et al. [148], Kamble et al. [139], Kumar et al. [30], Moktadir et al. [140], Muller et al. [141], Munodawafa and Johl [143], Raut et al. [149], Thomas et al. [144], Tsai and Lu [150]
Cloud	Dev et al. [137], Gupta et al. [147], Jena et al. [148]
ERP	Gupta et al. [147]
Smart factory	Jena et al. [148], Zhang et al. [151]
C: Cyber-Physical Systems and Interconnection of Real and Digital World	
Cyber-physical system	Banyai et al. [152], Chiarini et al. [138], Jena et al. [148], Martin-Gomez et al. [153], Senechal and Trentesaux [154], Stock et al. [146], Tsai and Lu [150]
Digital twins	Banyai et al. [152], Kannan and Arunachalam [155]
RFID	Dev et al. [137], Kannan and Arunachalam [155], Stock et al. [146], Tsai and Lu [150]
MES	Garcia-Muiña et al. [156], Tsai and Lu [150]

D: IIoT and Sensors in Robotics and Communication	
IIoT	Banyai et al. [152], Dev et al. [157], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Jena et al. [148], Moktadir et al. [140], Muller et al. [141,160], Tozanli et al. [161]
Sensors	Dev et al. [137,157], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Santos et al. [162], Tozanli et al. [161], Yazdi et al. [163]
Robots	Braccini and Margherita [136], Martin-Gomez et al. [153], Yazdi et al. [163]
Blockchain	Tozanli et al. [161]

The area labelled A, Industry 4.0 and Smart Systems Implementation, is typically represented by Muller and Voigt [160], aiming to compare Industry 4.0 and Made in China 2025 with respect to the sustainability conditions. Kamble et al. [139] confirmed the hypothesis that Industry 4.0 has a positive effect on the concept of lean manufacturing. The study also finds that Indian enterprises are in various stages of implementation, the main obstacles being poor management and low awareness of the Industry 4.0 concept. Similarly, implementations are discussed by Chiarini et al. [138]. Using a questionnaire, they report that 34.7% of the manufacturing enterprises in Italy are not interested in new I4 technologies and only 18.1% completed the implementation phase. Moktadir et al. [140] notice that a key management success factor for the implementation of Industry 4.0 is having a strong management team and qualified IT staff. The lack of technological infrastructure is a more significant obstacle than the environmental burden. This is confirmed by Muller, Kiel and Voigt [141], reporting that the implementation of I4 requires the involvement of top management and quality change management. The concept is better accepted in the enterprises with a flat organizational structure.

Part B—Use of Big Data in Information Systems and Smart Factories, is discussed by Dev, Shankar and Qaiser [157], dealing with the design of an Enterprise Resource Platform (ERP) system for refrigerator enterprises in India based on RFID and cloud technology. Gupta et al. [147] notice a positive effect of the Cloud ERP on the economic, social and environmental performance of an enterprise. The dynamic resources of an enterprise depend on the size of the enterprise, the offer of cloud services and their type. Jena et al. [148] define a sustainable manufacturing model and framework for Industry 4.0 with the help of vertical integration and big data, cloud, CPS in a smart factory.

Part C—Cyber-Physical Systems and Interconnection of Real and Digital World, is discussed by Kannan and Arunachalam [155], analyzing the use of RFID chips and digital twins technology to obtain and provide data on grinding wheel wear, in order to avoid wasting material.

Part D—IIoT and Sensors in Robotics and Communication between Machines or Enterprises, is found, for example, in Dev, Shankar and Swami [157], designing the procedures and exploring the virtual factory component of Industry 4.0 and IIoT through a reverse logistics model, using extensive simulations of the platform. Defining Industry 4.0 requirements for real-time H2M (human-to-machine) communication using BLE (low energy Bluetooth) and LoRaWAN (broadband network) is discussed by Garrido-Hidalgo et al. [159].

4.8. Green Context Analysis

Furthermore, the green context of publications was analysed before the evaluation of sustainability outcomes. This area was more difficult to process due to rather the vague definition of the "green" label itself. These are, in particular, publications in which the processes are not called "green", although they have a direct link to increased performance, reduced emissions and greater energy savings. In some publications, therefore, the green processes are directly referred to by this term, while in others they are not. For this reason, the authors noted the use of the terms "green", "eco", "environmental", and the context of the use of the term "process". Based on this content analysis, the authors created 23 new keywords defining the "green context" of the publication. The most used "green processes" in publications include "green manufacturing", "green logistics", "green production", "recycling" and "eco-design" (green design). Based on the performed cluster analysis, the following three dominant areas focused on green processes (min. cluster size: 4) are identified:

- X: Green Logistics and Supply Chain;
- Y: Green Manufacturing;
- Z: Green Design and Development.

As reported by the results, it is possible to divide the green processes into three rather consistent areas—logistics, manufacturing and development. Such areas are the core of the value chain and their "green" implementation increases the degree of sustainability of the whole enterprise. The three areas are used for the classification of publications in reports, labelled as X, Y, Z; see Table 6. In the publications, however, these processes are closely interlinked.

Table 6. Classification of green processes.

X: Green Logistics and Supply Chain	
Green logistics	Banyai et al. [152], Dev et al. [137,157], Chiarini et al. [138], Jena et al. [148], Martin-Gomez et al. [153], Nascimento et al. [145], Stock et al. [146], Yazdi et al. [163], Zhang et al. [151]
Reverse logistics	Dev et al. [137,157], Nascimento et al. [145]
Green supply chain	Dev et al. [137,157], Gupta et al. [147], Kamble et al. [139], Martin-Gomez et al. [153]
Green operations	Kumar et al. [30], Nascimento et al. [145]
GreenpPractices	Gupta et al. [147]
Recycling	Braccini and Margherita [136], Garcia-Muiña et al. [156,158], Martin-Gomez et al. [153], Nascimento et al. [145], Stock et al. [146]
Reusing	Nascimento et al. [145]
Dismantling	Dev et al. [137]
Y: Green Manufacturing	
Green manufacturing	Banyai et al. [152], Braccini and Margherita [136], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Chiarini et al. [138], Jena et al. [148], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Martin-Gomez et al. [153], Moktadir et al. [140], Muller et al. [141], Munodawafa and Johl [143], Raut et al. [149], Santos et al. [162], Stock et al. [146], Thomas et al. [144], Tozanli et al. [161], Tsai and Lu [150], Yazdi et al. [163], Zhang et al. [151]
Reprocessing	Braccini and Margherita [136], Jena et al. [148], Moktadir et al. [140], Saudi et al. [142]
Monitoring	Braccini and Margherita [136]
Green lean manufacturing	Santos et al. [162]
Green value creation	Muller et al. [141]
Green crushing	Jena et al. [148]
Green grinding	Jena et al. [148], Kannan and Arunachalam [155]
Green mining	Jena et al. [148]
Z: Green Design and Development	
Green product	Dev et al. [157], Saudi et al. [142], Tozanli et al. [161]
Eco-innovation	Muller and Voigt [160], Munodawafa and Johl [143], Saudi et al. [142], Yazdi et al. [163]
Eco-design	Dev et al. [137], Garcia-Muiña et al. [158], Raut et al. [149], Senechal and Trentesaux [154], Zhang et al. [151]
Remanufacturing	Tozanli et al. [161]
Green purchasing	Raut et al. [149]

Maintanance	Senechal and Trentesaux [154]
Recovery	Dev et al. [137], Stock et al. [146], Tozanli et al. [161]

Area X—"Green Logistics and Supply Chain", includes the publications usually dealing with reverse logistics. Banyai et al. [152] analyse sustainable in-plant supply using an in-house matrix production model, which allows to describe the impacts of operations related to time, capacity, energy and emissions in the field of green logistics and production. The methodology for implementing a sustainable and intelligent material handling system is developed by Yazdi et al. [163]. Tozanli et al. [161] define a simulation model (disassembly-to-order system) based on blockchain technology, which determines the optimal expected costs for disassembly to order.

Area Y—"Green Manufacturing", includes for example Santos et al. [162], who recommend the Plug and Glean (green lean) concept, which makes it possible to measure environmental results and productivity in production. A measurement tool for evaluating the readiness to adopt smart systems is proposed by Thomas et al. [144]. The system helps with the selection of priorities in the implementation of smart and green systems for food production enterprises in the UK.

Area Z—"Green Design and Development", includes the publications dealing with eco-design. Garcia-Muiña et al. [158] show that eco-design together with IoT makes it possible to predict the economic, social and technical performance of the alternative industrial solutions. Eco-design is then the balance between sustainability and the circular economy. The ability to process high-volume data helps eco-innovation [143]. However, such ability requires qualified employees. Verification of theoretical knowledge about the impact of the operation of intelligent factories on the environment, business processes and especially the product life cycle is analyzed by Zhang et al. [151]. According to Raut et al. [149], sustainable production is based on a complete product life cycle, including its development and design.

Another important area is green technologies used to perform green processes. We did not provide a comprehensive overview of all green technologies due to the use of a large number of technologies in different sectors. Based on the search and analysis of papers, Table 7 shows at least the main categories of technologies with examples classified into four areas: energy saving technologies, resource/material technologies, climate/emission reduction technologies and cleaner production technologies.

Table 7. Examples of green technologies.

Energy Saving Technologies	
Alternative energy production	Bio-fuels [164], fuel cells [165], hydro energy [166], wind energy [167], photovoltaics [168], geothermal energy, tidal energy [169], solar tower [170], natural gas, fossil energy [171], nuclear power generation, plasma production [172], oxyfuel [173], micro-structure reactors, H2 fuel cells [174].
Energy conservation and distribution	Power supply circuitry[175], thermal building insulation [176], recovering mechanical energy, green building [177], energy security technologies [178], energy convertors, low emission burners [179], energy saving modules [180], plasma arc gasification [181].
Energy recycling	Waste heat recycling [182], natual heat usage, composting [183].
Energy storage	Physical energy storage [184], electrochemical energy storage [185], electromagnetic energy storage [186], li-ion batteries [187], storage of thermal energy [188], new devices, molten salt storage [189].
Energy efficiency	Low energy lighting [190], consumer electronics, measurement of electricity consumption [191], appliances [192], micro and smart grid technologies [193], PLED displays [194].
Resources/material technologies	
Material exploitation	Green mining [195], eco-material design [196], bio-degenerative materials, biogenic material [197], compressed-air production [198],

	inert anodes for aluminum production [199].
Resource conservation	Water conservation [200], land conservation [201], material efficiency, bio-mimicry [202], green concrete [203], silicon cells [204].
Recycling technology	Paper recycling [205], plastic recycling [206], electronic recycling [207], industrial waste recycling [208].
Natural resource management	Air [209], water, soil cleanup [210], noise and vibration reduction via chokes [211], wetlands prevention [212], land degradation [213], biodiversity [214], lake protection [215], data storage, evaluation [216], planning [217], monitoring [218], computational tools [219], green computing [220].
Climate/emission reduction technologies	
Transportation technology	Clean transportation [221], electric vehicles [222], fuel cell cars [223], marine vessel propulsion [224], autonomous vehicles [225].
Waste management technology	Waste treatment [226], consuming waste by combustion [227], reuse of waste materials [228], municipal waste treatment [229], household waste treatment [230], hazardous waste treatment [231], liquid wastes of pesticides [226], carbon capture and storage [232].
Environmental quality management	Radiation [233], solid waste [234], low carbon and mitigating CO_2 technologies [235], disaster prevention [236], purification [237], protection, remediation [238], greenhouse gas (GHG) reduction [239], dust removal [240], desulfurization and denitration [241], heavy metal pollution prevention [208], rural pollution control technology [242].
Monitoring and regulation	Pollution control [243], quality monitoring, pollution prevention [244], pollution treatment [245], emissions control [246], carbon footprint [247], commuting [248], high-occupancy vehicle lane (HOV) [249], teleworking [250], carbon/emissions trading, pollution credits [251].
Household and health safety technologies	Indoor air pollution treatment [252], green decoration materials, air conditioning and cleaning [253], urban sewage and sludge treatment [254], human-induced disaster prevention, pandemic prevention [255], disease prevention models [256].
Cleaner production technologies	
Agriculture/forestry technologies	Forestry techniques [257], alternative irrigation techniques, pesticide alternatives, soil improvement [258], fertilizer, harvest technology, animal husbandry [259], environmental friendly farming, ecological fishery, GPS navigation [260], biostimulants, genetic resources [261], tuberization in vitro.
Manufacturing technologies including minerals, iron/steel production	Laser technology [262], cryogenic technologies [263], hot charging, converter gas recovery [264], gas turgines, impulse dying, permeable radiaton walls, batch preheating [265], high pressure grinding rolls [266], sand miling, mechanical conveyance of materials [267], new furnace technologies, fast firing [268], tunnel drier [269], EAF optimization, oxygen combustion [270], refrigeration absorption [271], vapour compression [272], evaporative drier [273].
Chemistry and bio technologies	Nanocellulosic fibers [274], nano-tubes and nano-cells [275], phytotechnologies [276], oxidation usage, bioremediation [277], bio-plastic production [278], calcium loopingn [279], polymers, thermochemical conversion [280], ozone-based technologies [281], enzymology [282], anaerobic processes, new catalysts [283], membrane reactors [284], improved electrolysis, 2-stage crystallization [285], QSL lead production [286], olefin optimization [287], thermal depolymerization [288], bioreactor [289], biofiltration

	[290], artificial photosynthesis, ionic liquids [291].
Industry 4.0 technologies	IIoT [292], Big Data analytics [55], additive manufacturing/3D print [293], robots, CPS [294], digital twins [295], neural networks [296], drones [297].
Green infrastructure	Repair technology[298], green services [299], distributed production [300], downscale processes technologies [301].

Energy saving technologies includes production from alternative energy sources, energy conservation and distribution, recycling and storage. In this area, solar energy [302] is to be given greater importance. A special attention is focused on energy efficiency applications which are based on the evaluation, planning and monitoring processes. Resource- or material-related technologies are characterized mainly by the focus on material exploitation, resources and material conservation, and recycling. Bio-degenerative materials [303] can be a significant promise for future sustainability. Natural resource management means reduction, prevention, protection or evaluation and planning processes for more environmentally friendly use of natural resources. Climate (emission) reduction technologies consist of transportation technologies, waste management technologies, environmental quality enhanced technologies and technologies for monitoring and regulation. The main factors of pollution are manufacturing and transport. The last category is related to cleaner production processes in agriculture and forestry, manufacturing including iron/steel production or chemistry. Important technologies here are, for example, nanotechnologies [304] or cryogenic technologies [305]. Pereira et al. [305] find a balance between the technical and environmental aspects of the use of cryogenic cooling in machining processes and the use of natural degradable oils as an alternative to traditional lubricating oils [306] and further present a methodology for evaluating the performance of machine tools [307]. Special attention is paid to Industry 4.0 technologies which are analysed in more depth in Chapter 4.4.

4.9. Sustainability Outcomes Overview

Based on the content analysis of the publications, an overview Table 8 is compiled, revealing the most important sustainability outcomes. In some cases, these are also the main conclusions and contributions of the publication. Three different types of sustainability outcomes are viewed in the context of Industry 4.0 and the green processes—environmental, economical and social.

Table 8. Overview of sustainability outcomes.

Environmental Sustainability Outcomes	
Emission reduction	Banyai et al. [152], Braccini and Margherita [136], Dev et al. [137], Jena et al. [148], Kamble et al. [139], Munodawafa and Johl [143], Nascimento et al. [145], Raut et al. [149], Stock et al. [146], Tsai and Lu [150], Zhang et al. [151]
Energy saving	Braccini and Margherita [136], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Jena et al. [148], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Moktadir et al. [140], Muller et al. [141,160], Nascimento et al. [145], Santos et al. [162], Saudi et al. [142], Senechal and Trentesaux [154], Stock et al. [146], Thomas et al. [144], Tsai and Lu [150], Yazdi et al. [163]
Resource optimalization	Banyai et al. [152], Braccini and Margherita [136], Dev et al. [137], Garcia-Muiña et al. [156,158], Gupta et al. [147], Jena et al. [148], Kamble et al. [139], Kannan and Arunachalam [155], Martin-Gomez et al. [153], Moktadir et al. [140], Muller et al. [141,160], Nascimento et al. [145], Santos et al. [162], Saudi et al. [142], Senechal and Trentesaux [154], Thomas et al.[144], Tozanli et al. [161], Tsai and Lu [150], Zhang et al. [151]
Economical Sustainability Outcomes	
Economic performance	Banyai et al. [152], Dev et al. [157], Garcia-Muiña et al. [158], Gupta et al. [147], Kamble et al. [139], Martin-Gomez et al. [153], Muller et al.[141], Munodawafa

	and Johl [143], Raut et al. [149], Saudi et al. [142]
Economic development	Braccini and Margherita [136], Jena et al. [148], Munodawafa and Johl [143], Stock et al. [146]
Productivity and efficiency	Braccini and Margherita [136], Garcia-Muiña et al. [156], Garrido-Hidalgo et al. [159], Gupta et al. [147], Jena et al.[148], Kamble et al. [139], Kannan and Arunachalam [155], Muller and Voigt [160], Munodawafa and Johl [143], Nascimento et al. [145], Santos et al. [162], Saudi et al. [142], Senechal and Trentesaux [154], Thomas et al. [144], Tsai and Lu [150], Yazdi et al. [163], Zhang et al. [151]
Cost reduction	Braccini and Margherita [136], Dev et al. [137,157], Garcia-Muiña et al. [156], Garrido-Hidalgo et al. [159], Gupta et al. [147], Chiarini et al. [138], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Martin-Gomez et al. [153], Muller et al. [141], Munodawafa and Johl [143], Raut et al. [149], Thomas et al. [144], Tozanli et al. [161], Tsai and Lu [150], Yazdi et al. [163]
New business models	Garcia-Muiña et al. [156,158], Muller et al. [141,160], Nascimento et al. [145], Stock et al. [146]
Product and process quality	Braccini and Margherita [136], Garcia-Muiña et al. [156,158], Kamble et al. [139], Thomas et al. [144], Tozanli et al. [161], Tsai and Lu [150]
Supply chain integration	Dev et al. [137,157], Chiarini et al. [138], Kamble et al. [139], Martin-Gomez et al. [153], Raut et al. [149], Tozanli et al. [161]
Social Sustainability Outcomes	
Human resources development	Garcia-Muiña et al. [158], Kamble et al. [139], Muller and Voigt [160], Stock et al. [146], Thomas et al. [144]
Social welfare enhancement	Braccini and Margherita [136], Dev et al. [157], Garcia-Muiña et al. [156], Garrido-Hidalgo et al. [159], Kumar et al.[30], Martin-Gomez et al. [153], Muller et al. [141], Raut et al. [149], Senechal and Trentesaux [154], Stock et al.[146]
Workplace safety management	Braccini and Margherita [136], Garrido-Hidalgo et al. [159], Kamble et al. [139], Moktadir et al. [140]

Most of the outcomes of environmental sustainability related to energy saving and resource optimalization. Energy savings are closely linked to the use of renewables, but they can also be the result of the use of cleaner technologies. Resource optimization is associated with the production and elimination of waste, logistics and optimization of material flows. Emission reduction also includes carbon reduction. Economical sustainability outcomes are most often in publications focused on cost reduction (production, logistics, etc.), productivity and efficiency in manufacturing and economic performance. In addition, new business models focused on sustainability, economic development, product and process quality and supply chain integration are mentioned. The most important social sustainability outcomes include human resources development (which also includes the creation of new jobs), social welfare enhancement and workplace safety management (including ergonomics).

The different types of sustainability concepts are classified into sustainability groups for better clarity, and the abbreviations (E, C, S, TBL, CE) are used to label the main groups (Table 9). Environmental (E) sustainability, economic (C) and social sustainability (S), and the concept of the triple bottom line (TBL) are the most common in the papers. The circular economy (CE) concept has also been introduced in some papers. Other types of sustainability include supply chain and logistic sustainability, organizational and technical sustainability, sustainable development and sustainable manufacturing. These other types of sustainability are most often derived from the main types and form a certain subgroup of the main types.

Table 9. Classification of sustainability.

Sustainability (3P Concept)	
Environmental sustainability (E)	Banyai et al. [152], Dev et al. [137], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Gupta et al. [147], Chiarini et al. [138], Jena et al. [148], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Moktadir et al. [140], Muller et al. [141,160], Munodawafa and Johl [143], Nascimento et al. [145], Santos et al. [162], Saudi et al. [142], Stock et al. [146], Thomas et al. [144], Tozanli et al. [161], Tsai and Lu [150], Yazdi et al. [163], Zhang et al. [151]
Economical sustainability (C)	Banyai et al. [152], Dev et al. [137], Garcia-Muiña et al. [156,158], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Muller et al. [141,160], Munodawafa and Johl [143], Nascimento et al. [145], Saudi et al. [142], Stock et al. [146], Thomas et al. [144], Tozanli et al. [161], Tsai and Lu [150]
Social sustainability (S)	Dev et al. [137], Garcia-Muiña et al. [156,158], Garrido-Hidalgo et al. [159], Kamble et al. [139], Kannan and Arunachalam [155], Kumar et al. [30], Muller et al. [141,160], Nascimento et al. [145], Stock et al. [146], Thomas et al. [144]
Sustainability Models	
Triple bottom line (TBL)	Braccini and Margherita [136], Dev et al. [157], Gupta et al. [147], Kamble et al. [139], Muller et al. [141,160], Nascimento et al. [145], Martin-Gomez et al. [153], Raut et al. [149], Senechal and Trentesaux [154]
Circular economy (CE)	Dev et al. [137], Garcia-Muiña et al. [158], Garrido-Hidalgo et al. [159], Martin-Gomez et al. [153], Nascimento et al. [145]
Other Sustainability Dimensions	
Sustainable supply chain and logistics	Banyai et al. [152], Dev et al. [137], Martin-Gomez et al. [153], Stock et al. [146], Thomas et al. [144], Tozanli et al. [161]
Organizational & technical sustainability	Braccini and Margherita [136], Dev et al. [137], Kamble et al. [139], Garrido-Hidalgo et al. [159]
Sustainable development	Garcia-Muiña et al. [158], Muller et al. [141], Munodawafa and Johl [143]
Sustainable manufacturing	Jena et al. [148], Kannan and Arunachalam [155], Kumar et al. [30], Muller and Voigt [160], Raut et al. [149], Stock et al. [146], Thomas et al. [144], Tsai and Lu [150], Yazdi et al. [163]

As an example, the triple bottom line is discussed by Braccini and Margherita [136], reporting that the implementation of Industry 4.0 supports all three dimensions of sustainability from an environmental point of view. Similarly, Senechal and Trentesaux [154] propose a framework for the integration of environmental elements in the maintenance of CPS systems in the automated industry. The connection between the concept of triple bottom line and circular economy is supported by Martin-Gomez et al. [153]. Their conceptual framework integrates social, economic and environmental performance in accordance with the principles of circular economy.

Nascimento et al. [145] discuss a circular model for electronic waste that improves all areas of sustainability in accordance with the triple bottom line. In relation to circular economy, Garcia-Muiña et al. [156] worth mentioning as they discuss the methods in the transition to a circular economy, respecting the principles of sustainability. Kumar et al. [30] analyze a mathematical model that integrates sustainability into the design of cellular manufacturing systems (CMS) layouts in accordance with the principles of circular economy.

Some studies deal only with sub-areas of sustainability. As an example, Stock et al. [146] deal only with factors that positively contribute to the environmental and social dimension of sustainability in the context of Industry 4.0. Similarly, Saudi et al. [142] report a positive impact of Industry 4.0 on the environmental and economic performance of the SMEs and on the competitive position of the enterprise. Tsai and Lu [150] dealt only with the environmental and economic aspects of sustainability for the purposes of planning and controlling production with respect to the carbon footprint.

4.10. Synthesis and Development of New Framework

The classifications of the areas Industry 4.0, green processes and sustainability as used in the paper are summarized in Table 10. It also includes an overview of the methods used in the publications. It is clear from the overview that the authors focused differently on different areas. In terms of classification there are practically no two equally focused publications. From the Industry 4.0 point of view, most publications were devoted to the first area focused on the implementation of Industry 4.0 and smart systems. These publications discuss ways to introduce new technologies with regard to sustainability and green processes. In terms of green processes, most publications dealt with the area of green manufacturing. Production as the primary process is the content of most of the analyzed publications. From the point of view of sustainability, the publications focus on several aspects, most often all three sustainability concepts, i.e., social, environmental and economic sustainability, often through the concept of the triple bottom line or circular economy. The symbols and abbreviations used are explained below Table 10.

Table 10. Synthesis of Industry 4.0 technologies, green processes and sustainability outcomes.

Authors	Method	I4 [1]	GP [2]	SO [3]
Banyai et al. [152]	simulation	C	X	E,C
Braccini and Margherita [136]	case study	A	Y	TBL
Dev et al. [137]	simulation	B	X	E,C,S,CE
Dev et al. [157]	simulation	D	X	TBL
Garcia-Muiña et al. [156]	case study	D	Y	E,C,S,CE
Garcia-Muiña et al. [158]	experiment	D	Z	E,C,S,CE
Garrido-Hidalgo et al. [159]	experiment	D	Y	E,S
Gupta et al. [147]	survey	B	X	TBL
Chiarini et al. [138]	survey	A	Y	E
Jena et al. [148]	case study	B	Y	E
Kamble et al. [139]	survey	A	Y	TBL
Kannan and Arunachalam [155]	experiment	C	Y	E,C,S,CE
Kumar et al. [30]	case study	B	Y	E,C,S,CE
Martin-Gomez et al. [153]	simulation	C	X	TBL,CE
Moktadir et al. [140]	case study	A	Y	E
Muller et al. [141]	survey	A	Y	TBL
Muller and Voigt [160]	survey	A	Z	TBL
Munodawafa and Johl [143]	survey	B	Z	E,C
Nascimento et al. [145]	case study	A	X	TBL,CE
Raut et al. [149]	survey	B	Z	TBL
Santos et al. [162]	case study	D	Y	E
Saudi et al. [142]	survey	A	Z	E,C
Senechal and Trentesaux [154]	experiment	C	Z	TBL
Stock et al. [146]	simulation	C	X,Y	E,S
Thomas et al. [144]	survey	A	Y	E,C,S,CE
Tozanli et al. [161]	simulation	D	X,Z	E,C
Tsai and Lu [150]	case study	C	Y	E,C
Yazdi et al. [163]	experiment	D	X	E
Zhang et al. [151]	case study	B	Z	E

[1] I4 (Industry 4.0 technologies are grouped into: A—Industry 4.0 and Smart Systems Implementation; B—Big Data and Smart Factories; C—CPS interconnection of real and digital world; D—IIoT and

sensors in robotics and in communication); GP (Green technologies focused on: X—green logistics, Y—green manufacturing, Z—green product); SO (Sustainability outcomes: E—environmental, C—economic, S—social, CE—circular economy, TBL—triple bottom line).

Other types of sustainability, including supply chain and logistic sustainability, organizational and technical sustainability, sustainable development and sustainable manufacturing are not reported in Table 10. The main reason is their close connection with the main concepts of sustainability (E, C, S, TBL, CE). Such derived types are often linked to the processes in the enterprise (such as the logistics), however, the measure of relevant sustainability outcomes is ultimately the economic, social and environmental dimension of sustainability (logistics sustainability is expressed as the way the sustainability of logistics impacts on the environment, its economic demands and social impacts on the interest groups).

Based on the synthesis of the created classifications, the SGI 4.0 conceptual framework (Sustainability Green Industry 4.0) is developed by the authors' team, as shown in Figure 8. The framework captures the relations of Industry 4.0, green processes and sustainability in manufacturing. The framework is structured into three vertical levels: technological, process and development, integrated through the circular economy. The horizontal axis consists of three main processes (design, manufacturing, supply chain and logistics), integrated through the life cycle and the value chain. Their implementation is ensured at a higher level by Industry 4.0 technologies and green technologies. The development level follows them in terms of sub-goals of sustainability (organizational and technical sustainability, sustainable manufacturing, sustainable supply chain and logistics) and the main outcomes of sustainability (environmental, economical and social) through the triple bottom line.

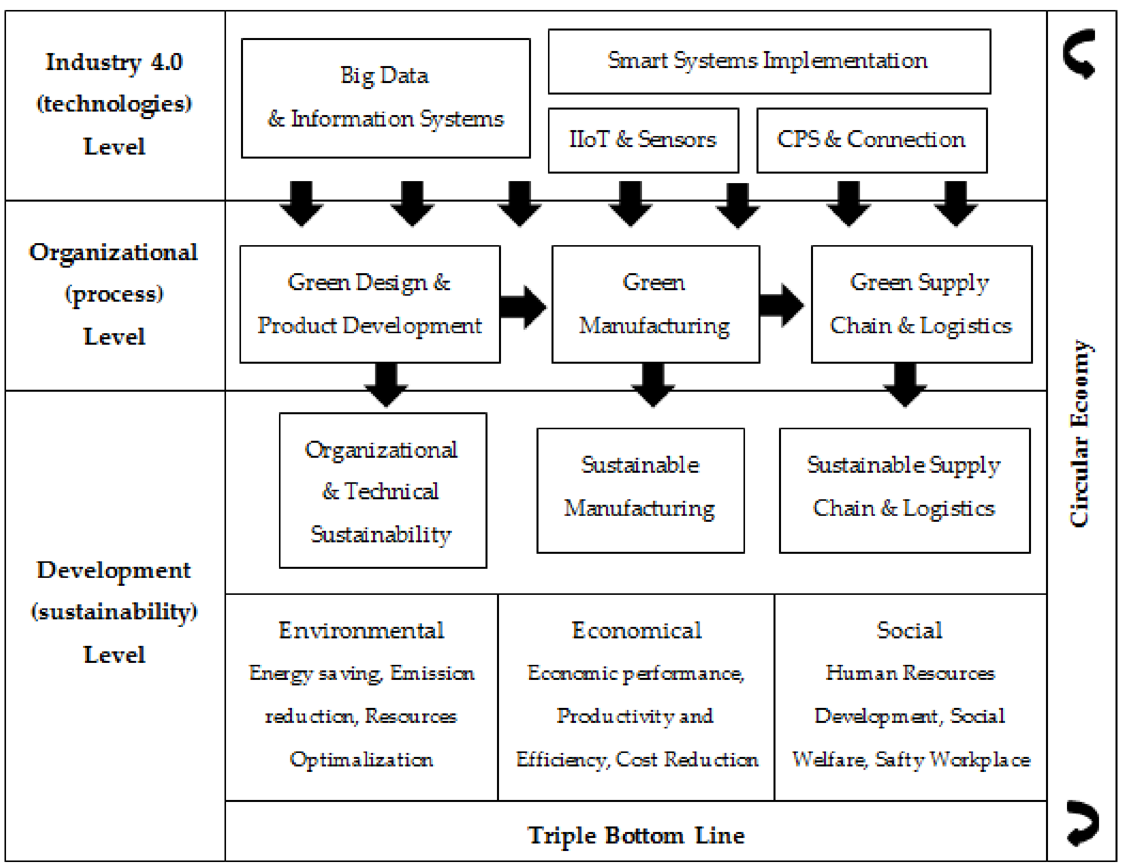

Figure 8. Sustainability Green Industry 4.0 (SGI 4.0) conceptual framework.

The SGI 4.0 framework can explain how Industry 4.0 technologies create sustainability outcomes through green processes. Green processes are an important part of the relationship between Industry 4.0 and sustainability outcomes. The core of green processes is based on green technologies. Industry 4.0 technologies enable full use of green processes to achieve sustainability objectives. The importance of green processes lies in functions they can perform to create sustainability outcomes:

- The supporting function of green processes connects organizational and technical sustainability with technologies. Green processes use current technologies to create an environment for innovations, working, social and technical conditions at the workplace. This includes processes of eco-design, innovation, maintenance and desirable recovery.
- The facilitating function of green processes refers to technologies and systems that ensure a continuous and uninterrupted material and information flow from suppliers to end customers. These processes also include reverse flow based on reverse logistics of packaging, recycling, reuse and dismantling of products.
- Activation function of green processes means the creation of sustainable production system via green value creation, appropriate lean practices, monitoring and the possibility of reprocessing products. Finished manufactured products through these processes minimize negative environmental impacts by conserving energy and natural resources.

Technological level:

- Big data and information systems—in the context of using information systems for big data analytics. This part of the framework allows using information systems for the processing of large volumes of data (big data are quantified in petabytes 10^{15}) stored on the servers and on the Internet in the Cloud through real-time information systems. The information systems and data are the backbone of smart factories, integrated into ERP and visualized through business intelligence technologies. The users access the data using a web browser and a software client for the application virtually from anywhere.
- IIoT and sensors—includes the technologies (sensors, switches), which are a source of information for a control system (computer, brain), and technical devices (robot, machine), which measure certain physical and technical quantities (temperature, pressure, speed, humidity, movement, position, sound, power, time, etc.) and convert them into a signal that is transmitted and further processed remotely. The IIoT devices are useful because they are able to communicate with each other thanks to the CPS systems (i.e., they can receive and send information).
- CPS and Connection—The basis is the cooperation of independent control (computer) units, which are able to make autonomous decisions, manage the technological unit and especially to become an independent and full member of complex production units. This intelligent connection (Bluetooth, RFID, Z-Wave, Zigbee, WiFi, etc.) of various products and devices brings new functions to each other and connects the virtual world with people. Their goal is to connect the real and digital world in production through MES and Digital Twin technologies, in the field of development using CAD tools, augmented (AR) and virtual reality (VR) and in logistics in various CRM (customer relationship management) and SCM (supply chain managmeent) applications.
- Smart Systems Implementation—the area includes the integration of the above-mentioned technologies into a fully functional system. The implementation is associated with digitization, development of robotics and processes based on automation and artificial intelligence. The smart systems are based on technologies that allow sensors, databases, and wireless to work together, adapt, and modify their behaviour to adapt to the environment and their users. They are able to learn, use experience, anticipate future behaviour and use the skills of self-management and self-regulation. This area also includes other Industry 4.0 technologies such as 3D printing used in additive manufacturing.

Organizational (process) level:

- Green Design and Product Development—eco-design of the product means the use of recyclable and recycled materials, recovery parts, reductions in chemicals, energy saving in products, the possibility of further use (re-use), long product life cycle (LCA), possibility of product sharing, durability, disclosure of environmental information, low carbon footprint measure, using standards, renewable resources.
- Green Manufacturing—it is basically the production of the products used in less energy-intensive equipment and the products that minimize the impact on the environment. At the same time, it is a method of production that reduces the occurrence of harmful emissions and waste of natural resources, using the renewable resources and "clean" technologies.
- Green Supply Chain and Logistics—includes the introduction of systemic measures and the implementation of logistics activities enabling recycling and reusing the waste and reducing emissions. It involves the use of renewable and recyclable packaging, environmentally friendly fuels, means of transport (meeting emission standards), etc.

Development (sustainability) level:

- Organizational and Technical Sustainability—such type of sustainability is focused on the inside of the enterprise. It deals with the optimal use of the resources. It involves the use of human labour, maintenance of technical equipment and machinery and IT infrastructure.
- Sustainable Manufacturing—it includes the sustainability of production processes in the production of environmentally friendly products in accordance with the conditions arising from the requirements of environmental protection and optimization of the production costs.
- Sustainable Supply Chain and Logistics—the sustainability of the supply chain and logistics networks is based on the requirements for continuous security of supply, with careful waste management at the same time. The key in terms of the management and optimization of supplier networks is the cooperation between enterprises in the distribution, warehousing, transport and implementation of other logistics functions. In the area of logistics, it is mainly about sustainability resulting from the negative impact of transport on the environment.
- Triple Bottom Line—a basic concept of sustainability based on the concept of 3P (People, Planet and Profit). The triple bottom line includes meeting human needs and achieving a satisfactory quality of life while allocating resources efficiently (economically), conserving natural resources, including ecosystems and their biodiversity (ecologically), and social resources accessible to all while preserving cultural diversity (socially).
- Circular Economy (circularity)—an economic system aimed at reducing waste through the unlimited use of resources. In the SGI 4.0 framework, it consolidates the use of technologies and resources through the green processes enabling long-term sustainability.
- Sustainability Outcomes—these outcomes are divided into three groups (economic, environmental, social) and are characterized by the most frequently found benefits for each dimension.

5. Discussion

In this section we examine prior work and discuss the results in perspective of previous studies and our research questions.

5.1. Industry 4.0 Technologies Classification Discussion

The first research question aimed to classify Industry 4.0 technologies that provide sustainability outcomes of green processes in manufacturing. We found that the papers focused on Industry 4.0 mostly contain keywords: "big data", "IIoT", "cyber-physical systems" and "sensors". The classification of different technologies has created four areas on which the currently included papers focus. The first group consists of papers generally dealing with Industry 4.0 and the concept of smart systems and their implementation. Papers focusing on big data in information systems and smart factories describe the use of big data, Cloud, ERP and other technologies in manufacturing and smart factories. Another area consists of papers focusing on cyber-physical systems and their connection to the real and digital world through digital twins, RFID and other technologies. The last area is created by papers on IIoT and sensors that are used in manufacturing, robotics or blockchain technology.

Asiimwe and de Kock [308] show that major concepts including Industry 4.0 and sustainability highlighted IIoT, cyber-physical systems and automation in the production and manufacturing applications. Bonilla et al. [309] presented experimental conclusions of successful implementation of Industry 4.0 technologies in relation to environmental challenges. The deployment phase scenario shows negative impact trends based on the increased flows of raw material, end-of-life products, energy flow, fuel for transport etc. Some technologies as IoT, CPS, big data analytics, additive manufacturing and on-demand production and customization have expected a positive impact on environmental sustainability in decreased material flow or waste. The integration of these Industry 4.0 elements and their implementation has a positive effect on decreasing flows and emission.

Beier et al. [310] describe the most relevant key characteristics of Industry 4.0 and their relation to sustainability. These characteristics are divided into human, technology and organization features. From a technology perspective, it is clear that the most used are technologies based on automation, and big data. However, CPS, IoT and Cloud are also significant. Sartal et al. [311] state that the Industrial Internet of Things, autonomous and collaborative robots, simulations systems, system integration (communication, vertical and horizontal systems, production processes), virtualization (virtual reality), cloud computing and additive manufacturing (3D printing) have the most significant influence on the sustainability of manufacturing. The findings of this study are compatible with those obtained in the SGI 4.0 framework.

Tirabeni et al. [312] analyzed literature from technological, organizational, social and economic perspectives to find emerging themes in Industry 4.0. The results show that four areas are identified: novel images of work and workers (new type of work, skills and competences), transformative business models (customer and service oriented, integrated and networked, sustainable business models), organizational transformation (new organizational structures, organizational culture, new intra and extra-company activities), training and educational patterns. Hovever, these dimensions and themes did not explain which technologies of Industry 4.0 are used and what sustainability outcomes are important.

5.2. Green Processes and Technologies Classification Discussion

The aim of the second research question was to find out which conventional green processes produce sustainability outcomes as a part of Industry 4.0 in manufacturing. We found that green processes can be divided into three main areas: green logistics and supply chain, green manufacturing and green design and development. The sub-processes were then structured into these three groups. These processes create the internal value chain of companies, and therefore it is necessary to focus on them if the enterprise wants to achieve sustainability. These are also the main application areas of Industry 4.0 technologies. We classify green technologies into four categories: energy saving technologies, resources/material technologies, climate/emission reduction technologies and cleaner production technologies. Asiimwe and de Kock [308] state that key Industry 4.0 applications include manufacturing, smart factories, production, supply chain management, logistics, etc.

Similarly, if we compare the obtained green processes with the primary activities of Porter's value chain [313], we find that there is an agreement. Primary activities are inbound logistics, operations, outbound logistics, marketing and sales and service. Sustainability outcomes mainly affect the logistics process and operations from these activities (mostly manufacturing). Less emphasis is currently placed on green marketing, green sales and green services. This implies the need for greater information for consumers and partners about the implementation of green processes and practices in enterprises. According to Porter [313], a competitive advantage stems from the many discrete activities an enterprise performs in the design, production, marketing, delivering and providing support for its product. From this point of view, it is therefore important that the concept of "green" be integrated into all the main processes and primary activities of the enterprise.

Mendoza-Fong et al. [23] determined 24 attributes of green processes which determine the level of the green manufacturing implementation. These attributes include processes themselves, which support the sustainability benefits of green processes. These are, for example, green purchases, green product and process design, environmental collaboration with suppliers, green practices (in provisioning, productive processes, distribution), reduction of emissions, lean manufacturing, implementation of green technologies, remanufacturing of products, etc.

5.3. Sustainability Classification Discussion

Through the third research question, the authors sought to determine the main sustainability outcomes of conventional green processes in the context of Industry 4.0 in manufacturing. Based on the content analysis, sustainability outcomes were organized into three areas—environmental, economical and social. In environmental sustainability, outcomes focus mainly on energy saving and resource optimization. The most common economical sustainability outcomes are cost reductions, productivity and efficiency, and higher economic performance. One of the most important social sustainability outcomes is human resources development, social welfare enhancement and workplace safety management. Different types of sustainability are then classified into groups for better clarity and overall summary (environmental, economic, social sustainability, triple bottom line and circular economy).

The most-measured sustainability indicators of German and Italian SMEs are according to Trianni et al. [314] classified as the economic (business models, economic growth, enterprise size, product costs, lead time, quality), social (employment, work conditions, employee development, social investment) and environmental (budget and certification, recyclable waste, air, water and land pollution, dangerous inputs, outputs and waste) dimensions of the triple bottom line. According to Beier et al. [310], the economic and social aspects of sustainability in the context of Industry 4.0 predominate in the literature. Environmental aspects only play a minor role in technology-, human- and organization-focused publications. According to Kamble et al. [12], the main contribution and outcomes of Industry 4.0 technologies is attributed to the economic and envronmental dimensions of sustainability. However, the social dimension of sustainability has a high potential for realizing sustainable industrial value creation.

We can use sustainability outcomes to distinguish or define different terms for manufacturing. Raut et al. [149] summarized differences between the terms "green manufacturing", "lean manufacturing", "mass manufacturing" and "sustainable manufacturing" according to economic, social and environmental sustainability areas. In this sense, the objective of green manufacturing is based on social and environmental sustainability. In lean manufacturing, economic and environmental sustainability is preferred. Mass manufacturing is aimed towards classical socio-economic sustainability. However, sustainable manufacturing includes all dimensions of sustainability, i.e., economic, environmental and social sustainability.

Sangwan and Bhatia [315] discussed the sustainable development challenges of Industry 4.0 in three dimensions. The economic dimension of sustainability focuses on economic performance, market presence, indirect economic impacts and procurement practices. The social dimension contains pillars for capability to guarantee welfare in terms of safety, equity (justice), eco-prosumpton and urban forms. The ecological dimension of sustainability has more pillars, such as healthy ecosystem, preventing pollution, welfare preference, shift to renewable resources, waste receiver and resource supply, etc. Varela et al. [316] examined the relationship between Industry 4.0 and sustainability dimensions including their outcomes. In the case of economic sustainability, an increase in profit, value creation, efficiency, flexibility and competitiveness; increasing turnover and new business models; market share; process performance and reduction in operating costs are reported. Environmental sustainability outcomes are decreasing industrial waste, energy consumption and an increase in renewable energy usage, collaboration with partners on good environmental practices. The social dimension focuses on increasing the quality of work conditions, decreasing working accidents (safety work), increasing the participation of employees, etc.

5.4. New Conceptual Framework Discussion

Based on the synthesis, the authors created the SGI 4.0 framework (Sustainability Green Industry 4.0), which summarizes all the important findings from the content analysis. The information retrieved from analyzed papers allows to develop the SGI 4.0 framework. The framework captures the relations of Industry 4.0, green processes and sustainability in manufacturing. The framework is structured into three vertical levels: technological, process and development, integrated through the circular economy. The SGI 4.0 framework's purpose is to explain how Industry 4.0 technologies create sustainability outcomes through green processes. The facilitating, enabling and supporting functions of green processes allow to understand how modern technologies can be linked to the concept of sustainability. In the literature we can find various concepts connecting Industry 4.0 and sustainability, however, the key role of green processes is not mentioned.

The Sustainable Industry 4.0 framework by Kamble et al. [12] is based on three main components: Industry 4.0 technologies, process integration and sustainable outcomes. This framework describes major technologies such as the Internet of Things, big data analytics, cloud computing, simulation and prototype, 3D printing, augmented reality, robotic systems protected by cyber security. Process integration means human-manchine collaboration and shop floor equipment integration on the workplace through the CPS. These processes are related to the Industry 4.0 principles (interoperability, virtualization, real-time capability, decentralization, modularity, service orientation) for successful deployment of Industry 4.0 technologies. As sustainable outcomes are highlighted economic, environmental process automation and safety.

Ghobakhloo [9] presented the Interpretive Structural Model (ISM) of Industry 4.0 sustainability functions and then established contextual relationships among these functions. The analyzed sustainability functions were: business model novelty, carbon/harmful gas emission reduction, corporate profitability, economic development, energy and resource sustainability, environmental responsibility, increased production efficiency and productivity, human resource development, job creation, manufacturing cost reduction, production agility and flexibility, modulatority, product personalization, safety and risk management, social welfare, supply chain digitization and integration. Many of these functions represent the sustainability principles of Industry 4.0 that contribute to economic, environmental and social sustainability. The sources from which Ghobakhloo [9] drew, in contrast to our study, also included conceptual (theoretic) papers, which we excluded from the content analysis.

Machado et al. [317] proposed a conceptual framework for sustainable manufacturing in Industry 4.0 based on technological pillars, scope of sustainable manufacturing, Industry 4.0 and sustainable manufacturing challenges and a dynamic sustainability model. The main challenges are business models, value creation networks, equipment, the human factor, organization of smart factories, sustainable processes and product development and products lifecycles. According to Brozzi et al. [318], the environmental advantages of Industry 4.0 lie in the optimization in logistics, time savings, flexible organization of work, reduction of errors, higher quality, lower physical stress, reduction of workforce, lower costs and lower environmental impacts. Garcia-Muina et al. [319] recommended using instead of tradional business model canvas new tool "triple layered business model canvas". These new models have higher envrionmental (more efficient consumption of raw materials, water reuse, electricity from cogeneration, etc.), social (job creation, transparency of financial information, fair management, regulatory compliance, etc.) benefits for enterprises and society.

5.5. Limitations and Potential Biases

The authors strived for a high quality of records, however, some reserves can be found here. In determining the research questions and scopes of the paper, the authors decided to link the concepts of Industry 4.0, green processes and sustainability. The definition of some topics in the search may be insufficient due to the number of synonyms used in the search phase. In particular, defining "green processes" requires a certain amount of experience. For this reason, the authors sought to reduce potential bias by using experts and software tools to help identify keywords. The authors evaluate very positively the possibilities of using the PICO logic grid to make it easier to capture the researched problem.

Overall completeness of studies is biased by selection, inclusion and exclusion criteria. In the phase of filtering, screening and eligibility assessment of title, abstract and keywords, the authors set criteria that excluded from the content analysis publications focused on agriculture, smart city, chemistry and energy. The main reason was the relation of the papers to manufacturing and production. The works that were originally marked as "potentially eligible" were examined independently by two team members, using the defined selection criteria. However, this evaluation was subjective despite the methodological effort and can be biased by authors' opinions.

The authors sought a clear definition of methodology to avoid different interpretations. The final selection of included studies may be unsufficient. The main goal was to make the methodology understandable and the work replicable. From content analysis in the last phase were excluded publications which do not explicitly discuss Industry 4.0. The concept of Industry 4.0 is not mentioned in these excluded papers at all, but related technologies (such as nanotechnology, robots) are elaborated. This excluded some publications that could be included in the overview. For the same reason, additional records identified through other sources were not included in the identification of results. The authors thus keep rather high-quality publications from the Web of Science database in the included studies. This potential bias is described in results and excluded studies are more closely characterized.

The applicability of evidence may raise the question of whether all sustainability outcomes of Industry 4.0 and green processes have a real positive impact. While the implementation of Industry 4.0 in companies brings economic benefits, it is necessary to mention that it can also lead to negative impacts on sustainability, especially in relation to the environmental and social environment. This review focuses in particular on the positive sustainability outcomes that have been examined in relation to Industry 4.0, sustainability and green processes. Negative impacts are often the opposite of positive impacts (cost reduction vs. cost increasing, etc.) and are often a barrier to the introduction of green processes and new technologies in manufacturing. Focusing more on positive impacts of outcomes could lead to a lower ability to find significant negative effects in content analysis.

6. Conclusions

In conclusion, our review paper highlights the challenge of how conventional green technologies provide sustainability outcomes as a part of Industry 4.0 in manufacturing. We have classified Industry 4.0 technologies, green processes and sustainability outcomes related to manufacturing. The result of the synthesis of the created classifications is a developed SGI 4.0 framework. In summary, this novel review shows that green processes are an important part of the relationship between Industry 4.0 and sustainability outcomes. We came to the conclusion that Industry 4.0 technologies enable the full use of green processes to achieve sustainability objectives primary based on traditional energy saving, resources/material, climate/emission reduction and cleaner production green technologies. The importance of green processes lies in functions they can perform to create sustainability outcomes. The facilitating, enabling and supporting functions of green processes explain how Industry 4.0 technologies create sustainability outcomes through these processes.

Through a systematic review, the main focus of current literature linking Industry 4.0, sustainability outcomes and green processes was identified. It was found that the publications in the examined area deal with Industry 4.0 and smart systems implementation, big data and information systems, cyber-physical systems for connection between real and digital world, IIoT and sensors, green logistics and supply chain, green manufacturing and green design and development, environmental, economic and social sustainability, triple bottom line and circular economy. These areas are then interconnected and their results lead to sustainability outcomes, which are most often energy saving, emission reduction, resources optimalization, cost reduction, productivity and efficiency and higher economic performance, human resources development, social welfare and workplace safety. From these conclusions follow implications, contributions and suggestions for future research.

Our study is nevertheless a valuable contribution to the field as it suggests implications for practice and policy. The study summarizes which technologies and green processes are important for achieving a higher level of sustainability. Green logistics and supply chain, green manufacturing and green design and development should be key enterprise processes. This provides a general, yet practical solution for managerial decisions, policy and strategy development and investment. Enterprises should focus on sustainability based on processes analysis rather than implementing new technologies without strategic direction.

The key contribution of this work for knowledge and research is the solution that provides a classification and framework for sustainability outcomes of green processes in the Industry 4.0 era. There is a lack of studies addressing the issue of summarizing the outcomes of sustainability. This research is a first step towards a more profound understanding of the sustainability of the Industry 4.0 connection to green processes. This finding reinforces the notion that enterprise processes are crucial for the implementation of green technologies in manufacturing.

New research seeking to use our SGI 4.0 framework should attempt to show empirical results of sustainability outcomes of green processes in relation to Industry 4.0. The SGI 4.0 framework allows to develop assessment tools for evaluationg the sustainability of green processes in the context of Industry 4.0. The framework highlights which sustainability outcomes should be included in these methodologies. This study develops a framework for adopting and facilitating sustainability via green processes across enterprises that use Industry 4.0 technologies. It is conceptual and theoretical preparation for the empirical verification of the interconnection between these various concepts.

For further directions of future research, it is essential that the limitations of this study are considered in the subsequent analyses of the negative impact of the sustainability outcomes. This aspect should be taken care of in comparison with future studies. Other issues and challenges not mentioned or which do not occur frequently (for example, additional technologies such as virtual reality, augmented reality, autonomous vehicles, other green processes, etc.) should be anticipated and addressed in future analysis and synthesis.

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Appendix A

The PRISMA Checklist.

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