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Review

Relevance of Environmental Factors in the Steel Life Cycle for a Transition toward Circular Sustainable Production and Consumption Systems: A Joint Bibliometric and Bibliographic Analysis

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Abstract: The design of steel structures has evolved thanks to the increased ability to model the behavior of more complex structures. However, further constraints arise from the need for a transition toward more sustainable production and consumption systems. In particular, the assessment of the economic benefits and efficiency of existing production systems should be integrated with assessment of environmental, economic and social sustainability. In the case of steel, and limited to the environmental dimension, the literature covers various study areas, ranging from the analysis of resource flows to the assessment of steel's environmental impacts. However, an integrated view of existing peer-reviewed studies is currently missing. The purpose of this work is to overcome this shortcoming with a review that considers and integrates research on the steel life cycle from various perspectives: analysis of material flows; quantification of emissions; environmental monitoring and indicators; and circular economy aspects, including reuse and recycling. This study is based on a deep bibliometric and bibliographical analysis of the above-cited aspects, including the key topics, authors and journals, to single out some potential research directions that have previously been neglected. The results of the analyses indicate that, even though discussed in the literature, the redesign of products is still lacking adequate consideration. The same gap was also evidenced when it came to studies on the management of waste materials and recommissioning. There is also still a lack of knowledge on the possible meaningful indicators of environmental sustainability in the case of steel. Moreover, while digital technologies that enable sustainability are being intensely developed and widely implemented, the design, testing and application of sensors for the environmental monitoring of steel production is under-studied and the interaction of environmental factors with steel structures is poorly addressed. Finally, this work evidenced poor attention with respect to water and soil pollution generated in different phases of the steel life cycle. All these aspects should be considered in future research, which would also have a beneficial effect in the implementation of informed policies for a transition toward a circular and sustainable steel life cycle.

Keywords: green steel; environmental sustainability; environmental monitoring; environmental impact; materials flow analysis; environmental physics; circular economy; sustainable production and consumption

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1. Introduction

The design of steel structures has evolved, thanks to the increased ability to model the behavior of more complex structures [1]. The growing number of design specifications based on the desired structure's performance has made material-oriented integrated design and construction of structures (MIDCS) more popular and relevant [2]. MIDCS combines the definition of materials' characteristics with the structural requirements, starting from the design stage. The implementation of this design paradigm in civil engineering needs to be supported by results from multiple research areas, including those of high-performance materials, smart materials and structures, as well as sustainable materials and structures [3].

On the other side, not only the design but also the construction must include the environmental dimension as part of the whole construction life cycle, supporting the transition toward more sustainable production and consumption systems [4–6]. However, as remarked in a recent study, designers and constructors have different visions when it comes to the definition and quantification of steel structures' greenness and socio-technical factors [7]. The same work revealed also that the number of possible environmental sustainability indicators is high and that their use is often not sufficiently harmonized (e.g., the materials flows are separate from waste and emissions). Finally, this study evidenced a discrepancy between constructors' and designers' opinions on various indicators' relevance. For example, constructors considered the "utilization ratio of underground space", "construction land area" and "construction electricity consumption" to be critical indicators that were neglected by designers.

The existence of the above contradictions, along with the lack of an integrative perspective on the topic of environmental sustainability in steel design and construction—and, more generally, in the steel life cycle—underpins the need for a review on this topic. The review is also motivated by the growing penetration and impact of the concepts of circular economy and sustainable transition into national and international regulations, which should transform existing practices on the basis of assessed scientific and technological knowledge [8,9]. This work aims to answer to the following questions: What are the key journals, authors and topics discussing the key environmental dimensions of steel production and consumption? What are the topics that can be derived from a more in-depth analysis of the contents of selected works?

After a section introducing the data on which the analysis is based and the tools used to derive the basic bibliometric results, the key findings are detailed. In particular, a set of bibliometric indicators is defined to answer to the first question. Then, an in-depth analysis of literature contents is presented, preceded by a ranking of keywords derived from the selected journal articles. Finally, the discussion draws on the results to focus on gaps in the research and future perspectives.

2. Materials and Methods

2.1. Bibliographic Research Base

A literature review was conducted via the Scopus (SCO) and Web of Science (WOS) databases. The purpose of a first search round was to identify the main journals, authors and topics associated with some of the most important environmental aspects of steel production and consumption. The search identified literature published from 2019 onwards and focused on a set of eight-word groups: "steel" AND "circular economy"; "steel" AND "emission"; "steel" AND "indicator"; "steel" AND "LCA"; "steel" AND "material flow"; "steel" AND "monitoring"; "steel" AND "recycling"; "steel" AND "reuse". The search results were then limited to research and review articles. The number of published works, grouped according to the keywords and database in which the work was reported, is synthesized in Table 1. After removing duplicate works, the total number of remaining articles was 3361. The full list of considered works is given in the Supplementary Materials.

Table 1. Preliminary number of indexed journal articles (research and review articles) published in the years 2019–2023, as found in the Scopus and Web of Science databases. The first column indicates the last and variable research keyword that was combined with "steel" through the logical connector "AND". This list refers to the first round of bibliographic research. The last column on the right reports the sum of found articles before removing duplicates that existed between the two databases. The bottom row reports the total number of articles found on Scopus, Web of Science and the total of the two.

Variable Keyword	Papers on Scopus	Papers on Web of Science	Total Number of Papers
Circular economy	155	197	352
Emission	1508	592	2000
Indicator	298	70	368
LCA	258	269	527
Material flow	96	130	226
Monitoring	792	262	1054
Recycling	737	571	1308
Reuse	287	215	502
Total	*4131*	*2406*	*6437*

A second round of literature search was conducted, aimed at identifying some key papers that, when integrated with the previous research, could constitute the basis for an in-depth literature content analysis. The search was performed via the SCO and WOS databases. Selected results were then limited to research and review papers published from year 2019. The performed search was based on the following keywords: "steel" AND "sustainability" AND "emission" (174 items, after duplicate removal); "steel" AND "sustainability" AND "circular economy" (22 items, after duplicate removal); "steel" AND "sustainability" AND "environmental indicator" (7 items, after duplicate removal); "steel" AND "sustainability" AND "environmental monitoring" (5 items, after duplicate removal); "steel" AND "sustainability" AND "material flow" (19 items, after duplicate removal). After removing the duplicates, the total number of selected works was 237, subdivided according to Table 2.

Table 2. Total number of indexed journal articles (research and review articles) published in the years 2019–2023, as found in the Scopus and Web of Science databases. The first column indicates the last and variable research keyword that was combined with "steel" AND "sustainability" through "AND" logical connector. This list refers to the second round of bibliographic research. Numbers refer to the total number of articles, obtained by merging the works found on both databases after removing duplicates. The bottom row reports the total number of found articles.

Variable Keyword	Total Number of Papers
Emission	174
Circular economy	22
Environmental indicator	7
Environmental monitoring	5
Material flow	29
Total	*237*

As remarked before, these works, coupling the topic of sustainability with different environmental aspects of the steel life cycle, were used, together with a sub-selection of works derived from the prior bibliographic research, for a deeper analysis of the contents. The selection criteria were the highest number of citations and the higher relevance of used keywords, as found from the bibliometric analysis performed during this research.

2.2. Bibliometric Analysis Software

The citations were exported from the SCO and WOS databases as complete files using a "*.ris" file extension, including all the available fields derived from the databases. Exported files for each study were first imported into Zotero [10], citation freeware that can identify duplicates in the literature, merge different files, and export the citations as a list in a text file or in a bibliographic file format extension such as "*.ris", which was used for this work.

The merged files were then exported into SciMAT (Science Mapping Analysis Tool) software, which is downloadable for free online [11]. Among other functions, this software enables the user to map the works, authors, recurrence of keywords and time periods for an imported set of publications. In particular, the above-mentioned functions were used to analyze the basic properties of the found literature dataset.

3. Results

3.1. Bibliometric Analysis

Table 3 reports the top 10 ranking of journals, which published indexed papers on the environmental sustainability, environmental impacts and environmental aspects related to circular economy in the case of the steel life cycle.

Table 3. Ranking of the top 10 journals, as identified through Scopus and Web of Science databases, which published indexed papers on environmental sustainability, environmental impacts and environmental aspects related to circular economy in the steel life cycle. The results derived from the analysis of articles identified during the first round of bibliographical research and refer to works published between 2019 and 2023.

Journal	Number of Papers
Journal of Cleaner Production	371
Sustainability (Switzerland)	182
Science of the Total Environment	119
Resources, Conservation and Recycling	108
Energies	86
Environmental Science and Pollution Research	82
Journal of Hazardous Materials	62
Journal of Environmental Management	54
Chemosphere	53
Journal of Industrial Ecology	43

Table 4 indicates the top 10 authors who published indexed papers on environmental sustainability, environmental impacts and environmental aspects related to circular economy in the steel life cycle. It is worth noting that the most important authors working on the searched topics are, with no exceptions, Chinese authors. This result might depend on the relevance of ecological civilization, cleaner production methods and other environmental topics of concern within Chinese policies and long-term policy plans.

Table 4. Top 10 authors who published indexed papers on environmental sustainability, environmental impacts and environmental aspects related to circular economy in the steel life cycle. The results derived from the analysis of articles identified during the first round of bibliographical research and refer to works published between 2019 and 2023.

Author	Number of Papers
Wang, Y.	68
Li, Y.	56
Zhang, Y.	49
Wang, J.	47
Zhang, X.	47
Li, H.	44
Zhang, J.	40
Liu, X.	35
Zhang, H.	35
Li, J.	34

Table 5 reports the number of indexed articles per year, starting from year 2019, considered for this review. Excluding the current year of submission of this work (2023), the number of papers published on the topics of interest for this review increased year-on-year, indicating a growing interest in this topic among the scientific community.

Table 5. Number of indexed articles per year, over the 2019–2023 period, considered for this review. Reported results derived from the analysis of articles identified during the first round of bibliographical research.

Year	Number of Papers
2019	726
2020	821
2021	889
2022	911
2023	14

3.2. Keywords Analysis

Table 6 indicates the ranking of keywords according to the number of documents (i.e., papers) in which each keyword is cited.

Table 6. Ranking of keywords used in the analyzed articles. Reported results derived from the analysis of articles identified during the first round of bibliographical research. The results refer to selected works published between 2019 and 2023.

Keywords	Number of Papers
Recycling	410
Carbon dioxide	407
Life cycle assessment	338
Environmental impact	277
Emission control	260
Environmental monitoring	213
Greenhouse gases	213
Sustainable development	209
Performance	179
Energy	175
Air pollution	162
Particulate matter	162
Climate change	151
Circular economy	149
Risk assessment	132
Energy efficiency	128
Air pollutant	126
Global warming	124
Waste management	123
Efficiency	121
Carbon footprint	118
Chemical composition	105
Pollution	100
Air quality	98
Wastewater treatment	98
Industrial emissions	93
Source apportionment	93
Atmospheric pollution	92
Energy consumption	92
Environmental management	89
Material flow analysis	89

Table 6. *Cont.*

Keywords	Number of Papers
Water pollutants	86
Soil pollution	60
Toxicity	60
Carbon sequestration	59
Pollutant removal	58
Detection method	56
Fossil fuels	55
Contamination	53
Monitoring	53
Health risks	52
Quantitative analysis	52
Environmental policy	51
Industrial ecology	49
Water pollution	48
Environmental protection	46
Economic and social effect	45
Mitigation	45
Sewage	44
Pollution control	43
Environmental performance	38
Low-carbon steel	38
Decarbonization	37
Landfill	36
Effluents	36
Sediments	36
Sludge	36

3.3. Literature Content Analysis

The performed bibliographic research confirmed that there is still great uncertainty around what 'greening' means for steel and its market [12]. The quantification of emissions, and especially carbon emissions, is considered crucial, as evidenced by the ranking in Table 6. Conversely, one study proved that in the analysis of environmental parameters, a comprehensive view is infrequent when characterizing the impacts generated by the transformation, consumption, recycling, reuse and recommissioning of steel structures and end-of-life of steel [13]. This fact is confirmed by the absence of a set of environmental indicators, parameters and reference values to qualify and quantify the potential characteristics of 'green' steel.

With respect to the flow of resources, the knowledge and control of material and energy flows in iron and steel production processes is crucial. In fact, the intensity of materials' use (amount of materials per unit of time) influences the intensity of energy use. This is the reason behind a substantial technological effort to improve the quality of management of material flows. This effort is especially relevant for reducing extraction and limiting the amount wasted of critical metals, such as nickel or indium, that are used in steel production [14]. In parallel, the knowledge of energy flows is crucial, given that the steel industry is still energy intensive, despite the fact that current improvements have reduced its impact to 5% of global annual energy consumption [15]. This is why energy efficiency and the optimization of the energy network throughout the steel production process has proven to be an effective way to increase the greenness of steel production. However, the design of production processes and the adjustment of product structures can be still improved. For example, excess heat could be recovered and converted into steam or electricity to save energy [16]. In parallel, the refinement or redesign of production processes should include reduction in waste materials.

As shown in Table 6, waste, as keyword, does not occupy a top position in association with steel. Considering that current research on the circular economy of production and consumption systems focuses on avoiding waste materials, this result might suggest that research and technical discussions have already moved toward this direction. In the case of steelmaking, slag is the main byproduct. One study considered the possible reasons for the low reuse rate of steel slag and, in the case of China, the research identified some causes: outdated treatment methods; the limited use of these byproducts, especially in the case of road construction works; and legal restrictions [17]. Moreover, economic costs further limit the viability of available technical solutions [18]. Another review analyzed the current methods that can be applied to modify hot slags and convert them into value-added materials [19]. These approaches include the crude modification of hot slags to modify their properties; fine modification, used to prepare products such as glass-ceramics and fertilizers; and methods to recovery valuable metals. In parallel, waste gas recycling is also possible as a way to reduce the emission of air pollution [20]. A potential method for reducing CO_2 emissions in an oxygen blast furnace and an oxygen blast furnace under hydrogen-enriched conditions was assessed [21]. From an integrated steelmaking perspective, off-gases generated during the various steel production steps can be valorized as feedstock for the synthesis of methane and methanol, based on various technologies that now can be integrated with the production and addition of hydrogen [22]. The option of top-gas recycling in blast furnaces is currently able to produce a 65% reduction in CO_2 intensity compared to the traditional blast furnace process [23]. Within steelmaking process, it was observed that the recirculation of blast furnace gas back into to the blast furnace itself could achieve an energy saving of 4.9 MJ/kg CO_2 [24].

In the case of scrap, current production, limited to the EU-28 steel industry, is about 15.5 Mt per year [25]. Fabrication scrap in 2017 was 26.5 Mt, dominated by the production of flat products (77%), an area characterized by lower efficiency in materials' use. In the case of scraps derived from end-use production sectors, car production still dominates, with 30% of overall scrap production in the EU 28. In the same geographical area, looking to the amount of scrap steel from the consumer's perspective, the end-of-life (EoL) scrap derived from statistical data was approximately 68 Mt/year in 2017. With regard to the quality of scrap in Europe, the majority was of a high quality, characterized by a low content of tramp elements (in particular, Cu, Sn, Cr, Ni and Mo). Another study forecasted that post-consumer scrap (previously identified as EoL scrap) would grow to 100 Mt/year by 2050 [26]. Within this framework, the same study found that low-purity scrap would increase from the current level of 20 Mt/year to 43 Mt/year by 2050.

To increase the circularity of materials, the first step is to improve the management of waste materials. In this regard, one work proposed the implementation of a waste management system in the steel industry in South Africa. In particular, it proposed integrating into a management tool data on the assessment of generated waste, including the amount and characteristics of waste, as well as defining various risk profiles based on the type of collected waste. According to the study's authors, such a tool would be able to provide a comprehensive set of statistical indicators for the collected data [27]. The reliability of the proposed tool would depend on the ability to define the characteristics of waste streams with regard to their potential reworking. This is why knowledge of resources stocks and flows constitutes a premise for this tool and other systems for improving the environmental management of steel production and steel products. In fact, accounting procedures are based on the knowledge of material amounts and intensities (i.e., rate of use) [28]. This knowledge is also relevant in the case of redesign and recommissioning. A correct assessment of material flows and their dynamics, which should include the assessment of alloying elements used in steel [29], facilitates knowledge of how to manage resources from a circular perspective, starting from raw materials, as discussed in the case of the steel life cycle, and including the EoL of products [30,31]. For example, there is an increased awareness of the amount of steel potentially derivable from buildings and construction EoL, as an alternative to demolition and downcycling [32].

Supply-chain integration strategies are relevant in reaching the target of greater circularity in industrial productions, as shown in a case study on the European steel industry [33].

Such strategies include vertically integrating and hedging slag recycling into steelmaking process, which would reduce the consumption of iron ore; horizontally hedging EoL steel as an alternative to new steel production; EoL steel maintenance and repair, either via planned obsolescence or by control of warranty coverage; and convergence of third-party repair and recycling and landfill. Another effective strategy contributing to the implementation of circular economy solution is residual processing; in the case of the European steel industry, this currently allows 95% of existing steel byproducts to be recycled [34]. A further strategy relevant to steel scrap is to increase the amount of information being collected and shared, in order to support the growth of scrap's marketability. This strategy should take into account that different actors have different needs with respect to the chemical nature and physical parameters of various types of scrap.

Recycling is not the only circular solution for the steel industry. Reuse could be especially relevant in the case of slag [35]. Due to its physical and chemical characteristics, slag can be reused in land-based applications, such as for aggregate in cement; as an agent to raise soil pH or enhance the physical properties of soft soils; in marine-based applications such as coral reef repair and replacement, or seaweed and phytoplankton growth promotion; or for triggering the absorption of metalloids and H_2S.

Another relevant aspect for the environmental dimension of the circular economy is the design, or redesign, of products. In fact, design defines the need for resources as inputs, as well as the desired structural and functional characteristics of the output. One study defined some key design parameters: the mass of the various materials used in the product; the lifetime of the product; losses during the manufacturing process; the content of the primary material; recyclability; and cascadability (materials that can be recovered to produce a lower-quality product) [36]. The definition of parameters for upcycling or disassembly (i.e., design for disassembly) are key elements in the definition of circular design strategies [37].

The efficiency of materials is a key parameter from a circular (closed-loop) perspective. Life cycle assessment (LCA), as a standardized procedure to quantify the flow of resources and the potential impacts generated by the transformation of resources into products through their life cycle, can be used to account for the recovery and reuse of materials from the production phase to end-of-life [38]. For example, in the case of steel structures, LCA can be integrated with a Building Information Mode (BIM) framework, supporting the assessment of deconstructability [39]. On the other side, LCA can be used to assess the potential environmental impacts of the steel life cycle. Within the LCA procedure, key steps include accurate data collection and the construction of an inventory, which is used as an input in the subsequent impact analysis phase (LCIA). Details on constraints, methodological suggestions and data uncertainties associated with the Life Cycle Inventory (LCI) phase are given in the literature [40,41].

The potential risk for steel industries of emitting a large amount of air pollutants including both greenhouse gases (GHG) and toxic compounds, is well known. In respect to this, one study detailed resources flows and their relation to produced emissions in the Chinese steel industry [42]. Another study identified the presence within various atmospheric aerosols emitted from a steel plant of irregular Ca-, Fe-, Mg- and Si-rich particles; carbonaceous particles; spherical Al-, Fe- and Si-rich particles; and agglomerate particles derived from gas-particle conversion processes, later polymerized with volatile minerals [43]. With respect to GHG emissions, it has been assessed that steel production consumes a global average of 5.17 MWh of energy per ton produced and emits 1.9 tons of CO_2 per ton produced [44].

While a great deal of attention is paid to digitization and machine learning as key technologies for reducing the environmental footprint of steel production processes [45], the number of recent studies on the environmental monitoring of steel production is disappointingly low. This fact is not directly reflected in our analysis of the occurrence of keywords, where "environmental monitoring" occupies the sixth position (see Table 6). Nonetheless, the SCO database identified only 343 documents combining "steel production", "environment" and "monitoring", of which only 42 were research or review articles published in indexed journals from 2019 onwards. In particular, only three works focused on sensors, measurement methods or field measures for the environmental monitoring of steel production [46–49]. Updated environmental field data are necessary to assess the environmental impacts embedded in steel products as generated by various production processes, especially in the case of life cycle impact analysis (a phase of LCA) the reliability of which depends on the quality of the input data and impact databases. Conversely, considering that the current volume of peer-reviewed studies on environmental field analyses of steel production is low, the reliability of LCA analyses might be much poorer than thought.

The available field studies published from 2019 onwards prevalently concentrated on the monitoring of environmental parameters in the production of steel products. Further studies are needed to assess the long-term transformation of steel in different environmental conditions, with particular regard to steel corrosion processes [50–52]. The steel-environment interaction affects the durability of steel-derived products such as structures. Durability, in turn, is a key parameter for managing material flows from a circular perspective. If we exclude the topic of corrosion processes, published literature on the environmental monitoring of steel structures is limited. In fact, the SCO database turned up 174 works (35 journal articles published from 2019 onwards), while WOS surfaced 23 works (6 journal articles published from 2019 onwards). Among the applied monitoring techniques, instruments and platforms, the studies found reported on the use of LiDAR and UAV [53,54]; wind and temperature in integration with acceleration and stress sensors [55,56]; and vibration sensors [57–59].

Alongside the impact indicators used in LCA, the key environmental indicators for the steel life cycle are mainly related to the assessment of resource (i.e., material and energy) flows [60]. Several works concentrated on energy-related indicators and, in particular, on energy efficiency [61,62]. While the concept of quantity and its derived indicators has been widely used to assess the amounts of resources used and their flows, the concept of quality has been less thoroughly considered [63]. Nevertheless, the quality of resources is crucial. For example, when it comes to materials, the quality (in terms of purity) of molten steel influences the amount of energy consumed during the steel production process (i.e., a higher number of inclusions leads to higher energy consumption) [63]. In the case of energy, quality indicators such as emergy [64] and exergy [65] are also applied in the assessment of material flows and environmental sustainability of the steel life cycle.

Among the environmental factors challenging the iron and steel industry, the literature reports on the impact of energy demand and emissions, and also explores the evolution and impact of regulatory frameworks for production and consumption systems [66]. The current uncertainties—at least those in Europe—are further triggered by the existence of barriers to commercialization, starting from the unclear status of demand for greener steel [67]. However, some researchers expect that artificial intelligence (AI), as key enabling technology, will play a beneficial role in the transition toward more sustainable steel production and consumption processes. In particular, experts have indicated that AI could be used for predicting process parameters, managing the flow of resources, predictive applications in the context of contaminant emissions, and pollution forecasting around production sites [68]. Moreover, AI could be integrated within cyber–physical systems based on the Internet of Things (IoT), becoming a core tool in smart steel manufacturing under an "Industry 4.0" paradigm [69]. In this regard, there are already several tools that support a more sustainable use and management of resources such as energy [70]. As well as AI and IoT, researchers mention several enabling digital technologies to support sustainability in the built environment, including Big Data analytics, blockchain technologies, digital platforms/marketplaces, digital twins, geographical information systems, and material passports/databanks [71].

4. Discussion

Based on the research question defined in the introduction, this section will discuss some aspects derived from the bibliometric and bibliographical review, the results of which were given in the previous section.

In terms of the bibliometric analysis of authors and their countries, strong geographic disparities were found, with articles from China dominating the literature, as is clearly evident from Table 4. As mentioned in the results section, this geographic unbalance might at least partially be due to China's policy focus on ecological civilization, cleaner production and the circular economy, as well as its support for research projects on these topics. Consequently, there is a clear need to widen the knowledge base with regard to the environmental sustainability and circularity aspects of the steel industry. In fact, the current lack of widespread expertise could hinder the process of decarbonization of steel production and consumption systems.

As reported in Table 6, steel recycling and the assessment and management of emissions were the most popular topics discussed in the literature over the study period. The combination of the results from the bibliometric analysis and an in-depth literature review supported the identification of some research gaps that need to be addressed.

With respect to the transition to 'closed loop' systems typical of circular economy, reuse is underdiscussed. The redesign of products, especially taking into account their decomposability, also requires more discussion. However, closing loops—that is, operating material flows in a circular way—is not enough to guarantee the sustainability of steel production and consumption. In fact, together with materials, energy and emissions also need to be managed.

While energy flows and energy efficiency are often discussed, there is an imbalance with respect to the characterization of pollution and the impact of pollutants on various environmental matrices. In fact, as can be seen from Table 6, the greatest attention goes to atmospheric emissions, while water and soil pollution are widely neglected. In parallel, while solid waste is considered within the analysis of the steel life cycle, wastewater and other byproducts, such as sludge, are often disregarded.

Digital tools and technologies are considered key enablers for the transition toward "green steel". Researchers, designers, constructors and production managers already rely on such instruments. However, there are too few recent peer-reviewed articles presenting the results of environmental campaigns in the field. This poses a serious question as to the reliability of impact assessment procedures based on the use of impact factor databases which might be outdated, as is the case with LCA. On the other side, the same problem exists when it comes to the complete monitoring of environmental parameters in relation to ageing of steel structures. Experimental studies are necessary not only to assess structural health but also to understand the durability of products, a relevant parameter circular planning of the steel life cycle.

As a consequence, the field in which knowledge appears to be most lacking is environmental monitoring. Only strong growth in this direction, and its eventual integration with supporting digital technologies, will improve the reliability of results from impact, life cycle and material flow analyses, as well as the development and implementation of digital twins. In fact, an increase in the number of validated experimental field studies would ensure a continuous dataflow is generated, supporting the development of training and validation datasets for various digital tools. Finally, only the implementation of environmental monitoring integrated with digital technologies can guarantee the reliable adaptive management of environmental issues connected to steel production and consumption.

5. Conclusions

This work presented an integrated bibliometric and bibliographical analysis dealing with environmental factors considered relevant in the published literature for the steel life cycle, from production to end-of-life.

Key journals, authors and topics of papers published in journals, indexed either in Web of Science or Scopus databases between 2019 and 2023, were identified. The results indicated that there is a wide discussion about the management of resource (i.e., materials and energy) flows and their efficiency during production phase of steel. Moreover, from a circular economy perspective, the reuse, recycling and recovery of materials is also considered by the literature. However, the redesign of products still lacks adequate consideration. This study revealed a similar deficit in research on the management of wasted materials and recommissioning.

The results revealed that there are various opinions on the meaning of 'greening' in the case of steel and its life cycle. This lack of a comprehensive view on the environmental sustainability, consumption and end-of-life processes of steel production was also shown by the lack of assessed definitions and agreed environmental indicators that could support the identification and quantification of what 'greening' means in practice. In parallel, while relying on the implementation of enabling digital technologies, the role of environmental monitoring is poorly addressed in the literature. Conversely, environmental monitoring is needed to assess both the environmental impacts of the different phases of steelmaking process and the role played by environmental factors in the degradation and durability of steel products. Moreover, in the case of steel infrastructures, environmental monitoring is needed to assess their structural health.

Finally, while the climate impacts of the steel life cycle and atmospheric emissions of steelmaking are adequately addressed, studies on water and soil pollution generated in the various phases of the steel life cycle are less common, albeit not excluded from the literature. This lack of attention limits the possibilities for implementing adequate solutions to reduce future impacts, and hampers the search for the most effective remediation solutions in the case of already-polluted areas. All these aspects should be considered in future research, which also would have beneficial effects on the implementation of informed policies for a transition toward a circular and sustainable steel life cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/met13030592/s1, File S1: Reference bibliographical list.

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