Review

An Interdisciplinary Systematic Review on Sustainability in Tunneling—Bibliometrics, Challenges, and Solutions

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Abstract: Sustainability is defined by current research as an interdisciplinary field comprising environmental, social, and economic aspects. This paper presents a systematic literature review following the PRISMA guidelines investigating how authors currently view sustainability issues in the specific context of tunneling. Thereby, we introduce a new methodology for reviewing sustainability aspects in an interdisciplinary way, where key bibliographic metrics are derived from the metadata of the reviewed literature. Regarding the content of the articles, we cluster sustainability aspects into specific topics and discuss challenges and solutions. In addition, we examine the role of digital technologies applied in sustainable tunneling. Our results show that there is a lack of interdisciplinary studies and that the current research does not represent all three dimensions of sustainability equally. The current research focuses on assessing the status quo instead of presenting specific solutions. Finally, we see great potential to further leverage digital tools to enable sustainable tunneling.

Keywords: sustainability; tunneling; tunnel construction; green building; life-cycle; environmental, economic and social; systematic literature review; multidisciplinarity; digital technologies

1. Introduction

In 1992, over 170 countries participated in the United Nations (UN) Conference on Environment and Development (UNCED) in Rio de Janerio and jointly formulated the "Agenda 21" [1], a global development and environment action plan. This plan defines a concept including three dimensions—also called pillars—of sustainable development, which are still valid today considering an economic, ecological, and social aspect. These aspects are in tension with each other and should ideally be brought into balance. In 2015, all UN member states adopted the currently active 17 goals for sustainable development as part of the *2030 Agenda*. This represents "*a universal call to action to end poverty, protect the planet, and improve the lives and prospects of everyone, everywhere*" [2] and, in turn, placed the concept of sustainability on a broader foundation.

Despite the broadness of sustainability and its relevant factors in all three dimensions, there is no doubt that environmental issues such as climate change mitigation are among the most urgent challenges humanity faces today [3,4]. In this regard, the *2019 Global Status Report for Buildings and Construction* of the International Energy Agency [5] noted that 11% of global greenhouse gas (GHG) emissions and 6% of the global energy consumption are traceable back to the construction industry. The European Commission estimates that the construction industry's share of the EU's total GHG emissions is between 5% to 12% [6]. The building industry is additionally accountable for 50% of all extracted materials and over 35% of the EU's overall waste [6]. As a result, the construction industry plays an essential role in reaching sustainability targets such as those anchored in the *2030 Agenda* or in the

Paris Agreement [7] to limit the increase of the global average temperature to 1.5 °C above the pre-industrial level. Infrastructure projects, particularly tunnel construction projects, represent a fast-growing and resource-intensive, thus a very important sub-sector within the construction industry. The *International Tunnelling and Underground Space Association (ITA)* reported worldwide investments of USD 125 billion in the sub-sector of tunneling in 2019 [8]. This corresponds to an annual growth rate of 9%, which is 2.5 times higher than the overall growth in the construction industry.

Overall, underground structures can be categorized based on their purpose [9]. *Tunnels* are extended underground cavities to accommodate transport infrastructure such as rails or roads, energy lines, and other utility infrastructure or deliver access to mines and pits. On the other hand, caverns, chambers, and shafts are underground structures that are typically not ascribed to tunnels. The life-cycle of a tunneling project consists of different phases. It starts with the design and tendering phase, followed by the construction phase and subsequently the operation phase, where constant repair and maintenance tasks are performed. At the end of a tunnel's life-cycle, which is approximately 100 years for the structure and 20 years for operational and traffic management equipment, the structure is either upgraded or decommissioned [10]. Concerning the construction phase, a distinction is made between the universal (sometimes also called convectional) excavation method and the mechanical heading method. The universal method is characterized by cyclic working processes of excavation, mucking and rock supporting. The advance is performed either by drilling and blasting, roadheaders, or tunnel excavators. In the case of the mechanical heading method, the advance is performed continuously or stroke by stroke by a tunneling machine (TM) [11]. The decision of which building method is to be used strongly depends on the geological conditions and is made during the design phase. As shown, the life-cycle phases of a tunneling project are strongly interconnected and almost all of them are highly resource-intensive. Therefore, to reach overall sustainability in tunneling related issues need to be managed not only in one particular phase but also during the entire life-cycle "from cradle to grave".

In general, the three-dimensional concept of sustainability, as explained above, has been applied to the construction industry for some years already. The *ecological dimension* aims at protecting local, regional, and global ecosystems as well as protecting natural resources and human health. The *economic dimension* aims to optimize the total life-cycle costs of construction projects, whereas the *social dimension* focuses on considering human needs, human rights, and quality of life as well as inter- and intra-generational ethics [12]. Today, a large number of publications are dedicated to the concept of green building, a widely used synonym for sustainability in construction. While *systematic literature reviews* on this topic already exist for the construction industry in general [13–16], to the best of our knowledge, there is currently no in-depth literature review on sustainability issues in tunneling in particular. This gap motivated us to conduct a systematic literature review on sustainability in tunneling, give a comprehensive insight on the state of the art, and discuss challenges and solutions on how to manage relevant sustainability issues in tunneling presented in this article. Another differentiating factor from existing surveys lies in the interdisciplinary view on this topic from the research fields of civil and subsurface engineering, computer science, data science, business administration, as well as energy and sustainability management.

The rest of this article is structured as follows: Section 2 discusses the methodology we employed in this review. Section 3 presents the bibliometric facts derived from relevant papers. The research topics identified utilizing content analysis are described in Section 4. Section 5 discusses the results and answers the research questions. Finally, Section 6 concludes the article and provides further research directions.

2. Methodology

This study presents a systematic literature review following the PRISMA guidelines [17,18]. Since Ledford [19] points out that some of the world's biggest problems

such as sustainability can only be solved with a shared understanding of several research disciplines, an opinion that we strongly share, we focus on interdisciplinary in the implementation of our systematic literature review. In our case, the authors come from different research fields and have different scientific backgrounds. The team consists of authors coming from civil and subsurface engineering, computer science, data science, business administration, as well as energy and sustainability management. Thus, the interdisciplinary survey process is characterized by those different research perspectives.

A graphic representation of the modus operandi is shown in Figure 1 using the Business Process Model and Notation (BPMN) [20].

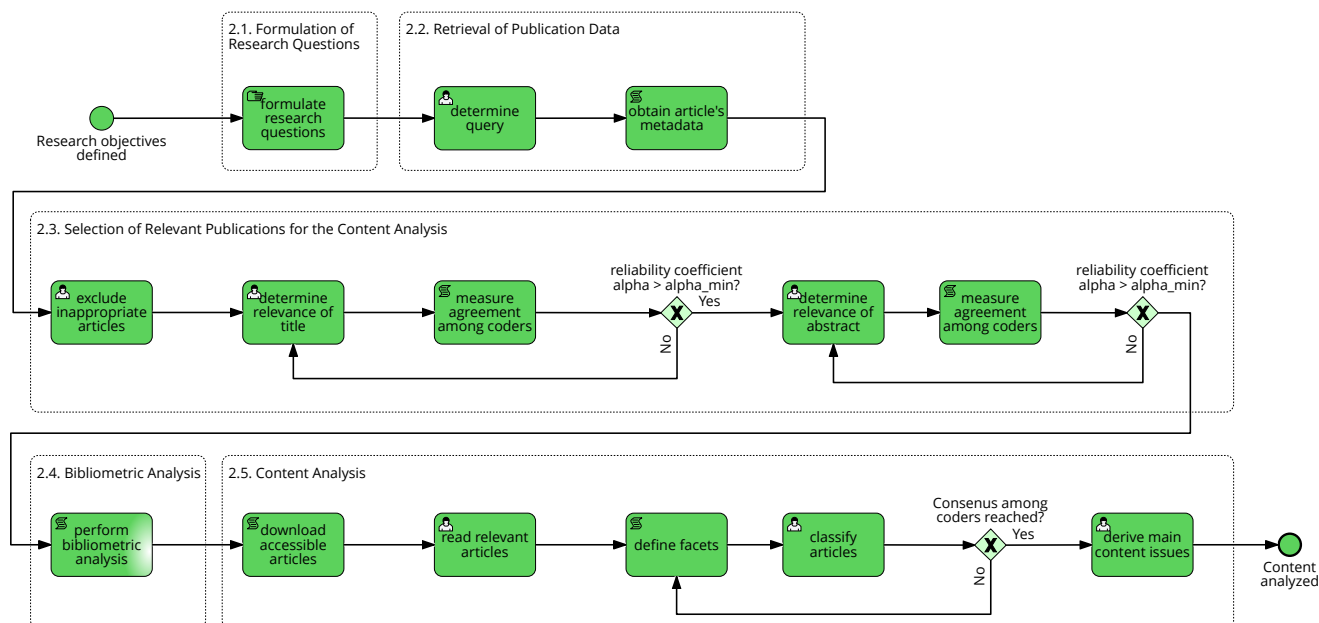

Figure 1. Literature review study methodology.

The review process consists of the following steps: In the first step, we formulate our research questions (Section 2.1). In the second step, we define the query for selecting relevant abstracts and build a database to store those abstracts as well as the corresponding publication meta-data (Section 2.2). Third, we reduced the number of publications based on their relevance and other defined selection criteria (Section 2.3). In the fourth step (Section 2.4), we derive bibliometrics for the selected publications. Finally, we perform a content analysis to derive quantitative and qualitative facts of the selected publications (Section 2.5). A detailed description of the review process is given in the following.

2.1. Formulation of Research Questions

There is no doubt that there is growing scientific interest in sustainability [21], not least because of global climate change and current social changes. The central goal of this review article is to investigate how sustainability is reflected in scientific publishing in the domain of tunneling. We want to get a high-level picture of the research community and review the current state of knowledge. Thereby, our aim is not to identify all research topics that could be categorized under the field of sustainability in tunnel construction but to obtain an overview of those research topics assigned to the context of sustainability in tunneling by the authors themselves. Finally, we want to determine if digitalization could serve as a viable tool to solve sustainability challenges in tunneling. This leads us to the following three research questions:

- RQ1: What are the bibliometric key facts of the scholarly literature on sustainability in tunneling?

- RQ2: What are the main research contributions to sustainability in tunneling? In particular, which challenges have been addressed and which solutions have been presented?
- RQ3: To which extent does digitalization foster sustainable solutions in the domain?

2.2. Retrieval of Publication Data

We used the curated abstract and citation database *Scopus* [22,23] to retrieve publication data for several reasons: Scopus is a well-established database known for its high data quality. In addition, it is popular in the research community and supports complex queries. Moreover, Scopus provides structured metadata about publications such as the authors' affiliation, information on citations, etc. We agreed on a basic set of words that must be included either in the title, the abstract, or the keywords while taking different spelling variants into account. In order not to bias the result toward what we understand by the term "sustainability", we refrained from using specific research topic-related terms such as "environmental protection", "social balance", or "life cycle costs" but only used general terms. This ensures to yield search results on what the community sees related to sustainability. In order to increase the precision of the result, the query was narrowed down to following subject areas: Engineering, environmental science, energy, social sciences, computer science, business, management, accounting, decision sciences, economics, econometrics, finance, chemical engineering as well multidisciplinary. A 10 year period starting in 2011 was deemed representative to capture the state of the art of sustainability in tunneling. To minimize the bias towards certain countries, we included only publications in English. These considerations led us to the following query for the publication data retrieval, which was run in July 2021:

```
TITLE-ABS-KEY(
("sustainability" OR "sustainable" OR "life cycle" OR "life-cycle" OR "lifecycle")
AND ("tunneling" OR "tunnelling" OR "tunnel") AND "construction")
AND SUBJAREA(engi OR envi OR ener OR soci OR comp OR busi OR deci OR econ OR ceng OR mult)
AND PUBYEAR > 2010 AND PUBYEAR < 2021 AND LANGUAGE("English")
```

2.3. Selection of Relevant Publications for the Content Analysis

The broad meaning and inflationary use of the term "sustainability" resulted in a large number of publications that needed additional filtering to extract the relevant ones according to a set of predefined exclusion criteria. Figure 2 gives the exact numbers along this process. Following the PRISMA 2020 flow diagram [18,24], the branches *wrong type*, *duplicate* and *no abstract* belong to the step "Identification". The step "Screening" is represented by the branches *title not relevant*, *abstract not relevant*, and *not accessible*. The "content analysis" of 99 publications represents the step "Included".

The relevant papers remaining represent the corpus of papers for the subsequent bibliometric and content analysis.

In the beginning, eliminations were carried out based on the *publication type*. We agreed that journal papers and conference papers are eligible, whereas books, book chapters, and proceedings as a collection of multiple papers were excluded. In the subsequent step, *duplicate publications* were found by checking for similar phrases in the titles and text passages in the abstracts using a text mining algorithm. Whenever titles, abstracts, and lists of authors indicate that more than a single publication covers the same research work, only the first journal paper was included. In case these are only conference papers, simply the first publication was chosen. One paper was excluded since the abstract was nonexistent.

Two reviewers independently classified the remaining 509 publications according to the *title's relevance*. For instance, if the title indicates that a publication deals with either a sustainability aspect or an aspect related to tunneling, the publication was classified as relevant. In order to ensure a sufficient agreement among the reviewers, we employed the agreement measure α, introduced by Krippendorff [25], where $\alpha \leq 1$ and $\alpha = 1$ in case of perfect agreement. According to Krippendorff, a reasonable agreement is achieved

when $\alpha \geq 0.8$, whereas the lowest acceptable value is $\alpha = 0.667$. The agreement for relevance according to the title was calculated as $\alpha_T = 0.859$, which gives evidence on our similar understanding of the title's relevance. If the title of a publication was classified as relevant, in the next step, its *abstract was checked for relevance* by the same reviewers while the following criterion was applied: the abstract, journal name, or conference name must indicate that the publication deals with a sustainability aspect in the domain of tunneling. The agreement for relevance based on the abstract was determined as $\alpha_A = 0.840$. This gives evidence for a similar understanding for the relevance derived from the abstract. A publication is considered as "overall relevant" thus was included if both reviewers classified the abstract as relevant. This resulted in a corpus of 99 publications that were analyzed as described in the following sections.
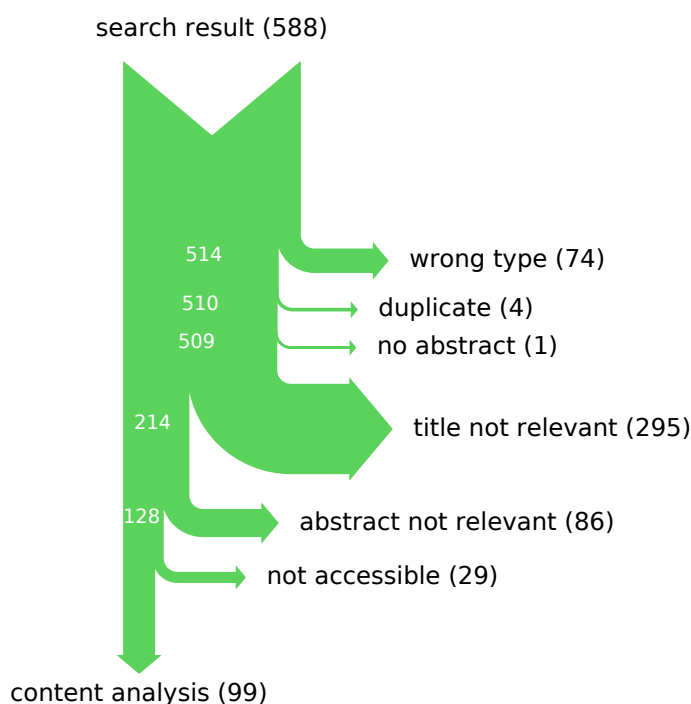

Figure 2. Selection of publications.

2.4. Bibliometric Analysis

Roemer and Borchardt [26] define bibliometrics as "*a set of quantitative methods used to measure, track, and analyze print-based scholarly literature.*" According to this, we employed a bibliometric analysis to get a clear picture on how academic publishing on sustainability in tunneling evolved over time as well as to gain insights into the research community. The analysis was based on the publication data obtained from Scopus with minor fixes for higher consistency. The data considered during the bibliometric analysis consists of the publication year, the publication type, the title of the journal the paper has been published in, the conference the paper has been presented at, the authors, their affiliation, and the citations within the paper. The results of this bibliometric analysis are presented in Section 3.

2.5. Content Analysis

We employed a quantitative and a qualitative approach to perform the content analysis of the remaining 99 publications. For the quantitative approach, we introduce six facets of two different types listed together with the categories in Table 1.

Table 1. Facets and corresponding categories used during the content analysis. Facets with a many-to-many relationship are marked with *; other facets have a many-to-one relationship.

Facet	Categories
Research	
Research method	Own experience, survey, lab experiment, field experiment, case study, archival research, secondary research, logical reasoning and modelling
Contribution type	Report, procedure/technique, qualitative model, quantitative model, notation/standard
Tunneling	
Tunnel type *	Road, rail, utility, mining, type unknown
Life-cycle phase *	Design, materials, construction, operation, decommissioning, phase unknown
Sustainability	
Main topic *	Project resilience, materials and resources, energy and GHG, ground and water, health, social, business and economy
Subtopic *	41 different categories

Publications have a many-to-one relationship with respect to the research-specific facets *research method* and *contribution type*, i.e., each publication is assigned to one and only one category. In a machine learning context, this is also known as multi-class classification [27]. Papers have a many-to-many relationship with respect to tunneling-specific facets *tunnel type* and *life-cycle phase*, as well as the sustainability-specific facets *main topic* and *subtopic*. This means that each publication can be assigned to an arbitrary number of categories, which is also called a multi-label classification.

In order to locate a publication in the research landscape, we adopted the two specific orthogonal facets *research method* and *contribution type*. The categories of the *research method* are based on the work of Buckley et al. [28] and can be found together with a detailed description in Table A1 in the Appendix A. The categories of the *contribution type* were adapted from Shaw [29] and are described in Table A2 in the Appendix A.

Regarding tunneling, we introduce the two specific facets *tunnel type* and *life-cycle phase*. The categorization of *tunnel type* is based on Maidl et al. [9] identifying the primary purpose of tunnels. Tunnels provide either transport routes on road or rail, serve as utility tunnels for water, other goods, energy or telecommunication, or give access to mines. We did not introduce a separate category for metro tunnels but considered them a particular rail tunnels case. The many-to-many relationship of this facet is justified because different tunnel types can be considered within a single publication. If the considered tunnel type could not be deduced from the text, we chose the category *type unknown*.

A publication was assigned to a certain *life-cycle phase* if the publication deals with decisions or effects during this phase within the tunnel life-cycle. The definition of this life-cycle phases is described in Table A5 in Appendix A. Additional to the usual phases *design*, *construction*, *operation*, and *decommissioning*, we added the phase *materials* to capture the selection, production, and use of construction materials. For example, a publication dealing with energy-efficient lighting systems was categorized as "operation" because the energy savings take effect in the operation phase even though the design decision has been made in the design phase. If the considered life-cycle phase can not be deduced from the text, we chose the category "phase unknown". The corpus of relevant papers contains many life-cycle assessments, which inherently consider more than one life-cycle phase, justifying the many-to-many relationship for this facet.

For the detailed breakdown of covered sustainability issues, we introduced the sustainability-specific facets *main topic* and *subtopic*. Main topics and subtopics are related to each other such that main topics are subdivided into different subtopics. The

topics are initially based on the work of Gijzel et al. [30] who used the Q-methodology [31] to examine different perspectives of the meaning of sustainability in tunneling among practitioners. By analyzing different sources, including project data, expert views, literature and tools, the authors compiled a list of 35 aspects relevant for the sustainability of tunnel projects and grouped them into seven different main groups. In our work, we used this set of aspects and groupings as a basis for our sustainability-specific facets, i.e., main topics and subtopics. We, however, incrementally adapted the original set of subtopics based on findings in the reviewed publications. For example, we added the new subtopic "service life extension", which was identified from the reviewed publications, or we merged the aspects "energy usage" and "energy efficiency" because these two concepts are so closely related that this categorization would be ambiguous. Additionally, we included new aspects from the sustainable development goals of the United Nations [32]. The result is a sustainability-specific set of 7 main topics and 41 corresponding subtopics, as listed in Table A4 in Appendix A together with the corresponding descriptions. We agreed to code at least one but not more than 10 subtopics per publication.

For the qualitative approach, we extracted relevant challenges and solutions regarding the coded sustainability-specific main topics and subtopics addressed in publications included in the content analyses. Particular attention was paid to digital technologies that boost or support the management of sustainability issues. The extracted content was merged and edited in a joint effort in the last step.

While selecting relevant publications for the content analysis was performed independently by two different reviewers the process of, the quantitative and qualitative content analysis itself (as described above) was only performed by a single content reviewer. During the content review, one article was determined not to be relevant and, therefore, excluded from further analyses. The quantitative and qualitative content analysis results are presented in Section 4.

3. Bibliometrics

This section presents a comprehensive bibliographic analysis of the corpus of reviewed papers. We start our analysis by inspecting the temporal evolution of the publication activity. Figure 3 depicts the number of published papers which have been classified as relevant for each year between 2011 and 2020.

Figure 3. Number of publications over time (green) and the trend (gray).

The figure illustrates the growing interest in the scientific community to investigate sustainability issues in tunneling. With 25 publications in 2019 the number of publications more than tripled compared to the beginning of the investigated period.

A total of 61 of the reviewed publications have been published in journals, whereas only A total of 38 have been published in conference proceedings. A total of 30 different journals have been identified from the reviewed papers. The left side of Figure 4 shows the number of publications in the different journals.
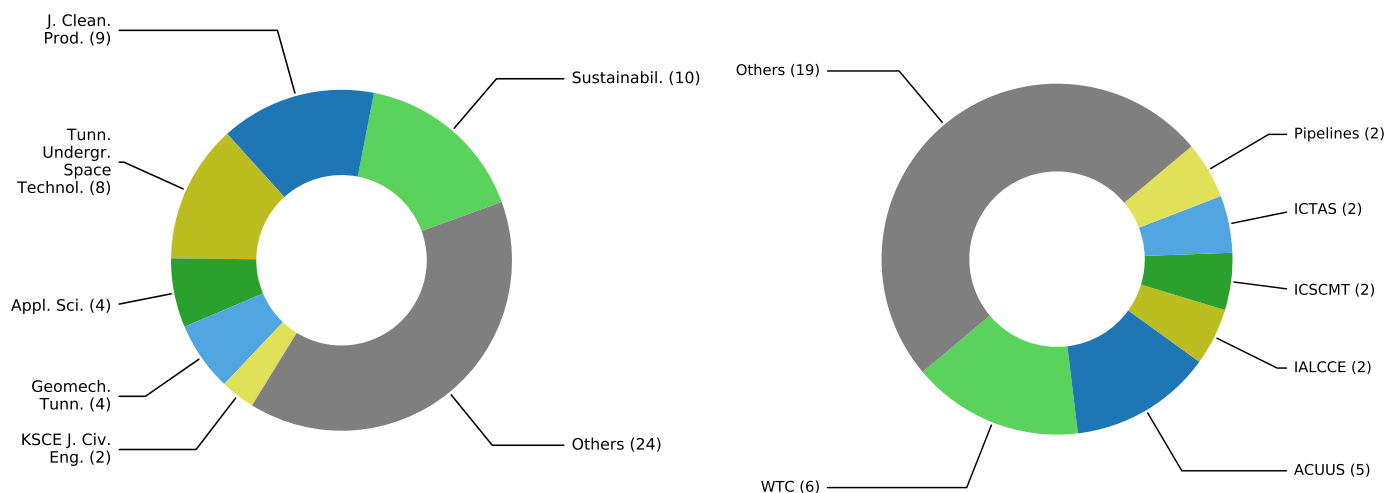

Figure 4. Number of publication in different journals (**left**) and for different conferences (**right**).

Approximately one third of all reviewed journal papers are featured in the two most popular journals *Sustainability* (Sustainabil.) [33] and *Journal of Cleaner Production* (J. Clean. Prod.) [34]. Both journals have a clear focus on sustainability issues. *Tunnelling and Underground Space Technology* (Tunn. Undergr. Space Technol.) [35] and *Geomechanics and Tunnelling* (Geomech. Tunn.) [36] are the most encountered journals with an explicit focus on underground structures. *Applied Sciences* (Appl. Sci.) [37] is a journal publishing papers on all aspects of applied natural sciences and *KSCE Journal of Civil Engineering* (KSCE J. Civ. Eng.) [38] is a journal of the Korean Society of Civil Engineers (KSCE). So the numbers suggest that authors tend to prefer journals with a sustainability focus over journals with an engineering focus to publish about sustainability issues in tunneling. One could argue as well that sustainability issues might not have yet attracted the attention of journals with an engineering focus.

Approximately one third of the papers have been published in conference proceedings. The reviewed conference papers correspond to a total number of 25 different conferences. Figure 4 illustrates the number of publications for different conferences. The results suggest that the *World Tunnel Congress* (WTC) is by far the most popular venue for sustainability in tunneling. It should, however, be noted that all of the six publications have been presented at the WTC 2019. The *World Tunnel Congress* is an annual conference organized by the *International Tunneling and Underground Space Association* (ITA-AITES). In 2019 the conference featured "Environment sustainability in underground construction" as one of the eleven groups of topics [39]. The other conferences are the *World Conference of the Associated Research Centers for the Urban Underground Space* (ACUUS), the *International Symposium on Life-Cycle Civil Engineering* (IALCCE), the *International Conference on Technology of Architecture and Structure* (ICTAS) and the *UESI Pipelines Conference*. It is noteworthy that all of the conferences mentioned above have a clear focus on engineering topics.

The left-handside of Figure 5 depicts a geographic analysis of the reviewed publications.
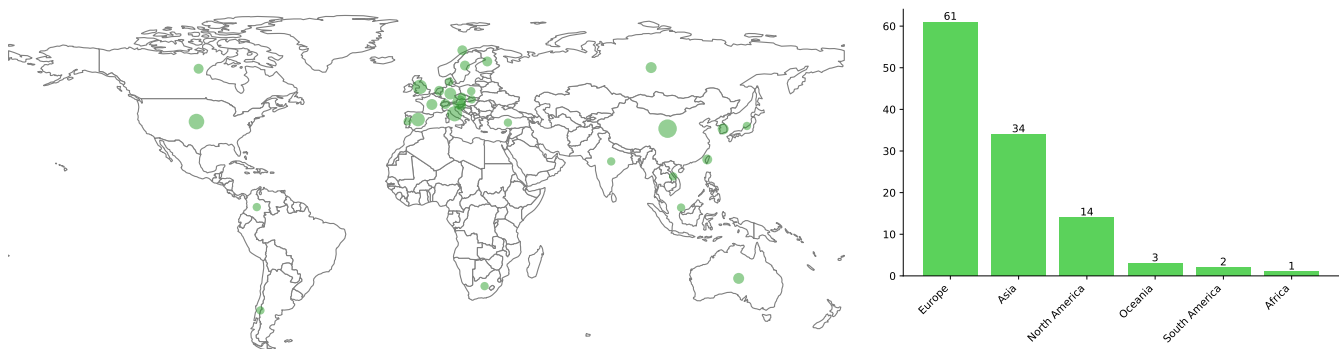
Figure 5. Number of publications per country (**left**). The area of the circles is proportional to the number of publications. Number of publications by geographic regions (**right**).

A publication is attributed to a certain country if at least one author is affiliated with an organization in that country. Since a paper potentially has authors affiliated with organizations in different countries, a single paper may count for multiple countries. Thus, the sum of papers per country is higher than the number of papers considered in the survey. A total of 32 different countries contributed to the corpus of reviewed publications. The countries with the most publications are China, the United States and Italy with 24, 12, and 11 publications, respectively. The number of publications for different geographic regions can been seen in the right-handside of Figure 5. By aggregating different countries to geographic regions it can be observed that sustainability in tunneling is of greatest concern in Europe with 61, followed by Asia with 34 and North America with 14 publications.

In order to get a precise picture of the research community in the field of sustainability in tunneling, we analyzed the organizations the authors are affiliated with. The left-hand side of Figure 6 shows the number of publications for different organization types.
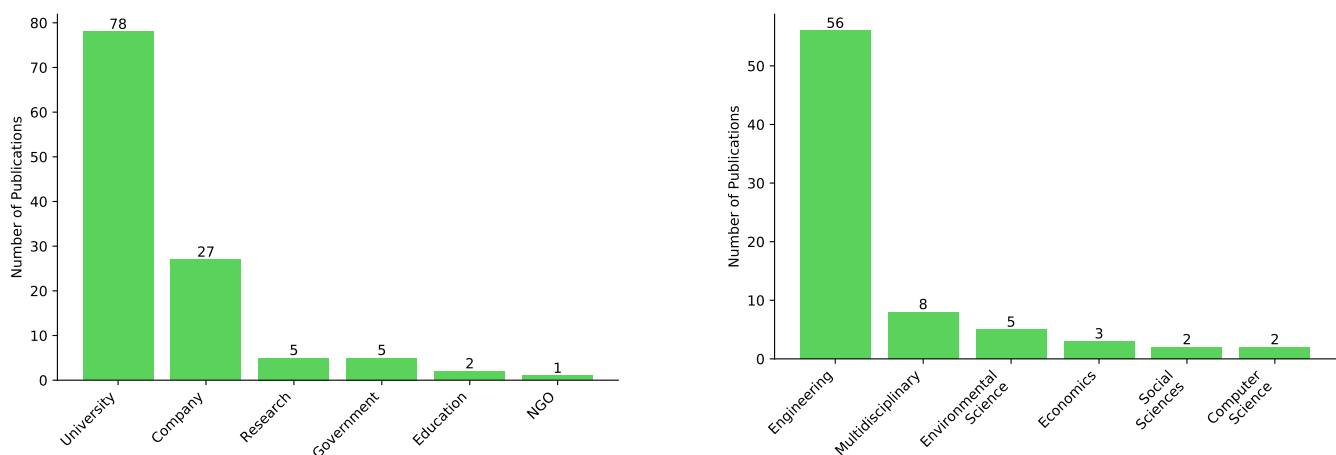

Figure 6. Number of publications for different organization types (**left**) and research areas (**right**).

Analogous to the geographic analysis, we assign a publication to a certain organization type if at least one author is affiliated with an organization of that type. The Figure 6 reveals that *universities* are the key drivers for sustainability in tunneling and *companies* have contributed significantly. In the figure, *research* represents non-university research institutions, *education* represents non-university education institutions, *government* represents governmental organizations, and *NGO* represents standards organizations. Compared to universities and companies, these organizations are only minor contributors to the research on sustainability in tunneling. Again, the number does not sum to the total number of papers, as one publication can have authors in different organization types.

It is intriguing to know which research area authors contribute to. To answer this question, we categorized authors by their research area according to the department they are affiliated with. The result can be seen in the right-hand side of Figure 6. It has to be noted that in some cases the department of an author is unknown and the research area can therefore not be determined. It is clear from the figure that the vast majority of authors have an engineering background. *Multidisciplinary* represent departments the name of which suggest an activity in multiple research areas. In the introduction, we presented the concept of three-dimensional sustainability. It is remarkable that departments in the research areas *environmental science*, *economics* and *social science* matching those three dimensions are barely represented in the selected publications. Another interesting fact is that there is hardly any involvement of departments with a focus on *computer science*. These numbers indicate that there is insufficient interdisciplinary collaboration across different research departments.

Next, we had a closer look at the authors of these publications, which showed that the reviewed papers correspond to a total number of 308 different authors. To get an indicator of how active authors are in the field of sustainability in tunneling, we analyzed the number of publications in the corpus an author has contributed to. The contribution is counted independently of the author's position in the list of authors of a particular paper. A total of 271 authors contributed to exactly one article, 32 authors contributed to two papers, and only five authors contributed to more than two papers: S. Mohsen Shahandasht from the University of Texas at Arlington (4 contributions), C.D.F. Rogers from the University of Birmingham (3 contributions), Mohammad Najafi from the University of Texas at Arlington (3 contributions), and Chun Guo and Jianfeng Xu from the Southwest Jiaotong University (3 contributions). The papers of S. Mohsen Shahandasht and Mohammad Najafi deal with different aspects of underground freight transportation (UFT) systems. C.D.F. Rogers focused on underground structures in urban areas. Chun Guo and Jianfeng Xu analyzed the GHG related to highway tunnels. These numbers suggest that sustainability in tunneling is still a side issue for researchers.

The publication with the most overall number of citations are those from Sterling et al. [40], Chang and Kendall [41], and Hunt et al. [42]. The publications with the most citations from within the corpus are those from Miliutenko et al. [43], Huang et al. [44], and Moretti et al. [45]. All of these papers performed an LCA (life-cycle assessment) of road tunnels. The first paper reports on the carbon dioxide equivalent (CO_2e) [46] and energy consumption related to different tunnel scenarios. The second paper discusses the global warming potential (GWP) and other environmental effects of tunnels and gives a detailed breakdown of different phases of the tunnel and processes during the construction. The authors of the latter paper evaluated the effect of different pavement designs on costs and energy consumption.

4. Sustainability in Tunneling

The previous section presented the results of the analysis of the relevant publications based on the data retrieved from the abstract database. We want to proceed in this section by presenting all qualitative and quantitative results that we derived by reviewing the actual content of relevant literature. Section 4.1 reports the classification results of the research-specific facets research method and contribution type, and Section 4.2 for the tunneling-specific facets tunnel type and life-cycle phase. Sections 4.3–4.9 display the analytical results for the sustainability-specific facets main topic and subtopic, which includes quantitative and qualitative results. As discussed in Section 2.5, the qualitative results cover challenges and solutions for each subtopic, where we only report substantial contributions to this subtopic. Frequently, there is a fluent transition between different subtopics. Reusing the excavation material can, for example, be classified as the subtopics *excavation material*, *recycled materials*, or *waste*. In cases where a single contribution matches multiple subtopics, we discuss the contribution along the best matching subtopic. For these reasons, the number of publications classified as a particular subtopic is generally higher than the number of qualitative contributions presented in the respective segments.

Section 4.10 concludes this chapter with the state of the art of digital technologies in sustainable tunneling.

Before we enter into the detailed results we want to give an overview over three approaches to derive an overall quantitative assessment of the sustainability of a tunnel project most frequently used in the reviewed literature based: life-cycle analysis (LCA), life-cycle costing (LCC), and different forms of multi-criteria decision making (MCDM). *LCA* is a systematic analysis of the potential environmental impacts of a tunneling project throughout their life-cycle. The systematic approach consists of four steps and is regulated in the standard ISO 14040 [47]. The first step is to define the objective and scope of the assessment, then form life-cycle inventories (usually extracted from bills of quantities), assess their impact (using factors form standardized databases), and evaluate the results. *LCC* represents a systematic economic assessment of total direct life-cycle costs of a tunnel project, possibly also including indirect environmental and social costs. *MCDM* approaches combine economic, environmental, and social indicators to perform an overall quantitative assessments of the sustainability of a tunneling project [48].

4.1. Results of the Research-Specific Classifications

The classification results in terms of the research-specific facets reveal how the reviewed literature fits into the research landscape and are depicted on the left-hand side of Figure 7.
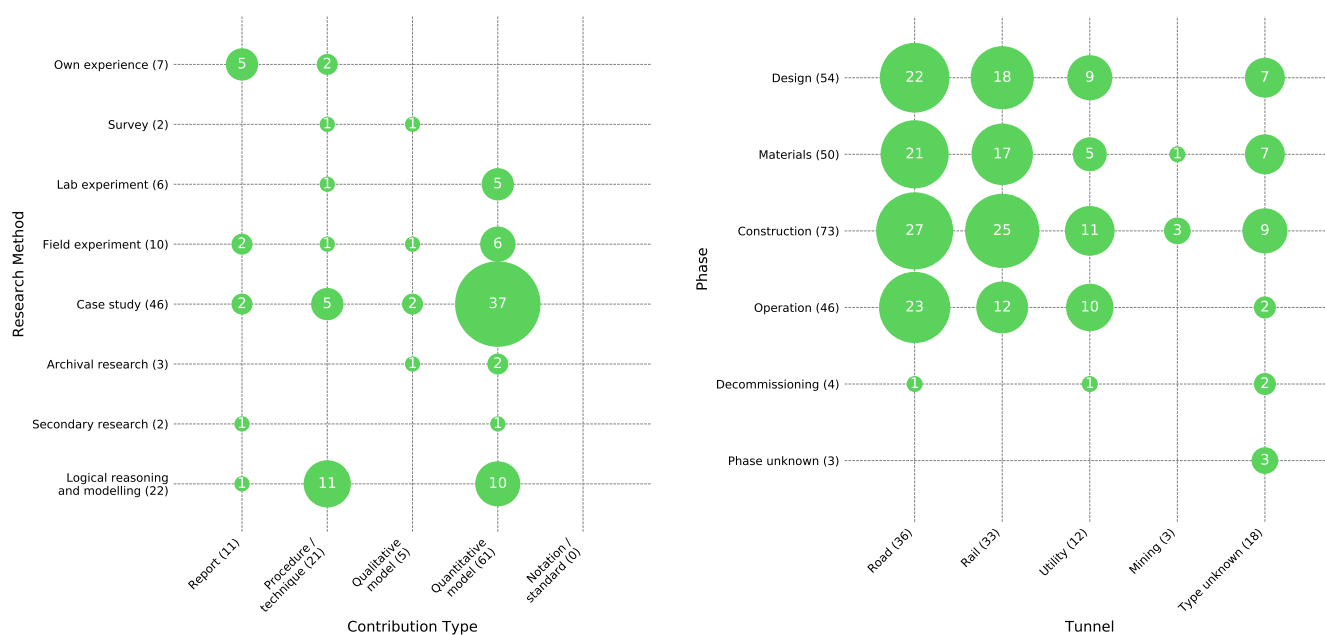

Figure 7. Number of publications for the facets research method and contribution type (**left**) and life-cycle phase and the use of a tunnel (**right**).

The counts at the intersections represent the number of papers that were classified as a specific couple of research method and contribution type whereas the counts in the row and column labels represent the total number of publications classified as a certain research method or contribution type, respectively. It is made clear by the figure that the vast majority of researchers followed a case study approach and contributed a quantitative model. This can be attributed to the numerous papers that applied LCA or LCC to tunnel projects that serve as a case study. "Logical reasoning and modelling" was the second most frequent research method. Most researchers applying this kind of research method contributed a novel evaluation procedure, algorithm, or quantitative model. A small number of publications haven been classified as "own experience", which primarily contain project reports. Figure 7 illustrates that other combinations of research method and contribution

type are rarely employed to investigate sustainability issues in tunneling. Unsurprisingly, there is no publication contributing a notation or a standard.

4.2. Results of the Tunneling-Specific Classifications

The right-hand side of Figure 7 shows the result of the classification of the tunneling-specific facets. Note that, the numbers at the intersections do not necessarily sum to the row or column subtotals, nor do the numbers at the intersections sum to the overall number of publications. The reason is that a publication could be classified as more than one tunnel type and more than one life-cycle phase. To make this clear, let us consider the three publications classified as "mining". One of the publications is classified as "materials", whereas all three publications are classified as "construction", resulting in counts of 1 and 3 at the intersections, respectively. It can be identified from the figure that the research effort for sustainability issues is balanced across road and rail tunnels. Utility tunnels received significantly less attention, and mining plays only a tangential role in the reviewed literature. This is in agreement with the total length of tunnels excavated and total investments, which are primarily made in rail and road tunnels [8]. Concerning the life-cycle phase, it can be observed that all phases except decommissioning are evenly discussed in the reviewed literature. We discuss the topics identified during the content review in the remainder of this section.

4.3. Project Resilience

The first main topic focuses on the optimization of the tunneling project itself and its ability to adapt to future necessities.

Diving in on the first subtopic, compared to conventional open-cut methods, especially in urban environments, multi-utility tunnels (MUT) provide the *functional flexibility* to sustainably install new or additional telecommunication, power, and other utility lines [49–51].

Concerning the subtopic *multifunctionality*, Audi et al. [52] discuss the case study of upgrading the safety of the existing road tunnel by supplementing it with an additional emergency tunnel. One scenario envisages using the new emergency tunnel for pedestrians, bicycle, or bus traffic at the same time.

Regarding *visual and experiential sustainability*, López et al. [53] propose a method to quantify the landscape integration of tunnel portals. Shau et al. [54] present the possibility of including local cultural design patterns (e.g., aboriginal imagery) into the tunnel design.

It is noticeable that even though *climate adaptation* is considered a primary environmental sustainability goal set by the European Union and included in the EU Taxonomy Regulation [55], no contribution was offered to this specific subtopic by the reviewed publications.

We identified *spatial consumption* as the most important subtopic for project resilience. Multiple authors believe that underground facilities can actively contribute to urban sustainability by providing infrastructure while preserving valuable above-ground space [40,56]. Gettinger et al. [49] go as far as to claim that for big cities, tunnels will be the best solution to provide the utility infrastructure for future demand. Similar to skyscrapers above ground, MUTs enable high-density subsurface development. Nevertheless subsurface structures also pose many challenges. Compared to above-ground structures, subsurface structures entail irreversible mechanical, geological, and hydrological effects on its surrounding. That is why underground facilities require thorough and long-term planning. With this challenge in mind, Vähäaho [56] developed a plan showing areas suitable for underground facilities for Helsinki while considering geological and non-geological criteria, for example, existing and planned underground structures, accessibility, ground-level uses. Sterling et al. [40] point out that a reservation policy for underground space could reduce the conflicts of future underground facilities.

The research community did not specifically cover the topic *design for disassembly*. However, Alberti et al. [57] identified that the dismantling costs of concrete refined with polyolefin fibres is significantly lower than traditional concrete.

Considering *service life extension*, it is a fact that underground structures have a long expected lifetime due to the absence of many environmental exposures and a heavy building stock. However, they are not immune to deterioration, and when needed to be repaired, the facilities most likely need to be shut down completely [40]. Specific challenges in maintenance management do also occur due to the difference in service life of the tunnel structure on the one side and the electro-mechanical and electronic equipment on the other [58]. As a proposed solution Honeger et al. [58] introduce their maintenance management methodology to provide a high level of tunnel safety. Scherz et al. [59] found an optimum solution for the trade-off between stronger cooling and shorter service life of telecommunication equipment due to thermal degradation by performing an LCC analysis.

4.4. Materials and Resources

The main topic *Materials and Resources* addresses challenges and presents solutions to boost sustainability in tunneling by rational usage of materials, recycling and waste prevention.

The reduction of *use of materials and resources* is of crucial significance for sustainability. In this context, various authors express their view that improved material classes for tunneling linings could reduce the overall amount of material and resources needed in tunneling. For example, Sauer and Fischer [60] proposes a means to decrease the width of the tunnel lining by using cement types with a higher strength class, which leads to the reduction of overall quantities of concrete needed having the additional benefit of reduced tunnel cross-section, thus the amount of excavation material required to be exploited.

In order to minimize the *environmental impact of materials* in tunneling, there are two basic approaches: either to minimize the usage of materials and resources in general or the usage of materials with lower specific environmental impacts. Regarding the latter approach, de la Fuente et al. [61] showed that tunnel ring segments made of self-compacting fiber-reinforced concrete are superior in cost and environmental impact to traditional reinforced concrete. Using the same methodology, Alberti et al. [57] compared steel-mesh reinforced concrete slabs with the ones reinforced with polyolefin fibers. They report polyolefin fiber reinforced concrete slabs to be superior not only in environmental but also in economic and social aspects.

Tunneling obviously generates large amounts of *excavation material*. It stands to reason to use this material as a landfill or as a construction material [44,49,62–67]. Recycling could lead to a significant reduction of costs, GHG and transport-related traffic [64,66,68] on the one hand but pose some additional challenges on the other hand. Both the geologic conditions and construction process is subject to big uncertainties [69]. Another challenge is the quality or the chemical properties of the excavation material [66,70]. Mitigations are to categorize the excavation material into different classes, to wash the aggregates or to adapt the concrete mixture. Zhang et al. [63] presented a guideline to find the optimal formulation of grouting material while using excavation material as partial substitute. The deposition of excavation material has also been studied in regards to an optimal renaturalization of an area [62].

Some authors deal with *recycling materials* others than excavation materials. Multiple authors investigate the recycling of ground granulated blast-furnace slag or fly ash as a partial replacement for Portland cement [54,67,71]. It was also shown that the recycling of steel has a positive effect on the GHG emission of road construction projects [72]. Praticò and Tramontana [73] showed that the recycling of extinguisher powders in asphalt has a positive effect on its fire resistance.

The subtopic *waste* is mainly discussed in a recycling context or when considering its environmental impacts while performing an LCA [52,57,74]. In tunneling, the excavation material represents a special case of waste material, as was discussed above. While developing a sustainable strategy for the underground transport in the Ljubljana Basin Jovičić et al. [75] considered excavated material and waste originating from the construction.

4.5. Energy and GHG

The main topic *energy and GHG* encompasses all topics that improve the sustainability of tunnel projects related to the use and generation of different energy carriers, GHG emissions, and transport.

First of all, several authors of the reviewed publications investigated *energy efficiency* in the construction and the operation phase of tunnels. Based on a specific highway project including multiple tunnels, Fei et al. [76] analyzed that nearly 50% of the total energy consumed can be ascribed to raw material production, 12% to the construction phase and 38% to the operational phase determined to 20 years. Using a more realistic assumption of an operational phase lasting 100 years, however, Miliutenko et al. [43] identifies the operational phase itself as the one demanding the most energy assigning only 8% of the total consumption to the construction phase. In order to reduce energy consumption and carbon emissions in the construction phase, Shau et al. [54] believe that optimizing the energy efficiency of equipment is an essential measure. In the operation phase of a tunnel, energy is mainly consumed for lighting, ventilation, temperature regulation, signaling, emergency systems, and maintenance. Since more than half of energy is consumed for ventilation and lighting [77], multiple studies are dedicated to finding appropriate reduction measures. Several authors proposed the usage of LED lighting systems to boost energy efficiency. Additionally, the illumination requirements hence energy consumption, can be lowered by using surface pavement material with a higher reflectivity or the specific use of sunlight [45,74,78]. Tunnel energy monitoring systems and high voltage distribution to reduce transmission losses have been identified as further promising technologies that increase tunnels' energy efficiency in the operational phase [79].

In general, the share of *renewable energy sources* used in tunneling projects has an significant effect on their sustainability in terms of GHG emissions. A few authors such as Cantisani et al. [74] and Audi et al. [52] touch on this topic by breaking down energy attributed to specific tunnel components or tunnel design variants into renewable and non-renewable parts. As a possible solution to reduce GHG in the construction phase, Shau et al. [54] suggests substituting fossil fuels used by construction equipment and machinery with biodiesel.

Not only is it reasonable to reduce the energy consumption of tunnels but also to use them as a means of *energy production*. Multiple authors present tunnels as heat sources or sinks that can be harnessed by heat pump technology and piping outside the final lining on the perimeter of the shaft walls installed during the construction phase [49,80,81]. Barla et al. [80] obtained power of 53 W per square meter of tunnel lining for heating and 74 W for cooling purposes. Especially in urban areas, this geothermal energy could be used for adjacent buildings to create additional revenue flows in the operation phase of a tunnel project [49] or for frost damage prevention within the tunnel itself [81].

When it comes to *GHG emissions*, the content analysis made it apparent that it is very challenging to compare the results of different LCA studies regarding GHG emissions per meter of tunnel. The difficulty primarily lies in the difference of the chosen system boundaries, tunnel designs, considered life-cycle phases, and used LCA databases. Based on the reviewed literature, we observed GHG emissions ranging from 10.7 t [44] to 113 t [77] CO_2e for one meter of tunnel. However, there is a consensus among authors that the whole life-cycle has to be considered for assessing the GHG footprint of a tunnel and, more importantly, that it needs to be reduced. When only considering the construction phase and the materials' provision, most authors agree that the production and provision of the materials is the most significant contributor to GHG emissions [43,72,82–85]. When considering the whole life-cycle, however, there are diverging views on whether construction and material provision [44,52,82] or the operation of the tunnel [43,77] has the largest footprint of GHG emissions. Many authors suggest using materials with a lower GHG footprint [57,61,67,71,82], but some go further by pointing out that different tunnel design approaches are necessary for sustainable improvement [82]. Optimization of the supply

chain [68,86] and more extensive electrical equipment usage [82] have also been suggested as possible solutions.

The subtopic *fossil fuels* is frequently dealt with by considering the fuel consumption caused by the transport of the materials to the construction site as well as equipment operation during construction and maintenance [43,44,61,72,76,77,83–90]. Only a few authors also considered the fuel consumption caused by general traffic in the operational phase of a tunnel [74,76]. In this context, Faltus et al. [91] showed that tunnels themselves are part of the solution by improving the traffic quality in urban areas hence decreasing the fuel consumption of cars.

The subtopic *transport* partially overlaps with previously discussed topics. First of all, today's logistic chains supplying tunnel construction sites still heavily rely on fossil fuel-powered vehicles. Secondly, some of the measures mentioned earlier, such as the local reuse of excavation material, could significantly reduce the necessary transportation volume in the construction phase of a tunnel. Arıoğlu Akan et al. [86] analyzed the CO_2e emitted from the raw materials of concrete used for tunnel rings. They conclude that besides cement, which is responsible for the most significant share of concrete GHG emissions, the supplier selection, hence transport-related emissions, must not be neglected. Thus, the increase in traffic during the construction phase has also been used as a criterion to assess the overall sustainability of tunnels [92].

4.6. Ground and Water

This section deals with the effects of tunnel projects on the surrounding ground and water resources.

Especially the construction process of tunnels can have a negative effect on the *water quality*. Multiple authors examined the effect of tunnels on the water quality by applying an LCA or a related technique based on the used material or energy [52,85,92]. However, this procedure is only a very rough estimate as it neglects many circumstances of a specific tunnel project. During the construction phase, wastewater originates from the excavation work of the tunnel, the washing and rinsing of different equipment, and the rainwater from paved surfaces [66]. The usage of a water treatment plant was reported to deal with the issue of water quality [66,93].

Closely related to the preceding topic is the topic of *water usage*. Like other construction projects, the construction and operation of tunnels consume significant amounts of water. Again, many authors approached this issue by an LCA or a related technique [57,74] or considered the water usage attributed to specific tunnel components [61].

It is evident that tunneling projects severely affect the *hydrological system* during construction and operation phases. Liu et al. [94], however, showed that the groundwater loss during the construction phase is 4.7 times higher than during the operation phase. Mohan [95] suggested the usage of simulation models to determine the best dewatering procedure. Ground freezing and low-pressure mortar have been suggested to avoid groundwater lowering measures [66]. Radial and curtain grouting were proposed to reduce the groundwater loss during both the construction and operation phase [94].

Some authors considered the *soil quality* by adopting impact factors such as terrestrial ecotoxity in an LCA [44,74]. A more in-depth approach was taken by Barla et al. [80], who investigated the possibility of using metro tunnels for heating or cooling by simulating the effect on the surrounding soil. However, not only do tunnels affect the surrounding, but the surrounding obviously has a substantial impact on the tunnels too. It was shown that the GHG is highly correlated with the properties of the surrounding rock [77,83,90].

The topic of *cultural preservation* is frequently discussed in the reviewed literature. Archaeological discoveries during tunnel construction could cause severe cost and time overruns due to a temporal suspension of the construction work [54,96]. Furthermore, the seismic impact caused by blasting and surface settlements can cause severe damage to historical buildings and cultural heritage. Frandi [96] claims that preventive archaeology carried out by a dedicated working unit proved an effective countermeasure. Using simu-

lation tools [97] and an integrated geomatic monitoring system [98] have been proposed to deal with surface settlements in the design and construction phases, respectively.

Closely related to the preceding topic are *surface deformations and vibrations*, including their impact on existing building structure. Lep et al. [99] measured the seismic impact resulting from blasting, a step frequently used in tunneling. Concerning surface deformations, Li et al. [100] state that especially excavation of accessory structures of metro stations pose a risk of damaging adjacent buildings. According to Khabbaz et al. [101], the horizontal position of a tunnel relative to building piles of high-rise buildings has a critical impact on the risk. The authors showcase the usage of simulations and monitoring systems to quantify the effect associated with the excavation mechanics nd the interaction between tunnel, rock, and building piles Low-subsidence construction techniques were also reported as effective countermeasures [102].

4.7. Health

This section discusses the effect of tunneling on the health of organisms, including humans.

The subtopic *biodiversity* in tunneling is covered by Shau et al. [54], who monitored the impact of tunnel projects on fauna and developed buildings to prevent roadkill of animals at tunnel portals. Makana et al. [50] proposed an assessment procedure for underground infrastructure taking the distance to vegetation into account. Dajelli [62] reports using the excavation materials to restore the biodiversity of abandoned quarries and deposit sites.

Noise was mostly used as a criterion in a multi-criteria evaluation [57,61,92,103]. Moreover, a methodology to assess noise-reducing devices has been proposed [104], and the implementation of absorption materials in tunnels has been studied [105].

The topic of *air quality* is mostly discussed at a superficial level. In most cases, quantitative results occur as a by-product while performing an LCA by considering impact factors such as particulate matter formation, ozone depletion or photochemical oxidant formation [44,57,71,85,92]. Giunta et al. [106] investigated the gas and dust emissions on road construction sites and identified carbon monoxide, nitrogen oxides, and particulate matter as the pollutant released in the greatest quantity. She reported that the topography heavily influences the CO concentration and identified the vicinity of the tunnel portals as hotpots in the operation phase [107]. However, it was also shown that tunnels could positively contribute to the air quality by improving the traffic organization [108]. Wetting the ground, covering trucks, using modern crushing plants [107], and the air-curtains [109] were proposed to reduce the emission of particulate matter in the construction phase. The dust concentration can also be significantly reduced by optimizing the airflow rate [110]. Roadside vegetation was suggested as a mitigation measure during the operation phase [107].

Toxic materials are frequently considered as impact categories such as human toxicity, aquatic, and terrestrial ecotoxicity as a result of performing an LCA or similar technique [44,52,71,74,85,92,111]. A more in-depth analysis was carried out by Praticò and Tramontana [73], who considered the environmental compatibility of the proposed fire-resistant asphalts.

Three authors considered *ionizing radiation* as an impact in their sustainability assessment [44,52,74]. Maestre et al. [112] and Rizo-Maestre et al. [113] performed a more thorough analysis by investigating the radon gas, which emanates from certain rock types and accumulates in closed underground spaces such as tunnels. Because of the danger for humans, they call for compulsory measurements and mechanical or natural ventilation for air renewal and resulting air quality improvement.

A few authors address the issue of *safety*. The stability of the tunnel is a big safety concern during both the construction and operation phase [114,115]. Another serious issue is the fire safety of tunnels [73,116]. On the other hand, tunnels can positively affect safety in the event of natural disaster [40,56]. Chiu et al. [114] examined the topic of stability by systematically analyzing anomalies in the tunnel lining. Mohd Ali and Sanjayan [117] and Dao and Forth [118] showed that geopolymer concrete has properties that make it

suitable as a material for the tunneling lining to increasing the tunnels' stability in the case of fire. Similarly, Praticò and Tramontana [73] obtained promising results for the fire resistance of hot and cold mix asphalt. Legal adjustments were also recognised as a means to increase the fire safety of tunnels [116]. Despite the safety hazards of tunnels, multiple authors point out the positive effects of tunnels on safety [54].

4.8. Social

This topic covers all social aspects of sustainability in tunneling, excluding health-related aspects since they are covered in a separate main topic (cf. Section 4.7).

Although not one publication reported on methods of systematic *knowledge exchange* between the tunneling industry and research institutions on sustainability issues, the mere existence of all scientific publications analyzed is evidence that it does take place.

When it comes to *local stakeholder involvement*, Antonias [68] stresses that from the very beginning abundant communication and collaboration between the client, the project teams and all involved stakeholders (including local authorities, associations, residents, users, etc.) is a critical factor for social sustainability. Thereby, inputs of various stakeholders need to be integrated into the process to develop an infrastructure meeting the community's true needs [68].

Most aspects that authors discuss regarding the subtopic of *human rights and labor conditions* are associated with health issues, e.g., noise and air quality, which have already been covered in the respective category.

The topic of *fair wages and local social return* is only touched on by including labor criteria in methodologies to assess the overall sustainability of tunneling projects [92,119].

The two subtopics *equality* and *peace and justice* were not covered at all in the reviewed publications.

Effects tunnels have on general *mobility* were among the few substantial contributions in this main topic. In this regard Faltus et al. [91] claim that large transport structures such as tunnels can positively impact the traffic quality and the urban ecology of cities by reducing travel times, congestions, time delays, number of stoppings, fuel consumption, and pollutants produced. Tender et al. [93] concur this view by discussing the effects the longest tunnel in Portugal has on mobility. According to their results, the tunnel increases local, regional, national, and international access and significantly contributes to road safety.

Altogether, this section clearly shows that social aspects play only a minor role in publications on sustainability in tunneling. This is a recognition also made by previous authors [14,120] and could be explained by the fact that social scientists participate to a lesser extent in interdisciplinary research projects [19].

4.9. Business and Economy

This topic encompasses sustainable management alignments in tunneling projects, their microeconomic effects, and their larger macroeconomic implications.

The presence of *sustainable leadership* in tunneling plays a crucial role. According to Antonias [68], a strong dedication of project managers to making sustainable design choices in the context of energy, materials, water, etc,. and effectively contributing to the redevelopment of the surrounding environment can significantly boost the project's overall sustainability level.

When it comes to the subtopic of *sustainable business operation*, Hu and Zhang [121] identify the loss of information between different units involved in the construction process as a major threat to the overall sustainability of a project. Optimizing this requires good collaboration within an interdisciplinary team including various experts beyond civil engineers [122].

The largest number of publications in this section is classified for the subtopic *project costs* reflecting a rather traditional view of business sustainability in research today. Some authors such as Kaewunruen et al. [87] claim that the construction phase is the biggest

contributor to the overall life-cycle costs of a tunnel project and must therefore be the focus. Salata et al. [78] shows that for example, the installation of more energy-efficient lighting systems may lead to higher original investments in the design and construction phase but results in overall lower financial life-cycle costs considering the operation phase. To reach economic sustainability on the project level, Engelhardt et al. [123] proposed the Modular-Process-Model as an LCC-based decision support methodology specific for tunneling projects, including a Monte Carlo simulation for risk analyses. Similarly, Davey et al. [124] used numeric risk models in the design phase to estimate construction and operation costs, the construction time, and heavy equipment construction duration. They also show how risk analysis can support assessing whether a single-bored or a twin-bored tunnel is economically more sustainable.

Research results on *economic costs* mainly refer to the fact that tunnel projects are often the more sustainable form of infrastructure from an overall macroeconomic point of view. In this context, Wu et al. [51] believe that MUT can significantly improve urban sustainability because they minimize the costs for repeated excavation and reinstatement of roads, which must no longer be performed for underground utilities maintenance and operation. In order to more accurately assess the economic sustainability of MTUs compared to conventional solutions, Gettinger et al. [49] recommend performing a net present value analysis of up to 50 years. As another specific research field, several publications address the LCC of underground freight transportation (UFT) systems [125–127]. Finding the overall UFT shipping costs higher than transportation by trucks, [128] argue that other benefits could nevertheless justify such systems. This is supported by the opinion that the decision-making process for selecting a tunnel system over a different form of infrastructure should not solely be based on a macroeconomic cost analysis but a broader benefit-value-analysis [126,129]. Last but not least, some research groups attempted to evaluate tunnel project life-cycle costs on a macroeconomic level by the additional consideration of direct and indirect GHG emissions costs on the basis of the EU-ETS [84,130].

The classification results of the main topics are presented in Table 2.

Table 2. Correspondence of the main topics with the reviewed publications.

Topic	Publications
Project Resilience	[40,42,49,50,52–54,56–59,67,74,81,92,103,114]
Materials and Resources	[41,43,44,49,52,54,57–77,81–87,89,90,93,103,111,131–133]
Energy and GHG	[41,43–45,49,52–54,57,59–61,64,66–68,71,72,74,76–90,92,103,110,111,130–134]
Ground and Water	[44,50,52,54,57,61,66,68,74,75,77,80,85,92–102,133,135–137]
Health	[44,45,50,52,54,57,58,61,68,71,73,78,79,85,91–93,99,103–117,119,129,138]
Social	[30,61,68,91–93,103,104,109,119]
Business and Economy	[42,45,49–51,53,54,57,59,61,63,68,78,81,84,87,103,104,119,121–130,138,139]

4.10. Digital Technologies

In this section, we report on any noteworthy usage of digital technology and data science approaches within the reviewed publications. The results give an impression of how digital technologies can support sustainable tunneling in the future.

It is uncontroversial that *Building Information Modeling* (BIM) is the most promising digital technology in the architecture, engineering and construction (AEC) industry [140,141]. BIM is seen as a tool to increase not only the productivity but also the sustainability in the construction sector [142,143]. Nevertheless, only three out of the reviewed publications explicitly report the usage of BIM. According to Hu and Zhang [121] BIM is seen as a technology to increase efficiency and to solve management difficulties alongside the lifetime

of a tunnel, especially for utility tunnels. Chen et al. [144] reported their experience with employing BIM during the design, construction and maintenance of a highway tunnel. BIM-software has also been used to calculate the CO_2 emission embodied in certain parts of the a road tunnel [84].

A high number of authors employed techniques which can be attributed to *data science* in the broadest sense. Linear regression models have been used to predict the construction cost as a function of the tunnel diameter [125,127,128], to predict environmental impact of tunnels [111], and to identify the geological and construction parameters most influential to the GHG emissions caused by tunnel construction [90]. More flexible models have been used to find the best formulation of a grouting mixture [63] or to predict embodied GHG emissions depending on the tunneling and at-grade lengths of rail infrastructure [132]. Despite traditional modelling two publications incorporate techniques that can be attributed to machine learning. Yan et al. [137] modified the AdaBoost algorithm in order to predict the time series of tunnel surface settlements, and Saadallah et al. [136] proposed a procedure based on active learning for modeling surface settlements cause by tunnel boring machines.

A related technique to make predictions about the behaviour of a system is *simulation*. Whereas machine learning derives a model from data, simulations often require a mathematical formulation of underlying physical phenomenon. The finite difference method (FDM) makes the formulation computable by partitioning the space into disjoint regions and discretizing differential operators. FDM simulations have been employed to simulate the water flow in a multi-aquifer systems [95] and to simulate surface settlements [97]. In a similar fashion, the finite element method (FEM) makes simulation problems computational manageable by approximating the solution with basis functions. Authors used FEM to investigate mechanical systems such as the interaction between tunnel, rock and piles [101] or to determine the settlement of adjacent buildings caused by the construction of a metro shaft [100]. FEM was additionally utilized to determine the groundwater flow caused by a tunnel in fractured rock [94] and to investigate the efficiency of the thermal activation of a metro tunnel and its influence on the surrounding ground [80]. Apart from FDM and FEM, simulations with different underlying principles exist. During the design phase of a tunnel project, an agent-based model allows to calculate travel losses covering a distance by existing road compared to using a conceptualized tunnel as well as associated social economic costs [51] or can simulate the impact of recycling waste rock on the total CO_2 emissions and project costs [64]. Monte Carlo simulation has been proposed to model the temporal behaviour of production and consumption of aggregates [69] or to estimate the LCC of tunnels [123]. In order to simulate the CO dispersion while taking the topography and meteorological data into account a Lagrangian particle model has been employed [107,145]. Two publications report to use a software tool to simulate the lighting system of road tunnels [45,74] and in one publication the simulation of temperature within the utility rooms in the cross-passages along a railway tunnel has been demonstrated [59].

A multitude of software tools are available which support researchers during their work, e.g., geographic information system (GIS) software has been reported to be helpful for performing time-consuming sustainability evaluations [50]. Multiple authors reported the usage of embodied carbon calculation tools or databases. Jackson and Brander [134] emphasized the importance to transition from these simple tools to whole-of-life assessment as a measure against burden shifting.

5. Discussion

In this section, we answer the research questions from Section 2.1, report on our lessons learned, and critically discuss caveats of our methodology.

5.1. Answers to Research Questions

RQ1: What are the bibliometric key facts of the scholarly literature on sustainability in tunneling?

The analysis of the relevant papers suggests a growing interest in the academic community for sustainability issues in tunneling. Since 2011, the number of relevant publications per year has more than tripled. This recent increase in publication activity is in line with other publications on sustainability [146,147]. Given the great importance of sustainable development, this is an encouraging development. We predict that this upward trend in the number of publications will continue in the near future. Another indicator for field's infancy can be found considering the number of articles one author contributed to. Only a handful of authors contributed to more than two articles, which we believe to change in the near future.

Europe, Asia, and North America are the most active geographic regions in terms of the number of publications. More than half of the publications can be attributed to Europe, followed by Asia and North America. In Asia, the publication activity is dominated by China. This is in agreement with the fact that 50% of the total length of tunnels under construction worldwide are located in China [8].

Looking at the publication channel, we have seen that journal papers on sustainability in tunneling are more likely to be published in journals focusing on sustainability. In contrast, conference papers are more likely to be published at conferences with an engineering focus. This confirms the interdisciplinary nature of the investigated topic of sustainability in tunneling. However, further analysis has shown that the vast majority of publications originate from research departments with an engineering focus, which suggests that true collaboration between different disciplines is rather the exception than the rule.

RQ2: What are the main research contributions to sustainability in tunneling? In particular, which challenges have been addressed and which solutions have been presented?

We found that research efforts were made primarily with road and railway tunnels. So far, little attention has been paid to utility and mining tunnels. Overall, the authors gave equal consideration to all life-cycle phases except *decommissioning*. Case studies contributing a quantitative model are the most frequently encountered research design. In this context, we found three approaches that have been extensively employed in the reviewed literature: LCAs assess the ecological aspects of tunneling [41,43,44,52,71,72,74,76,77,83–87,89,90,111,131,134]. LCC focuses on the economic issues of tunneling [42,45,51,59,60,87,125–128,130]. And third, the aggregation of various criteria to an overall measure by an MCDM [49,50,53,57,61,92,103,104,119,129,135]. The four most frequently investigated subtopics within the corpus of reviewed publications together with their respective occurrence are: *GHG emissions* (32), *Use of materials and resources* (29), *Project costs* (21), *Energy conservation and efficiency* (21). Three subtopics, on the other hand, have not been discussed in any of the reviewed papers: *Climate adaptation*, *Equality* as well as *Peace and justice*. Figure 8 gives a graphical representation of the topic frequency.

In the case of the most frequently investigated subtopic, many publications presented LCA approaches to investigate and manage the overall *GHG emissions* of tunneling projects using global warming potential (GWP) as the central indicator. We observed values ranging from 10.7 t to 113 t of CO_2e for one meter of tunnel. However, the results of different studies are difficult to compare due to different boundary conditions used, e.g., life-cycle phases considered, requirements tunnels have to meet, geological conditions, and a lack of standardization. There is consensus among the majority of authors, though, that the GHG footprint during the whole life-cycle has to be considered to take effective decisions that reduce the ecological footprint of tunnel projects. Among others, the utilization of alternative materials, the application of specific tunnel designs, supply chain optimization, and the usage of electrical building equipment have been suggested as possible solutions. Many reviewed publications emphasized the importance of reducing the demand for *materials and resources* to improve ecological sustainability in tunneling, which was also

supported by LCA results. However, only very few publications offer specific solutions for improving resource efficiency. Examples of such solutions are using cement types with a higher strength class to reduce the tunnel lining thickness and, therefore, the total volume of concrete needed. When it comes to the reduction of *project costs* in tunneling as part of the optimization of the economic sustainability dimension, a majority of authors agreed that the usage of LCC in combination with risk analysis considering all relevant life-cycle phases is the most effective approach. However, in many cases, macroeconomic impact costs need to be considered in order to holistically assess the economic sustainability of a tunnel project. *Energy efficiency* has been widely discussed in the reviewed literature. Due to different system boundaries in LCA studies, a generally valid statement on the proportion of the energy demand of different life-cycle phases cannot be given. Energy-efficient LED technology or increasing the reflectivity of the pavement is frequently proposed to reduce the energy consumption of lighting systems.
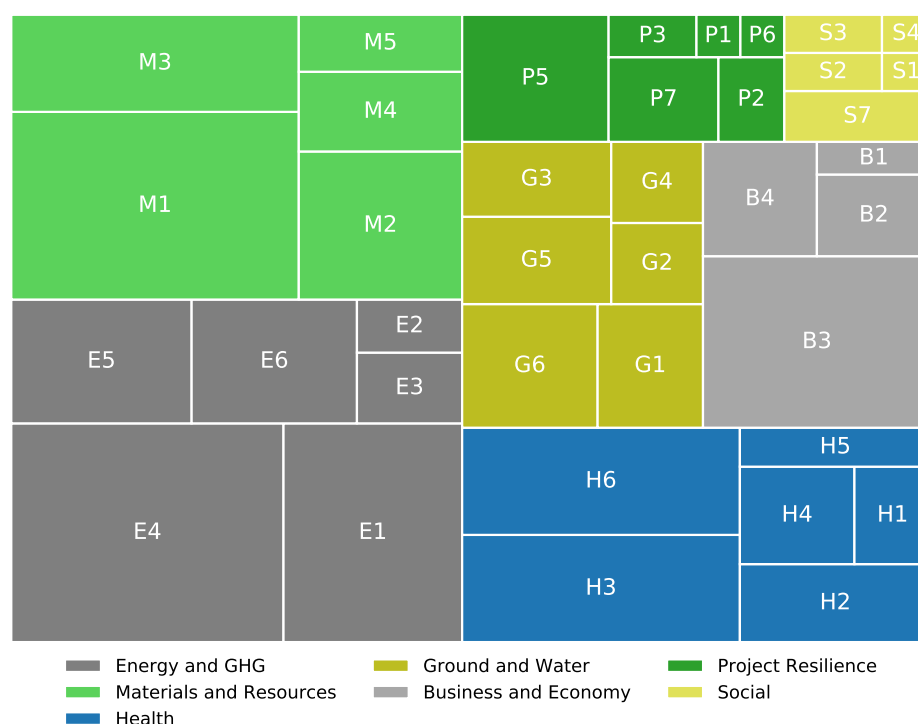

Figure 8. Overview of the main topic and subtopic counts where the squares' areas are proportional to the respective occurrences. For details and an explanation of the abbreviations, see Table A4.

RQ3: To which extent does digitalization foster sustainable solutions in the domain?

Surprisingly, the enormous interest in BIM in the research community is not reflected in the publications on sustainability in tunneling. Undoubtedly, BIM can be a valuable tool in sustainability in tunneling too. The only notable example is one publication [84] in which BIM is used to calculate the GHG embodied in certain tunnel parts. Statistical methods, machine learning, and simulations have been mainly used to analyze the properties of tunnel structures with the objective of later optimization. In summary, there is still an enormous potential for digital technologies to increase the sustainability of tunnels.

5.2. Overall Findings and Resulting Research Gaps

The quantitative results of the content analysis in Figure 8 depict that not all of the three dimensions of sustainability established in the introduction are addressed equally by the publications included in the reviewed corpus. The ecological dimension was covered extensively by contributions to the main topics of *materials and resources*, *energy and*

GHG or *ground and water* and also the economic dimension is comprehensively addressed by contributions to the main topic *business and economy*. The social dimensions is only slightly touched by contributions to the main topic *health*. This result is in line with other publications stating that social aspects only play a minor role in sustainability research in construction [14,120]. One could speculate the lack of interdisciplinary collaboration with social scientists as a reason [19]. Contributions to the main topic *social* consisting of subtopics such as *human rights and labor conditions*, *fair wages and local social return* or *equality* were hardly found. This research gap is probably a result of missing collaboration between social and engineering research disciplines as discovered in the bibliometric analysis and implies that further research should focus on interdisciplinarity to connect the approaches for a more holistic and balanced view on sustainability in tunneling. Similarly, contributions to the cross-dimensional main topic *project resilience*, which comprises subtopics such as *functional flexibility*, *climate adaptation*, *design for disassembly*, or *service life extension*, were also underrepresented. The only exception to this was the subtopic *spatial consumption* which can be considered rather native to the domain of tunneling. In combination with the finding that the reviewed publications hardly covered the life-cycle phase of decommissioning, another research gap can be identified. To achieve cross-dimensional sustainability, more research is required on how tunnel structures can serve multi-functional purposes, ways they can further be used after their original lifetime and how they can best be decommissioned to approach true circularity.

Many authors of the reviewed publications took a relatively high-level approach, merely pointing out adverse effects on ecological, economic, and partly social sustainability caused by tunneling projects without giving clear recommendations to reduce these effects. We believe it will be worth having a more comprehensive look at these aspects and investigating the dependencies from different sustainability dimensions. In Europe, this process will be driven by the EU Taxonomy regulation [55], which will require large construction companies to assess their infrastructure projects, such as tunnel projects, to determine whether they are environmentally sustainable using a standardized assessment catalog. This information must be disclosed in the annual non-financial report of a company starting from the 2021 financial year. Moreover, in the future, borrowing costs for the financing of tunnel projects will depend on whether or not a project can be classified as sustainable based on standardized evaluation criteria concerning the achievement of the six ecological sustainability goals of "climate change mitigation", "climate change adaptation", "sustainable use and protection of water and marine resources", "transition to a circular economy", "pollution prevention and control", "protection and restoration of biodiversity and ecosystems" while not interfering with each other [55,148]. Therefore, it can be anticipated that more ambitious and disruptive changes to the tunnel design, construction, material provision and decommissioning processes, as well as digital assessment will be necessary to improve tunneling projects' sustainability.

5.3. Threats to Validity

We want to briefly touch upon issues that might have a negative impact on the validity of our results and conclusions. Section 1 illustrated the broadness of the term "sustainability". Instead of this term, some publications might use a more specific term. E.g., a publication on work safety during tunnel construction is undoubtedly related to sustainability even though the authors might not use this term in their paper. A much more complicated search query would be necessary to capture all those publications. On the other hand, there is a plethora of publications dealing with sustainability issues in a broader context than tunneling. E.g., a publication on GHG emissions attributed to cement is obviously related to sustainability of tunneling even though the term "tunneling" is never used. The chosen query represents a trade-off between being general enough not to exclude relevant publications and specific enough to yield an amount of publications feasible for detailed screening. Much research was conducted in the last decade on the hazardous elements that excavation material may contain [149,150] and how mitigation strategies

could be implemented [151] to sustainably manage excavated soil [152]. The researchers themselves did not assign these topics to the interdisciplinary research tunneling and sustainability. Therefore we did not find these and other important issues during the content analysis, following the developed systematic review methodology. It is probable that with the increased awareness of sustainability, researchers will categorize their work to reflect the sustainability aspects of their research. This will result in a higher incidence of this topic in data-driven literature review processes. Another caveat is that we used only one data source, which was justified in Section 2.2. For example, Martín-Martín et al. [153] observed the highest coverage with Google Scholar, but the authors concede that the choice for an abstract database depends on other factors as the quality of metadata and availability of bulk retrieval options. We believe that using a curated database, which indexes only peer-reviewed publications and offers the availability of structured metadata, outweighs the higher coverage of other alternatives. Another challenge arises from the different backgrounds of the reviewers. For this reason, we adopted a methodology that measures the agreement among reviewers while determining the set of relevant publications. At the content analysis, level we ensured a coherent understanding among the reviewers by holding regular workshops.

6. Conclusions

We have argued in the introduction that sustainability in general and climate change, in particular, is one of the biggest challenges we are facing today. This article tried to support this increasingly important topic by reviewing the current state of sustainability in the specific field of tunneling. For this purpose, we conducted a bibliometric and content analysis of the relevant literature by following the PRISM guidelines. The results of these analyses gave detailed insights into the current research being conducted. A steadily increasing number of publications on sustainability in tunneling matches the growing interest in sustainability topics. Furthermore, we discovered that the general interdisciplinary nature of sustainability is not well reflected by the group of authors, who mainly have a strong engineering background and focus. In the content analysis, we extracted the essence of the selected publications by reviewing challenges the authors presented, and which solutions could be applied to sustainability in tunneling. The quantitative results were obtained by categorizing the publications into a number of different topics and subtopics. Based on this categorization, there is evidence that the broad spectrum of sustainability is not well represented in the field of tunneling. Current research concentrates more on the ecological and economical dimension of sustainability, while social topics are highly underrepresented. Quite surprisingly, results show that digital technologies were only barely utilized for solving sustainability issues in tunneling today. Our findings suggest that more interdisciplinary collaborations are needed to foster research. Future research work in sustainability in tunneling also needs to focus on social aspects such as fair wages, local stakeholder involvement, or knowledge exchange. We have seen remarkable achievements of the scientific community with an upward trend in research activity related to sustainable tunneling. However, many of the reviewed papers focus on assessing the status quo, and presenting solutions as incremental improvements. Significant efforts to implement disruptive innovations are needed to solve the major challenges we are facing today. This requires that the industry and contracting bodies embrace these achievements and promote the use of innovations on site. In our future work, we will have a closer look at some of the identified topics and gaps through the lens of the environmental, social, and economic aspects of sustainability.

Author Contributions: Conceptualization, M.H., M.W. and L.W.; writing—original draft preparation, M.H., M.W. and L.W.; writing—review and editing, A.M.-H.; supervision, A.M.-H., H.B.; funding acquisition, A.M.-H. All authors have read and agreed to the published version of the manuscript.

Appendix A

The original version of the manuscript had the left column of all tables in the appendix top aligned. We think that vertically centering makes the tables harder to read. Could you please top align the left columns again (in all tables in the appendix)?

Table A1. Research methode facet, adapted from [28].

Value	Description
Opinion	
Own experience	Publications which predominately reference the author's own experience without having any or only little scientific documentation [154]. An example is an author's description of his or her own professional experience on the importance of sustainability in tunneling projects.
Survey	Studies that primarily collect data by using questionnaires or structured interviews on numerous respondents. In general, data is either gathered and examined at a single point of time to detect patterns of association (cross-sectional design) or over a period of time to map change within these patterns (longitudinal design) [155,156]. An example is to interview professionals on the importance of sustainability in tunneling projects.
Empirical	
Lab experiment	These studies observe the relationship of variables and resulting phenomena in a controlled setting in the laboratory [155,157]. An example is to measure the physical properties of concrete containing aggregates from excavation material in a laboratory.
Field experiment	These studies observe the relationship of variables and resulting phenomena in a controlled setting in the field [155,157]. Examples are to measure the fuel consumption of heavy equipment under a specific test scenario in the tunnel. Another example is to take geological samples during the tunnel construction and analyze the samples in the laboratory.
Case study	Publications that present an in-depth inquiry into phenomena in a real-world setting of one or several defined cases which correspond to specific persons, organisations, projects, etc. [155,156]. It is important that the case study plays a principal role during the investigation and it does not merely serve as a means of evaluation. An example is to measure the fuel consumption of heavy equipment for the construction work in specific real-life tunneling projects. Another example is to derive an LCA model for a specific real-world tunnel project based on real-life or tabulated data.
Archival	
Archival research	Research generating new facts or findings from collecting and analyzing preexisting unstructured materials such as historical documents, existing statistics, contemporary records or other textual, visual and audio representations [156,158]. An example is to present the evolution of average costs per km tunnel in projects within a country over the last 30 years based on the analysis of archived project documents.
Secondary research	Studies that primarily are not based on new facts or findings but digest, classify, or simplify data from previous publications for the purpose of research synthesis [159]. Examples are systematic literature reviews or mapping studies on energy saving practices in tunnel construction.
Analytic	
Logical reasoning and modelling	Studies that predominately use simulations or models to determine or predict phenomena of interest by simplification of real-world settings [157,160]. This frequently involves a case study where the approach is evaluated. An example of this approach is to simulate the evolution of smoke in a tunnel in case of fire to determine its safety. Another example is to derive a novel LCA model based on analytic considerations.

Table A2. Contribution type facet, adapted from [29].

Value	Description
Report	Interesting observations, lessons-learned, rules of thumb but not sufficiently general or systematic to rise to the level of another contribution type.
Procedure or technique	New or better way to perform a task, such as design, logistics, construction, maintenance, measurement, analysis, evaluation, selection from alternatives. Includes technical as well as management methods.
Qualitative model	A qualitative statement about a specific object, process or system.
Quantitative model	A numeric statement about a specific object, process or system such as an empirical predictive model based on observed data.
Notation or standard	Formal language to support a technique or model. New technical or organisational standard of a national/international body or association.

Table A3. Topic facet, adapted from [30].

Value		Description
Project Resilience		
P1	Functional flexibility	The ability of the entire tunnel construction to undergo functional adaptations in the future.
P2	Multifunctionality	Practical combination of multiple functions within the tunnel.
P3	Visual and experiential sustainability	The tunnel should communicate a level of sustainability from an aesthetic and experiential perspective and call attention to sustainable solutions. Consider local conditions in tunnel design and aesthetics.
P4	Climate adaptation	Measures and proactive strategies to mitigate and adapt to potential negative consequences of climate change.
P5	Spatial consumption	Allow maximum space for future possibilities of above and below ground use.
P6	Design for disassembly	Design in such a way that elements can easily be disassembled for partial or complete re-use, storage or other forms of use at end of life-cycle.
P7	Service life extension	Take measures to proactively extend the service life of tunnel components.
Materials and Resources		
M1	Use of materials and resources	Minimize the amount of materials and resources used.
M2	Environmental impact of materials	Selection of (construction and supporting) materials with consideration for minimal impact on the environment or planet.
M3	Excavation material	Sustainable reuse of excavation material.
M4	Recycled materials	Maximum re-use of components and use of recycled materials.
M5	Waste	Minimize (construction) waste and impact thereof on environment.
Energy and GHG		
E1	Energy conservation and efficiency	Minimize energy usage in general while maximizing energy efficiency.
E2	Renewable energy sources	Maximize the share of renewable external as well as internal energy sources within the energy mix.

Table A3. *Cont.*

	Value	Description
E3	Energy production	Additional use of the tunnel infrastructure for generating and supplying renewable energy to internal or external consumers.
E4	GHG emissions	Minimize CO_2 and other GHG emissions.
E5	Fossil fuels	Minimize use of fossil fuels.
E6	Transport	Limit negative impacts of project-related transportation.
Ground and Water		
G1	Water quality	Prevent pollution and minimize impact on groundwater and surface water quality.
G2	Water usage	Minimize use of (drinking) water.
G3	Hydrological system	Maintain regular functioning of the (ground) water system and, if necessary, take mitigating measures.
G4	Soil quality	Prevent negative impact on soil quality.
G5	Cultural preservation	Preserve and protect any cultural value or archaeological heritage present in the land.
G6	Surface deformations and vibrations	Minimize surface deformations and ground vibrations as well as its effects on structure above the ground.
Health		
H1	Biodiversity	Conservation of biodiversity and ecological connectivity, and compensation of potential negative impact.
H2	Noise	Minimize noise pollution in the area surrounding the tunnel as well as on the tunnel construction supply routes.
H3	Air quality	Minimize emissions of air pollutants (e.g., smog, NO_x).
H4	Toxic materials	Minimize harmful emissions from toxic materials (e.g., Volatile Organic Compounds, VOC's) and resulting health hazards.
H5	Ionizing radiation	Minimize impact of harmful ionizing radiation and resulting health hazards.
H6	Safety	Implement all necessary safety and health measures to avoid accidents. Install security facilities to maximize tunnel safety during use phase.
Social		
S1	Knowledge exchange	Exchange of information and lessons learned (relating to sustainability practices) with educational and research institutes.
S2	Local stakeholder involvement	Create public support for the project and activate local expertise among future users, local residents and other stakeholders.
S3	Human rights and labor conditions	Comply with international labor standards, respect human rights, pursue fair trade and enforce an anti-corruption policy. (as per the UN Global Compact)
S4	Fair wages and local social return	Pay fair wages to workers and employees. Positive contribution to employment in the region and promote employment of people with poor job prospects.
S5	Equality	Enforce gender, social, economical, political, racial, ethical, religious and legal equality in tunneling projects.
S6	Peace and Justice	Exploit tunneling projects to interconnect countries and ensure peace. Comply with all national as well as international laws as well as regulations and prevent corruption.

Table A4. Topic facet, adapted from [30].

Value		Description
S7	Mobility	Increase the access to areas and foster the regional cohesion. Decrease traffic congestion.
Business and Economy		
B1	Sustainable leadership	Personal managerial long-term commitment to the project's sustainability goals, activating internal teams as well as the supply chain as a whole.
B2	Sustainable business operations	A culture of sustainable business practices. During construction but also during the rest of the tunnel's life-cycle.
B3	Project costs	Minimize direct costs and optimize value of the tunnel project.
B4	Economic costs	Optimize economic value by minimizing indirect costs of the tunnel project throughout the entire life-cycle with consideration of all stakeholders.

Table A5. Life-cycle phase facet [161].

Value	Description
Design	Process of deciding the form and construction of the building.
Materials	Selection, production and use of materials for the building, construction process and maintenance.
Construction	Phase from the beginning of the construction site, until the handover to the owner. Includes transportation of material to the construction site.
Operation	Concepts and processes maintaining and repairing the building during the service of the building.
Decommissioning	Demolition and recycling after reaching the end of service life.

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