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Sustainability in Computing Education: A Systematic Literature Review

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Research shows that the global society as organized today, with our current technological and economic system, is impossible to sustain. We are living in an era in which human activities in highly industrialized countries are responsible for overshooting several planetary boundaries, with poorer communities contributing the least to the problems but being impacted the most. At the same time, technical and economic gains fail to provide society at large with equal opportunities and improved quality of life. This article describes approaches taken in computing education to address the issue of sustainability. It presents results of a

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systematic review of the literature on sustainability in computing education. From a set of 572 publications extracted from six large digital libraries plus snowballing, we distilled and analyzed 89 relevant primary studies. Using an inductive and deductive thematic analysis, we study (i) conceptions of sustainability, computing, and education; (ii) implementations of sustainability in computing education; and (iii) research on sustainability in computing education. We present a framework capturing learning objectives and outcomes as well as pedagogical methods for sustainability in computing education. These results can be mapped to existing standards and curricula in future work. We find that only a few of the articles engage with the challenges as calling for drastic systemic change, along with radically new understandings of computing and education. We suggest that future work should connect to the substantial body of critical theory, such as feminist theories of science and technology. Existing research on sustainability in computing education may be considered rather immature, as the majority of articles are experience reports with limited empirical research.

CCS Concepts: • **Social and professional topics → Computing education;**

Additional Key Words and Phrases: Sustainability, computing education, engineering education, higher education, equality

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1 INTRODUCTION

The overall integrity of the biosphere on Earth is under serious threat. There are several tipping points for the Earth's climate system that we have already exceeded [170]. The accelerating socioeconomic trends of the past century [232] have put us on a path toward exceeding seven of eight globally defined safe and just Earth system boundaries that would provide safe living conditions for all humanity within the boundaries of the living systems on Earth [219].

According to the assessment of the **Intergovernmental Panel on Climate Change (IPCC)** from 2022, human-caused climate change has led to a range of strongly adverse effects. These effects include disproportionate warming of the Arctic regions, acidified oceans that threaten coral reefs and those who depend on them worldwide, glacial retreat that threatens freshwater supplies for billions of people, sea-level rise that threatens coastal communities worldwide, and extreme weather events that primarily affect poorer nations [170]. The report describes that many of the impacts of global warming are now already "irreversible," placing more than 40% of the world's population at high risk of the effects of climate change. Access to food, energy, and water is globally predicated on unsustainable practices and will be even harder to sustain with the unfolding climate crisis, and must change fundamentally in the coming years to support the human population (c.f. [160]). In parallel to these massive challenges to the biosphere that supports human life, social issues are just as pressing with more violent conflicts and democracy in global decline [165]. Addressing our current unsustainable situation thus requires "rapid, far-reaching and unprecedented changes in all aspects of society" [169].

Information Technology (IT) and education are prominently but ambiguously positioned on these issues. On the one hand, computing is seen as a necessary and liberating instrument of society, providing a low-footprint alternative to travel, cultural access, and trade, but at the same time even aggravating social and ecological issues. For instance, computing is aspiring but mostly failing to enable a rapid decoupling of the economy from carbon footprints through e-goods that reduce carbon emissions [132]. In addition, computing is aspiring to strengthen democracies [148] while simultaneously being criticized for threatening the social fabric of societies [196, 257]. Likewise, education is seen as having a great potential for change toward sustainability [246]. At the same time, universities and university education are set up or governed, to uphold and promote the current societal order by limiting orientations to the future [101].

With the present work, we explore the potential of IT for sustainability as it is conveyed in education and education research. More specifically, the aim has been to systematically review the existing work on sustainability in "computing education," a field of research that has grown and developed into a research discipline in the past years. We seek to collect and synthesize existing work and provide threads for which to further advance the work on sustainability in computing education. Another goal has also been to bring together relevant work from different research communities engaging with the topics of sustainability, computing, and education, and to consider various forums for publication. We answer the following research questions:

RQ 1: How does current research conceptualize sustainability?
RQ 2: How is sustainability in computing education being implemented?
RQ 3: What type of research design has been conducted on sustainability in computing education?

The analysis is developed as follows. Section 2 provides various perspectives on the role of IT in sustainability and an overview of sustainability as an emerging field of research in computing. It also includes different perspectives on the role of education for change and previous research reviewing sustainability in computing education. Thereafter, in Section 3, we present the research method for this systematic review. Sections 4 through 6 follow, each of them presenting results to one research question, synthesizing takeaway lessons at the end of the section. In Section 7, we discuss the findings of our results, especially providing themes or questions for future research and education development, as well as the threats to the validity of our study. Section 8 concludes this systematic review.

2 BACKGROUND AND RELATED WORK

In the following, we provide a brief overview of the evolution of research on sustainability in computing generally, and in computing education specifically. We refrain from providing nuanced conceptualizations as they are part of the results of our analysis.

The commonly used Brundtland sustainability definition encompasses two aspects: *distributive intragenerational justice* ("the essential needs of the world's poor, to which overriding priority must be given") [251, 37], but also *intergenerational justice*, for which the preservation of the biosphere is a prerequisite. As the trends towards climate disasters and social and ecological breakdowns have been known and communicated through science for several decades to little effect, analyses of driving structures and mindsets seem to call for new responses [236]. The current economic operating system of our global society [142], "narrow techno-economic mindsets and ideologies of control" [236], as well as increasing polarization [242] have been proposed as drivers of unsustainable practices.

2.1 Sustainability and Computing

Future trends for society and meaningful responses through computing depend on how we interpret our current predicaments. For instance, if we interpret our current predicaments as conditioned on economic growth coupled with increasing ecological footprints [161, 250], then economic growth will directly lead to ecological collapse irrespective of whether it is mediated through digital technologies, and any efficiency improvements would simply lead to increasing economic activity. Technology would therefore have to target opportunities for the reduction of the sum total of economic activities in human societies. If we see increasing inequalities as inherent in our current political economies [115] and a driver of instability in societies [244], then any tech that is funded by large economic interests and that promotes such inequalities [190, 196] will contribute to increased instability. If we see the path dependencies, inherent social complexity, and increasing marginal costs associated with socio-technical systems as a driver for our current predicaments [238], then only tech that contributes to a deliberate reduction of social complexity could offer a chance to reduce the risk of future societal collapse. Finally, if we believe that common but implicit narratives and myths of rational and objective problem solving that underpin computing are inherently harmful [108], then computing efforts that are not explicitly reorienting themselves risk causing more harm than good.

The notion of sustainability in relation to computing has evolved from being concerned with the longevity of software in the 1970s, to the relationship between computing and business or organizational contexts in which it is developed and deployed, to being concerned with the wider, societal implications of computing in the late 2000s [110]. Those wider implications of computing began as concerns about the footprint of computing in use (primarily as energy efficiency), in a paradigm that has often been called *green IT* [193].

Another approach is to use computing to address energy and resource conservation in all of the other domains of our societies—a paradigm known as "green by IT" [162]. Digital transformations are assumed to free the economy from the shackles of the physical world and make economic growth fair and decoupled from ecological footprints (c.f. [224]). However, not only does the ongoing digitalization come with its own growing environmental footprint, but its environmental benefits in other sectors are often overstated, while its detrimental indirect consequences, in particular through rebound effects, are often overseen [128]. Rebound effects, also known as Jevon's paradox, mean that any efficiency gains are always overcompensated by increased use in our current economic system [161, 250].

While there are examples of successful and dematerializing digital substitutions such as partly virtualized conferences [131], the substitution of e-goods for physical goods (e.g., e-books instead of physical books) has not proven to yield an overall reduction of energy consumption [132]. In contrast, Court and Sorrell [132] question such purported savings: "[W]e cannot conclude that e-materialization has delivered significant energy savings to date or is likely to do so in the future," as they depend on the embedding of computing in social and narrative structures as well as on values that undermine attempts at sustainability in computing [178].

Sustainability in computing is not limited to energy and material efficiency or the reduction of greenhouse gases. The field of *computational sustainability* [157], for example, deploys computing to address various environmental issues, such as the fine-granular assessment of ecosystems. Nor is it limited to the environmental dimension. One example is the role of IT for strengthening or undermining democracy. Digital connectivity is seen as key to increased participation in 21st-century democracies through e-voting and citizen participation [148]. Another is the role that social media platforms played in facilitating protests against authoritarian regimes throughout the Arab spring in 2011 [231]. However, the primary mechanisms for online connectivity are mediated through largely unregulated companies that promote toxic content and socially divisive business models that undermine the foundations for democracy [257]. These fundamental tensions illustrate conflicting views about the nature and future of IT and indicate potential tensions about what it would mean for computing education to contribute to a societal transformation toward sustainable and just societies. At the moment, digitalization has even been described as directly and negatively affecting democracy, equity, and planetary stability, with radical changes needed for digital industries [138].

The Karlskrona Manifesto for Sustainability Design [109, 110] aimed to provide a focal point for establishing a common ground for the computing community to engage with sustainability by advocating a set of fundamental principles and commitments that underpin sustainability design. The principles stress the importance of recognizing that sustainability is an explicit consideration, even if the primary focus of the system under design is not sustainability. Building on the work of Penzenstadler [204], it also advocates that sustainability should be viewed as a construct across five dimensions—environmental, economic, individual, social, and technical—and considers the potential long-term effects of systems. Pham et al. [210] proposed alternative dimensions including purpose, design aesthetics, and integrative and legal aspects. With the exception of the legal aspects, it is an open question whether these are dimensions equivalent to the ones listed previously.

Individual sustainability connects to education, as it is about reaching personal sustainability goals including sustainability skills and competencies transforming the role of individuals in their current life. As stated in the work of Pappas and Pappas [202], "Sustainable individuals are characterized by creating harmony, interconnection, and relatively high levels of self-awareness in their values, thoughts, behaviors, and actions as well as cultivating continued individual growth in their physical, emotional, social, philosophical, and intellectual abilities." For instance, developing individual sustainability with engineering students [106] aims at change as a combination of harmony, awareness, and behavior to engage with sustainability principles [229] and create a sustainable personality [202]. Thereby, emotional and intellectual sustainability are key factors supporting the abilities of individuals across a wide variety of disciplines [247]. While a focus on individual sustainability was until recently less common, this started to change by analyzing how the other sustainability dimensions can create a positive effect on individual and group well-being [206], and also inversely how human factors impact, for example, software sustainability [167].

There are endless possibilities to engage with sustainability in computing, and the field of research on sustainability and computing is growing and has matured. It covers a wide range of green IT aspects but also IT-supported sustainability initiatives [182]. There have been methodological efforts to understand and assess the economy- and society-wide indirect effects of computing, which are broad and subtle, and can be both beneficial and detrimental to sustainability [111, 126]. Terms used to refer to the work, besides *green IT* and *green by IT*, are *digital sustainability* [181], *sustainable computing*, or *ICT for Sustainability* (ICT4S) [163].

2.2 Education for Sustainability and Computing Education

Reflecting the growth of computing and sustainability into an established field of research, there have been efforts to also conduct research on sustainability in computing education. Existing publications, however, are scattered across numerous disciplines and venues. Some work has been done from within the field of *computing and sustainability*. By contrast, *computing education*, which is its own research field [230], paid so far relatively little attention to sustainability [213]. *Engineering education* is another separate field of research, in which sustainability is being discussed, sometimes also including perspectives on computing. Another field within which to find relevant research is *STEM (science, technology, engineering, and mathematics) education*, which includes computing and engineering education, yet is a research community that is distinct from the computing and engineering education community.

Another relevant field of research in which computing and computing education could possibly be discussed and that computing education could build on is the field of **Education for Sustainable Development (ESD)**, which provides conceptions of education and its role for sustainability. Different analyses are made in this field as to what should change in education. The United Nations sees the need for substantial changes to curricula and learning objectives, requiring a "profound transformation of how we think and act" [247, p. 7], and a reorientation toward key sustainability competencies such as normative thinking, anticipatory thinking, and systems thinking in a wider sense (c.f. [247, 252]). Other work suggests making education less focused on training and detailed learning objectives and curricula [91, 164]. An alternative role of education could be to become a democratic political space in which alternative futures are imagined [101, 198].

Works within ESD are critically discussed in a research field called *critical ESD* [156]. Recently, for example, Stein et al. [234] proposed a shift from "education for sustainable development" to "education for the end of the world as we know it." Another example is from Holfelder [164], who criticizes the focus on defining competencies in ESD as limiting possibilities for alternative futures. As expressed by UNESCO [247], developing education for sustainability is thus far more complex than integrating sustainability into existing curricula. The ways in which existing studies on sustainability in computing education build on education research generally, and ESD specifically, is part of this review.

Within engineering education, which only sometimes explicitly discusses computing education, calls have been made for doubling down on traditional engineering subject matter and problem-solving methods such as optimal resource use, green IT, and educating future engineers on the minimization of harm from engineering (c.f. [191, 193]). At the same time, others have called for engineering education to be more challenge based and transdisciplinary (c.f. [103, 192]).

2.3 Other Reviews on Sustainability in Computing Education

Only a few surveys [102, 116, 152, 183, 213, 221, 226, 240] have so far attempted to map the existing proposals of education for sustainability in computing, and their scopes have been rather limited. Fisher et al. [152] provide some examples of the integration of environmental and societal sustainability into **Computer Science (CS)** curricula at eight different universities, and Boyle [116] describes a theoretical analysis of what sustainability education for engineering studies should consist of, given third-party literature. Neither, however, reviews the current state of practice in computing education in general. Three studies provide perspectives specific to national contexts: Arefin et al. [102] provide an Australian perspective and propose guiding questions for program design, Leifler and Dahlin [183] present Swedish data on engineering degree program directors and their motivations for and challenges in integrating sustainability, and Sánchez-Carraced et al. [226] present a Spanish survey and map of sustainability integration, including in computing. Rodriguez-Andara et al. [221] present a roadmap of activities for integrating sustainability in engineering education, based on a sustainability literacy survey, a literature review, and an expert panel on pathways for integrating sustainability. Pollock et al. [213] reviewed the current state of research addressing the issue of climate change in computing education by searching the ACM and IEEE databases, conducted expert interviews, and collected data from the computing education community during a conference. Finally, Thürer et al. [240] outlined a research agenda for studying sustainability integration in engineering in general, centering on four main themes: (i) implemented practice; (ii) values and norms among teachers (often seen as "subjects"), and students (often seen as "objects"); (iii) the roles of other stakeholders; and (iv) the assessments of outcomes or results.

In our study, we address all of those four themes. In relation to the preceding reviews, our contribution is the first comprehensive study that addresses the conceptions, implementations, and research designs that have been used in prior studies on sustainability integration in computing, with a broad definition of sustainability, learning objectives, and pedagogical methods that include values and norms, the roles of stakeholders, and the assessment of outcomes.

3 RESEARCH METHOD

This section details the methods we applied and the process we followed in this systematic review of research on sustainability in computing education. The general process is summarized in

Table 1. Keywords Used for the Database Search

Theme	Proposed keywords
Education	Education, Teaching, Learning
Computing discipline	Computer science, Software Engineering, Computing
Sustainability	Sustainable, Sustainability, Green, Climate Change, Global warming

Figure 1. The process included identifying relevant studies to analyze and agreeing on a way of analyzing them. Figure 2 shows when in time the identified relevant studies were published. It suggests that the number of papers on sustainability in computing education has increased over the years, with a majority of search results being less than 10 years old. The result of our analysis process is a description of the various conceptions, implementations, and research conducted, which we identified in the collection of papers. More details on the process and the individual studies analyzed can be found in an online replication package at https://github.com/S2-group/sustainab-in-comp-edu-replication-package.

A result of our process of identifying relevant articles and agreeing on a way of analyzing them are refined research questions, as follows:

RQ 1: How does current research conceptualize sustainability?
SRQ 1.1: How is sustainability being perceived?
SRQ 1.2: How is the relationship between computing and sustainability understood?
SRQ 1.3: How is education for sustainability being understood in the context of computing education?
RQ 2: How is sustainability in computing education being implemented?
SRQ 2.1: What content is sustainability education about—that is, what are the learning objectives and the topics being taught?
SRQ 2.2: How is sustainability education being organized in terms of teaching practices and modules or curricula?
SRQ 2.3: What are the effects of teaching sustainability?
RQ 3: What type of research design has been conducted on sustainability in computing education?
SRQ 3.1: What epistemological stance has been adopted as part of the research design?
SRQ 3.2: What research methods have been adopted as part of the research design?
SRQ 3.3: What threats to validity are reported?

We use the term *computing* as proposed in 2021 by the ACM referring to an overarching discipline consisting of the following subdisciplines (ACM 2021): CS, computer engineering, software engineering, information systems, and IT. In this study, we follow the general guidelines for **Systematic Literature Reviews (SLRs)** by Kitchenham and Charters [175], and the protocol for snowballing as presented by Wohlin [253].

3.1 Defining Search Strategies and Selecting Research Sources

Table 1 presents keywords that were identified during a process of testing different search queries and analyzing the results. Those keywords were used to define the following search query, which was applied to search different databases. Different truncation (wild card) symbols were used in the searches to capture different word forms:

("Teach" OR "Educat*") AND ("Computer Science" OR "Software Engineering" OR "Computing") AND ("Sustainable" OR "Sustainability" OR "Green" OR "Climate change" OR "Global warming").*

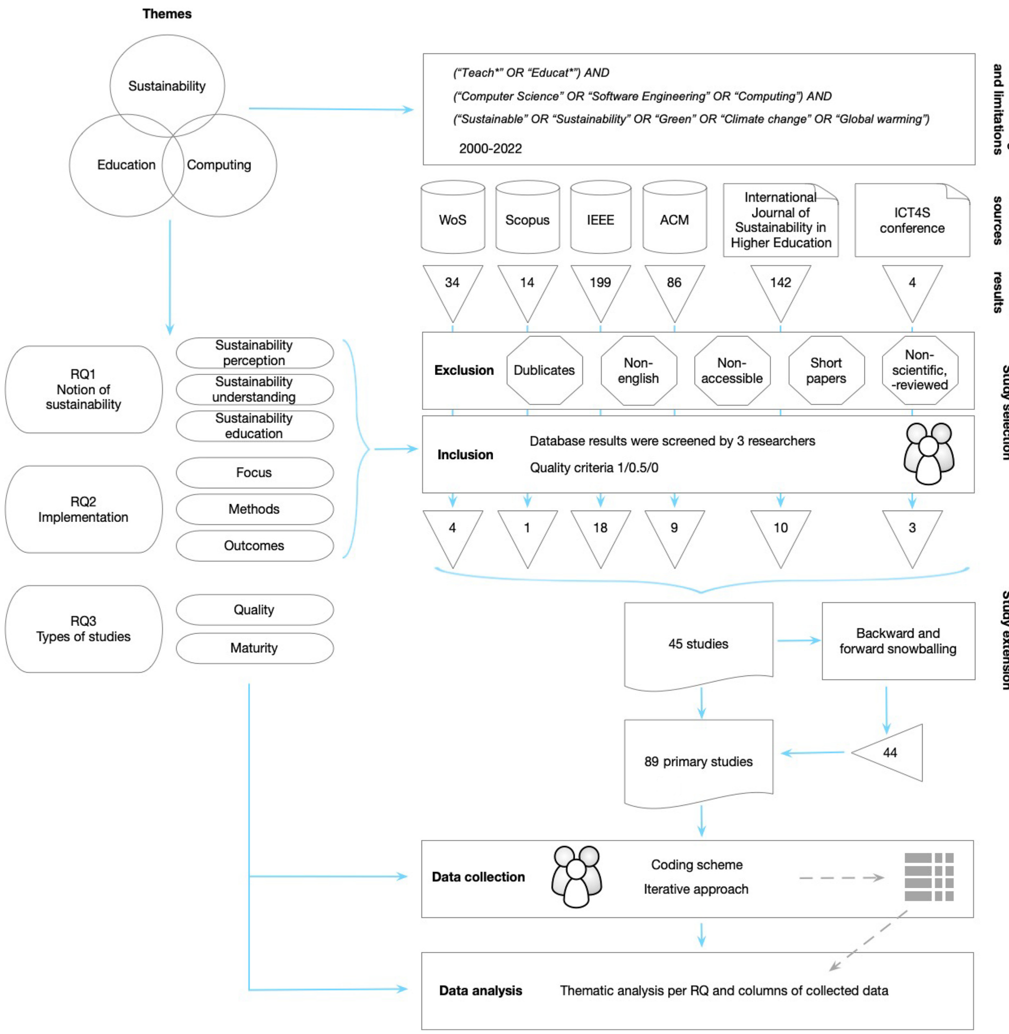

Fig. 1. The literature review process followed in this study.

In November 2020, we identified relevant papers by searching through the following databases: ACM, IEEE, **Web of Science (WoS)**, and Scopus. We also considered the Emerald database, but due to constraints in the search tool, we only considered the *Journal of Sustainability in Higher Education*. We also searched the Springer database. However, with limited options to specify the search, the number of results was too large. In all cases, we searched the fields title, abstract, and author keywords for our specified keywords. To mitigate the limitations of the search, we performed one round of backward and forward snowballing [253] (see Section 3.3) to identify further relevant papers. We repeated the scan of literature in March 2022 to identify additional papers published since the first search, thereby also conducting the snowballing process on additionally identified articles. Altogether, this step resulted in six new primary studies. We also decided to include relevant papers from the Computing Sustainability Education (ICT4SEdu) workshop of the ICT4S conference as the topics relevant to this study have been covered there. We covered all of the existing proceedings from the workshop until our date of search in 2022, hence years 2018,

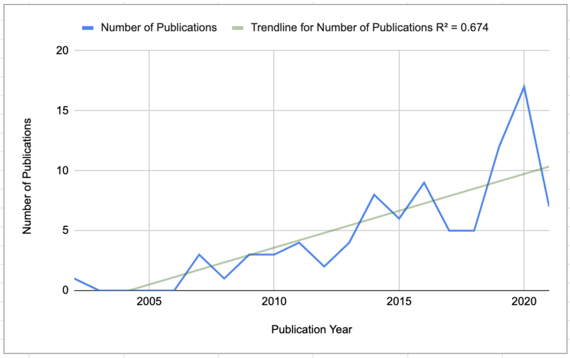

Fig. 2. The selected publications per year.

Table 2. Digital Databases, Limitations, Retrieved Publications, and Selected Primary Studies

Database	Search string	Other limitations	Results	Incl.
ACM	[[Abstract: teach*] OR [Abstract: educat*]] AND [[Abstract: "computer science"] OR [Abstract: "software engineering"] OR [Abstract: "computing"]] AND [[Abstract: "sustainable"] OR [Abstract: "sustainability"] OR [Abstract: "green"] OR [Abstract: "climate change"] OR [Abstract: "global warming"]]	AND [Publication Date: (01/01/2000 TO 27/3/2022)]	86	9
IEEE	(("Abstract":teach* OR "Abstract":educat*) AND ("Abstract":"computer science" OR "Abstract":"software engineering" OR "Abstract":computing) AND ("Abstract":sustainable OR "Abstract":sustainability OR "Abstract":green OR "Abstract":"climate change" OR "Abstract":"global warming"))	Timespan: 2000–March 2022	199	18
WoS	TITLE: ((teach* OR educat*) AND (computer science OR software engineering OR 'computing') AND (sustainable OR sustainability OR green OR climate change OR global warming))	Timespan: 2000–March 2022	34	4
Scopus	TITLE-ABS-KEY-AUTH ((teach* OR educat*) AND ('computer AND science' OR 'software AND engineering' OR 'computing') AND (sustainable OR sustainability OR green OR 'climate AND change' OR 'global AND warming'))	Timespan: 2000–March 2022	14	1
Emerald	((teach* OR educat*) AND ("computer science" OR "software engineering" OR computing) AND (sustainable OR sustainability OR green OR "climate change" OR "global warming"))	International Journal of Sustainability in Higher Education	140	10
ICT4S	Papers in the proceedings of the ICT4S conference series	International Workshop on Computing Sustainability Education (CompSusEd)	4	3

2019, and 2021. Table 2 lists the searched databases, the search string used, some limitations, the number of retrieved publications, and the number of selected primary studies for data extraction and analysis.

3.2 Selecting Studies Based on Inclusion and Exclusion Criteria

The search results were collected in a spreadsheet, noting metadata such as title, authors, abstract, and publication date. Study selection was done in two phases: first excluding papers by using the first five exclusion criteria and then including only papers fulfilling the inclusion criteria. The exclusion of the papers based on the exclusion criteria EC1–5 is simple, as one does not have to focus on the contents; only EC6 requires knowledge of the contents of the papers, and as such it was implemented as a part of the inclusion phase:

- *EC1*: Duplicates from different data sources
- *EC2*: Papers not written in English
- *EC3*: Papers not accessible by the researchers
- *EC4*: Short papers less than four pages long
- *EC5*: Nonscientific and peer-reviewed publications, posters, theses, or books
- *EC6*: Papers from the same authors presenting the same results.

In the inclusion phase, the search results were categorized for relevance (quality criteria toward research questions). Two researchers rated the results independently, marking the results with either 1 (include), 0 (not included), or 0.5 (undecided). Undecided papers were further checked by a third researcher. Articles with a sum of at least 1 were included in our study. As a result, we included papers based on the following inclusion criteria:

- *IC1*: Papers about computing and sustainability and education. As noted earlier, we understand computing in a broad sense, including fields such as CS, software engineering, and other related engineering disciplines. Papers that do not address education in CS and other related engineering disciplines or do not include sustainability topics were not included.
- *IC2*: Papers in which sustainability is a goal for education and teaching. If papers used the term *sustainability* in another sense (unrelated to the sustainability issues described in Section 2), they were not included. For example, we found a couple of papers discussing the sustainability of the workload for university teachers, with no reference to complex sustainability challenges, which is why we did not include them.

The original search in the databases yielded 473 results. Reading the metadata (abstract, title, etc.), we found 46 articles relevant. One of those articles was excluded after more detailed readings by several of the authors, resulting in 45 articles. Table 6 in the appendix shows the number of papers excluded by different criteria.

3.3 Study Extension by Snowballing

One round of backward and forward snowballing [253] was performed with the included 45 primary studies from the database searches. This entailed collecting potentially relevant articles from the references in the primary studies (backward snowballing) and the articles citing the primary studies (forward snowballing). We collected meta-information on potentially relevant articles in a list. Then, we applied the same exclusion and inclusion criteria as for the other articles identified in the database search (see Section 3.2).

Snowballing yielded 98 articles that were identified as potentially relevant. Those articles were then checked for relevance by one researcher, resulting in 44 more relevant articles to analyze in this work. Thus, the final count of primary studies selected for our study was 89.

3.4 Data Collection

We extracted and collected data from each of the papers we had identified—data relevant to answering our research questions. To do that, we identified themes as subthemes or subquestions from a smaller number of articles that we jointly analyzed. The aim was to use those subthemes for a more focused analysis of papers and extraction of data. After several rounds of discussions, we agreed on the following themes, which we captured as columns in a spreadsheet (see the replication package). Those themes were then used to divide the analysis of the remaining papers among the authors of this article, where each author extracted data from a portion of papers on the themes. Analyzing the data extracted for these different themes, we identified subresearch questions presented at the beginning of this section, then we continued the analysis of the extracted raw data working in groups of authors per research question as described in Section 3.5:

— Sustainability definition (perception of sustainability) [SRQ 1.1 and SRQ 1.2]
— Understanding of what education of sustainability is [SRQ 1.3]
— Learning objectives (goals) [SRQ 2.1]
— Best practices (means) [SRQ 2.2]
— Pedagogical methods [SRQ 2.2]
— Implementation level (single course, minor, program, curriculum, etc.) [SRQ 2.2]
— Pedagogical methods used in relation to recommendations for learning for sustainable development (see [97, 247]). Such techniques refer to learning methods reported to be helpful in developing strategic competencies, such as normative thinking and systems thinking [SRQ 2.2]
— Learning outcomes (students) [SRQ 2.3]
— Education outcomes (long-term attitude changes, awareness change, feasibility of subject integration, faculty acceptance, faculty competence improvement) [SRQ 2.3]
— Study objectives [SRQ 3]
— Research method including target group (who was studied)
— Where is sustainability education being done or who is doing it?

3.5 Data Analysis

The extracted data was analyzed in groups of researchers, with each group analyzing data in different columns of the spreadsheet to respond to different research questions. We worked in five groups on RQ 1, RQ 2.1, RQ 2.2, RQ 2.3, and RQ 3. Each of those groups developed an approach to analyzing their data, thereby responding to the difference in question and following their ideas about how the research question is best approached. For example, group 5 applied a deductive approach, whereas other groups followed more of an inductive approach. All groups analyzed the extracted data and also had to revisit the primary studies to gain a detailed understanding. The groups working on RQ 1 and RQ 2 performed a thematic analysis [118], a widely used method for identifying, analyzing, and reporting patterns or themes in natural language text. We used this method to capture themes or meanings in the collection of papers, such as themes to describe conceptions of sustainability. The results presented in the following two sections then were not the coding of individual papers but rather the content in the collection of the papers as a whole. The detailed processes for analysis per group were as explained in the following.

To answer RQ 1, three authors, and later in the process four authors, conducted an inductive thematic analysis in two steps. In the first step, we jointly analyzed the data extracted from 30 papers also revisiting the primary studies to come to an agreement on preliminary themes to use for further analysis. We then divided the analysis of the remaining papers, each of us working on one of the three subresearch questions: (i) conceptions of sustainability, (ii) sustainability and computing, and (iii) conceptions of education. We collected exemplifying quotes and the themes and subthemes in a separate document and refined and restructured the themes during the process of data analysis. Those themes and quotes with references to the papers that included them were then presented as a narrative in the results of the paper. We discussed and consolidated our findings in weekly subgroup meetings, thereby reviewing each other's work.

The thematic analysis of the content of education and learning objectives (RQ 2.1) was performed by two authors, each of whom first analyzed the learning content and objectives separately. Subsequently, they compared and synthesized their insights and results. We agreed upon a structure for the results, and the description was developed in iterations between the two authors. Finally, we illustrated with examples.

The analysis on the "how" of sustainability education (RQ 2.2) was also done by two authors in a similar process as for RQ 1, in two steps first analyzing papers together until an agreement of a preliminary structure of themes was derived and then splitting up the analysis of the remaining papers (the data that was extracted and revisiting the primary studies). Also here, we used a document to capture themes and add content from the extracted data or revisited papers, discussing and refining the results, which we then formed into a narrative text in the paper.

The approach employed to shed light on the effects of sustainability education (RQ 2.3) was comparable to the process followed to answer RQ 1 and RQ 2.2. Two authors undertook a two-step analytical process. Initially, a thematic framework was outlined and mutually agreed upon, providing the foundation for subsequent analysis and interpretation. The identification and categorization of individual themes and their relationships within overarching pillars evolved iteratively through regular collaborative discussions involving all authors. Using a structured shared document once more facilitated the convergence toward the narrative integrated into the paper.

For RQ 3, we adopted a deductive approach to analyzing the kind of empirical research and the research quality in the primary studies. To evaluate the quality of the studies according to the research method used, we adopted the ACM taxonomy of empirical standards [214] to compare each primary study versus the different categories of empirical standards. As a result, we classified the different studies in any of the existing categories based on the number of essential attributes each type of paper must fulfill according to the standard. Apart from this, we also analyzed the epistemological stance of the approaches and whether the threats to validity found in the studies report incorrect conclusions. In this way, we identified the quality of the empirical studies or identified if they were proposals or vision papers rather than empirical studies.

In a further step of the analysis, we synthesized the acquired results and explored how the results aligned and if there were overlaps, which we resolved. Furthermore, we discussed the current state of practice in relation to what we know about best practices for education and education research for sustainability. During the whole analysis process, we had weekly meetings with the subgroups and the overall group to report and consolidate the results.

4 CONCEPTIONS OF SUSTAINABILITY, COMPUTING, AND EDUCATION (RQ 1)

To answer *RQ 1: How does current research conceptualize sustainability?* we explored (i) descriptions of the current state of the world and sustainability, (ii) how computing relates to the current state of the world and potential directions for sustainability, and finally (iii) how education for sustainability is seen in relation to the first two points. Not all papers explicitly mention (i) and (iii), but naturally all have conceptions of IT in relationship to sustainability. Conceptions are also part of some of the motivations in the papers, about why sustainability education in computing is important. For example, sustainability in computing education is described as important [75, 85], as something that should be uncontroversial [19]. Mann [40] argues that computing and education are two disciplines with high leverage for change with respect to sustainability.

Answering the question of how sustainability is being perceived (SRQ 1.1), we found several categories useful for distinguishing the conceptions described in the papers. However, they are neither intended to be exclusive nor comprehensive. A single paper may be included in several of the categories, so inclusion in one does not exclude from inclusion in others. Not all papers were explicit about their conceptions of sustainability, computing, or education, so the list does not comprehensively capture conceptions in all papers. In some instances, a paper could feature several perspectives in one of the categories as well. However, these categories provide a lens through which we can understand the different conceptions and uncover the important differences.

4.1 Conceptions of Sustainability

We identified six categories in our analysis of conceptions of sustainability. In some cases, those categories were explicitly referred to in the papers, but in other cases, it was us as authors who interpreted the positioning of the papers from their identified descriptions in the papers.

The categories are as follows:

(1) *Temporality*: Present vs. future
(2) *Value transparency*: Implicit vs. explicit
(3) *Originality*: Common definitions vs. synthesis
(4) *Justification*: Anthropocentric vs. ecocentric
(5) *Relativity*: Weak vs. strong
(6) *Responsibility*: Systemic and global vs. individual and local

The *temporality* category makes a distinction between papers that primarily considered issues of sustainability related to the *present*, and awareness of issues to address [46, 69, 74], versus those that considered *future* states to be avoided (e.g., societal or ecosystem collapses) or desired (e.g., fulfilling the goals in Agenda 2030) [40]. For example, Stone and Cruz [74] noted that challenges of the present tend to be so-called wicked problems, not amenable to fixed solutions and optimal outcomes but rather to be managed as social issues to be renegotiated. This concerns the state of affairs in the present and the issues we face. In such papers, awareness of the current state of affairs was considered important: "It is necessary that engineering students of all engineering disciplines be aware of environmental issues" [69], or "*[G]reen thinking* and the broad adoption of green software in CS curriculum can greatly benefit our environment, society, and students" [71]. Alternatively, some papers focus on actions for future directions that require radical changes to society: "Sustainability is considered here in terms of system change actions resulting in restorative socio-ecological transformation" [40].

The *value transparency* category distinguishes between *implicit*, technical definitions of preserving the function of a system [7, 54, 62], versus *explicit* value-based reasoning on worldviews, the rights or needs of people living now and those who live in the future, as well as other life on the planet [42, 54]. By technical definitions, we mean definitions that make value concerns invisible. They are also more technical in their choice of terminology. Özkan and Mishra [54] provide a technical definition and describe that *sustainability* means to "use in a ternary relation as the use of a system S with regard to a function F and a time horizon L, which means using S in a way that does not compromise its ability to fulfill F for a period L" [54]. This follows from the tradition of System Dynamics and modeling the world in terms of systems of interacting components with feedback loops that can cause stabilizing, runaway, or generally unpredictable behavior (see, e.g., [215]). However, as noted by systems thinkers such as Ulrich [245], values always inform the way we choose factual statements and system boundaries. The value-based definitions in the papers included mention by Mann et al. [42] and Özkan and Mishra [54] of the New Ecological Paradigm (NEP) scale [143] and the worldviews assumed to be associated with it: "[W]e are particularly interested in understanding the deeper worldviews of the students—a focus on the affective attributes of values, attitudes, and beliefs" [42].

Regarding *originality*, we saw differences between the re-iteration of *common definitions* in the general literature on sustainability, and a *synthesis* of definitions produced by the authors themselves. Here, the definition from Our Common Future, also referred to as the "Brundtland definition," appeared most often [5, 7, 20, 44, 49, 54, 59, 67, 72, 79]; planetary boundaries [220] appeared as a concept in two papers [16, 66]; the Triple Bottom Line appeared in one paper [187] (a term the original author has since tried to revoke [146]); Agenda 2030 [95] appeared in two papers [3, 5]; and the three dimensions of economic, ecological, and social concerns were mentioned in another three papers [2, 72, 84]. There were several examples of extensions regarding the relationship to technology; however, Easterbrook [13] provides a definition that specifically relates sustainability to the construction and use of technology: "Sustainability is an emergent phenomenon from the interaction between (very large numbers of) people, and the ways in which we build and use technology." Others referred to the three dimensions of sustainability (environmental, economic, social) but also added individual and technical concerns [9, 67] or added a fourth ethical pillar [53].

In distinguishing different *justifications* of sustainability, we could see both anthropocentric and ecocentric perspectives [168]. From an *anthropocentric* perspective, sustainability is justified by the desires and needs of people. Environmental and social concerns are valid to the extent they concern the interests of human beings. An *ecocentric* perspective, however, justifies sustainability from the perspective of the inherent value of all life on the planet, treating life as sacred on its own terms. The nine papers that adopt the definition from Our Common Future [5, 7, 20, 44, 49, 54, 59, 67, 79] and the three that mention Agenda 2030 and the **Sustainable Development Goals (SDGs)** [3, 5, 22] can be considered anthropocentric, as Our Common Future centers on the needs of humans, 15 of the 17 SDGs concern humans, and only SDG 14 and SDG 15 list goals that pertain to all other life [98]. Two papers adopted an ecocentric perspective on sustainability [40, 42], as they describe sustainability as "restorative socio-ecological transformation" [40] and an "ecological worldview" [42].

The *relativity* category contrasts *strong* [16, 17, 57, 66, 69] versus *weak* [54, 88] ("vanilla") sustainability [194]. The concept of strong sustainability is associated with respecting absolute, unconditional planetary boundaries and social foundations [217], as recently integrated into the safe and just planetary boundaries [219]. The papers that mention the planetary boundaries framework and global limits to human activities were considered to adhere to the notion of strong sustainability. For instance, Eriksson and Pargman [17] write that "We have overstepped several planetary boundaries and risk overstepping several more [233]. We are about to reach limits as to the resources we can extract from the earth [105], and the changes wreaked are by now so profound that they will likely last for a geological period of time." Weak sustainability instead focuses on the relative balance between economic, social, and environmental concerns. For example, Zeegers and Clark [88] write that "[S]ustainability is about giving equal consideration to the economic, environmental, and social aspects. There is growing consensus among researchers that conceptions of sustainability must include consideration of environmental, economic, and social factors" [88]. An example of a study that explicitly compares these two perspectives is that of Pargman and Eriksson [57], which states that vanilla sustainability concerns "picking low-hanging fruit in the form of energy efficiency, incremental technological innovations, or by applying human ingenuity [that] will allow us to continue to live as we do today" [57]. They argue that the strong form of sustainability, however, is required to face serious problems "such as climate change, planetary boundaries, future scarcity of nonrenewable resources (fossil energy, minerals), and the consequent challenges this scarcity will pose for our economic system" [57]. "Strong sustainability" here represents a realignment of IT with a new societal project to enact "unprecedented changes in all aspects of society" in the words of the IPCC [169] and to "rethink economic growth as a measure of progress and set our societies on a safe pathway to well-being for all" as stated in the report *Earth for All* [142].

Finally, the *responsibility* category concerns whether sustainability is considered something that must be understood and addressed as something *systemic and global* [40, 54] or *individual and local* [62]. Here, there is not necessarily so much a conflict between different conceptions of what sustainability is but rather what makes most sense to direct the attention of teachers and students in the context of education. For example, Özkan and Mishra [54] take a systemic and global perspective and mention that "The key challenges of the 21st century can mainly be characterized by their global impacts" [54]. Penzenstadler et al. [62], however, begin by outlining global issues such as prolonged droughts that are the results of the climate crisis, but continue to focus more on individual action: "To become more resilient to future climate conditions [99], create a greener society, save money, and improve food quality [104], many individuals are practicing home horticulture" [62].

Of the papers that make it apparent how they conceive of sustainability, we notice that the most prevalent conception is of sustainability as synonymous with Agenda 2030 and the definition in Our Common Future, which are anthropocentric and established in related literature. Ecocentric perspectives, in contrast, are much less common, although a number of different perspectives exist in individual papers.

4.2 Conceptions of Computing and Sustainability

Regarding the relationship between computing and sustainability addressed by SRQ 1.2, we found three perspectives on the role of IT for sustainability: (i) an *incremental* perspective where the focus is on adjusting computing to reduce its footprint; (ii) an *enabling* perspective where IT is the means to address society-wide sustainability issues; and (iii) a *disruptive* perspective, which acknowledges the severe sustainability challenges we are facing that require—as also argued, for example, by the IPCC[1]—major, structural societal changes (e.g., the need to change persistent high-carbon lifestyles or the current carbon-intensive energy supply systems), and where also IT norms, practices, and processes must change to align with and support the core principles of sustainability.

Several primary studies focus on *incremental* changes within computing, adjusting the production of software and hardware to reduce their environmental footprint. Also beyond the education literature covered in our study, this paradigm has often been called *green IT* [127, 163] or *green computing*. This is in accordance with the work of Özkan and Mishran [54] that advocates the green use, disposal, design, and manufacturing of IT systems as proposed by Marugesan [193]. Several of the analyzed studies [7, 14, 16, 22, 25, 28, 54, 59, 71, 79] acknowledge the IT footprint and suggest adjustments to how we currently work. They acknowledge that energy and material consumption represent a problem and stress the impact that ICT infrastructures have on the environment due to their high energy demand ("3% of global electricity consumption" [54], greenhouse gasses [1, 59], raw materials required that also contribute to toxic waste [1, 59], and e-waste produced [79]). Adjusting IT to contribute to sustainability is the direction of some other studies that suggest handling sustainability as yet another quality attribute (e.g., [55, 59]).

We further found studies recognizing the value of CS or IT as an *enabler* to address many of the society-wide sustainability issues. This paradigm, often addressed as "green by IT" [163], "I(C)T enabling effect" [186], or occasionally also as "ICT handprint" [41], aims at using ICT to support sustainability throughout the entire society and economy, and it applies computing to contribute to societal change toward sustainability, without, however, expecting radical changes of the society or economy themselves. Sometimes this paradigm of greening outside IT is also called *green computing*, such as in the work of Cai [7], although such terminology can easily lead to confusion with the previous category, "green IT," which addresses greening within IT. The enabling paradigm widens the focus from the IT industry itself toward society and the economy at large, promoting a "new sustainable model by mutually advancing economic, environmental, and social goals" [7]. Similarly, Lago and de Boer [35] note that "we extend the focus of sustainability-related competencies and skills from the underlying digital technology to the needs of a digital society" (p. 2). In addition, Argento et al. [3] recognize the value of IT as an enabling technology, stating that "Computer science or IT does not explicitly correspond to any of the SDGs but is nevertheless considered to be crucial for the fulfillment of each of them." As well, Abernethy and Treu [1] use IT as an enabler when

[1] https://www.annualreviews.org/doi/abs/10.1146/annurev-environ-012220-011104

discussing how IT can "look outward to solve sustainability problems that IT isn't actually causing" (e.g., lights and room temperatures managed by IT systems, or transportation and logistics systems) and as a reporter when using data management and visualization to support those systems.

The third case focuses on a *disruptive* perspective that puts sustainability first and entails the realignment of IT with a new societal project, *demanding for radical changes* in our professional role through some or all of the following characteristics: responsibility, accountability, systems thinking, and affective reasoning, and perhaps activism (also supported by Schendler [227]) and challenging political structures and norms. This is in accordance with the idea of a transformation mindset by Mann [41] arguing that a transformation cannot be "met through marginal lifestyle changes [212], instead we need urgent and ambitious changes [239]." So, a change in professional behavior is in order. As Leifler et al. [37] formulate it, IT professionals should have abilities to "understand the principles [of] complex systems, . . . reason about systems of values . . ., and to deal with conflicts between the values of different stakeholders" while also having effective competencies for the "engagement, commitment and behavioral change towards sustainability" [37]. In particular, several papers emphasize responsibility, accountability, and the skills to contribute to solving complex problems with conflicting goals—for example, Huntzinger et al. [24] stress the need for creative solutions to complex problems and the importance of engineers being able to critically assess the implications of their professional actions. Such skills go beyond traditional computational thinking, demanding the ability to understand the circular nature of the world we live in. Systems thinking is also addressed by several authors (e.g., [13, 54]) as the approach that "provides the necessary bridge from computational thinking to sustainability practice." It "provides a domain ontology for reasoning about sustainability, a conceptual basis for reasoning about transformational change, and a set of methods for critical thinking about the social and environmental impacts of technology" [13]. Such disruptive perspective might mean challenging established computing norms, practices, and processes and aligning them with the core principles of sustainability [37, 54, 69] (e.g., reduce, reuse, and recycle), "finding innovative ways to use ICT in business processes to deliver sustainability benefits across the enterprise and beyond" [54], and also considering the Karlskrona Manifesto[2] [37].

4.3 Conceptions of Education and Computing Education for Sustainability

In the following, we describe how education for sustainability is understood and presented in the context of computing education (SRQ 1.3). We identify two categories for describing this understanding:

(1) *Level of response*: Incremental changes vs. rebuilding, re-aligning, and transforming
(2) *Purpose*: Training vs. emancipation.

The first category, *level of response*, is about approaches to change. What we find relates to Sterling's levels of transformation [235], from denial to adding and integrating sustainability into existing education to re-imagining and transforming education. It also reminds of the previous discussion of changes in computing, as either incremental change or more drastic change with sustainability being the central concern (see Section 4.2). We find many examples of *incremental changes* to education described in several works [3, 7, 16, 17, 19, 32, 34, 39, 42, 47, 55, 57, 60, 70, 76–79, 81, 85, 87]. For example, sustainability education can be included in lectures on software engineering [60], where, for example, sustainability can be discussed as yet another quality attribute of a software system [47]. Another example is promoting sustainability competencies [171, 201, 252], which is argued for in other works [32, 42].

[2] https://www.sustainabilitydesign.org

On the other side of the spectrum, *computing education as a whole is re-imagined, re-aligned, or transformed*. It means that computing education is recontextualized, with sustainability being the core value [44] or "nexus" of computing education [43]. Such a change of education to address sustainability is called *transformative* [7]. Mann [41, 42] and Mann et al. [43] developed computing education that centers around the learning objective to become a sustainable practitioner. Porras et al. [65–67], as well as Lago and de Boer [35], present master programs that were developed from the ground up centering sustainability.

Transformative change is difficult to achieve in the current system [16]. Adding courses or modules to the existing education is an easier and more straightforward approach to implementing sustainability [7]. Yet, inserting sustainability into a crowded computing curriculum can be experienced as a challenge [7], which means that the insertion of sustainability can become more of an injection—a "patch-on" [16], sustainability is "squeezed in" [17]. It requires balancing different stakeholder interests [78, 81]. However, even smaller modules such as a lecture may lead to more transformative changes in computing education later on [60].

The second category, *purpose*, is about what education aims to achieve. Education with a focus on *training* centers around equipping the students with certain skills, knowledge, or competencies, which also include attitudes or values. Most papers engage with education as training. Sections 5.1 and 5.2 provide a detailed description of the learning objectives as they are specified in the papers. Holfelder [164, p. 944] argues that education as training reduces education to an instrument for attaining certain specified objectives. As other researchers (see, e.g., [91]), she argues that such a view of education turns education into a tool for reproduction, hence limiting the possibilities for alternative futures. We use the term *emancipation* to capture alternative understandings of education that go beyond reproduction, a term that is also used in the literature on education for sustainability (e.g., [156, 173]).

A few studies [24, 35, 40, 44, 68] reflect about education as *emancipation*. Education here supports an inner journey and personal growth to forge the future with one's unique personal experiences and background. For example, Mann [40] argues for such an understanding of education: "Rather than specifying a predetermined set of behaviors to describe sustainability within a discipline, instead we aim to take students on a journey of themselves identifying what it means for them to think and act as a sustainable practitioner." Mann describes two student examples and suggests that technical content can be learned "on-demand," as needed by the student or the project. Such an idea of education would imply a change of power relation from lecturer as experts deciding on how to expose the student to sustainability and crisis, to lecturer and learner as more equal and co-learners [24, 35, 40, 68]. Lago and de Boer [35] write about the co-creation of real-world examples for local communities. Mann et al. [44] state a vision that graduates, practitioners, and academics understand concepts of sustainability so that they can "evaluate, question and discuss their role in the world and to enable them to make changes where and when appropriate." This vision emphasizes the individuals' unique possibilities in the world. The Vrije Universiteit Amsterdam lifts three core values, which could be interpreted as promoting emancipatory views of education [35]: (i) students' responsibility for their education; (ii) the interdisciplinary and open character of the program; and (iii) students' responsibility for issues such as "sustainability, ethics, privacy."

4.4 Takeaways for RQ 1

This section provides categories that help conceive of *sustainability*, *computing and sustainability*, and *education for sustainability in the context of computing education*. For several of the categories, we contrasted different values such as ecocentric versus anthropocentric, or incremental change versus rebuilding. Those values should not be seen as opposites or binaries that are clearly separated but rather reflective of the various, partly overlapping, sometimes difficult to match perspectives found in the papers.

Given this plethora of conceptions of sustainability that differ along various dimensions, it is perhaps surprising that they ultimately boil down to only three main possible roles that IT could take in sustainability: an *incremental* perspective focusing on reducing the direct environmental footprint of computing; an *enabling* perspective in which IT is the means to addresses society-wide sustainability issues; and a *disruptive* perspective, which acknowledges and responds to the need of unprecedented change.

Our review of conceptions of education for sustainability in the context of computing education suggests that most primary studies view sustainability as an important concern for computing professionals, but not in such a way that it would require radically new degree programs. A few authors, however, see that education needs to be reconceptualized to support change toward sustainability.

5 IMPLEMENTATION OF SUSTAINABILITY IN COMPUTING EDUCATION (RQ 2)

In *RQ 2: How is the implementation of sustainability education being presented?* we investigate how education for sustainability is being implemented in the context of computing education. We do so by researching the following aspects: (i) the intended learning objectives (i.e., what the students should know at the end of a course, see Section 5.1); (ii) the topics, or contents through which the learning objectives are being realized (Section 5.2, i.e., the content of education); (iii) the organization of education in terms of pedagogical approaches and educational structures (Section 5.3); and finally (iv) the reported effects (i.e., the achieved learning outcomes and other effects, Section 5.4). We close with a summary of the main takeaways (Section 5.5).

The SLR results related to the aspects mentioned previously are explained in the following sections and summarized in Figure 3. In this figure, the horizontal (white) pillars represent the types of intended learning objectives that were elicited from the primary studies. The topics are used to concretize learning objectives and are represented by the first three vertical pillars: they can be computing specific (i.e., ICT topics where sustainability provides the application context), sustainability specific (i.e., topics covering sustainability knowledge), or a combination thereof (i.e., topics that really mix both domains and as such cannot be classified as one or the other). Finally, the last two vertical pillars represent how education is being organized.

5.1 Intended Learning Objectives (SRQ 2.1)

The intended learning objectives identified in the primary studies are what the students are expected to learn in a course or teaching intervention—that is, the competencies the students should have acquired, or, in Bloom's terms, "what students should know or be able to do at the end of the course that they couldn't do before" [114]. We organized the learning objectives into four broad categories: Acquiring topic-specific competencies, Acquiring cross-cutting competencies, Gaining awareness, and Gaining practical experience. In the following, we explain each category and map it on the corresponding Dublin descriptor(s).[3] This way, given the widespread adoption of Dublin

[3]The Dublin descriptors are general statements about the ordinary outcomes that are achieved by students after completing a curriculum of studies and obtaining a qualification. They are neither meant to be prescriptive rules nor do they represent benchmarks or minimal requirements, since they are not comprehensive. The descriptors are conceived to describe the overall nature of the qualification. Furthermore, they are not to be considered disciplines, and they are not limited to specific academic or professional areas. The Dublin descriptors consist of the following elements: Knowledge and understanding, Applying knowledge and understanding, Making judgments, Communication skills, and Learning skills (European Higher Education Area: http://ehea.info) [158].

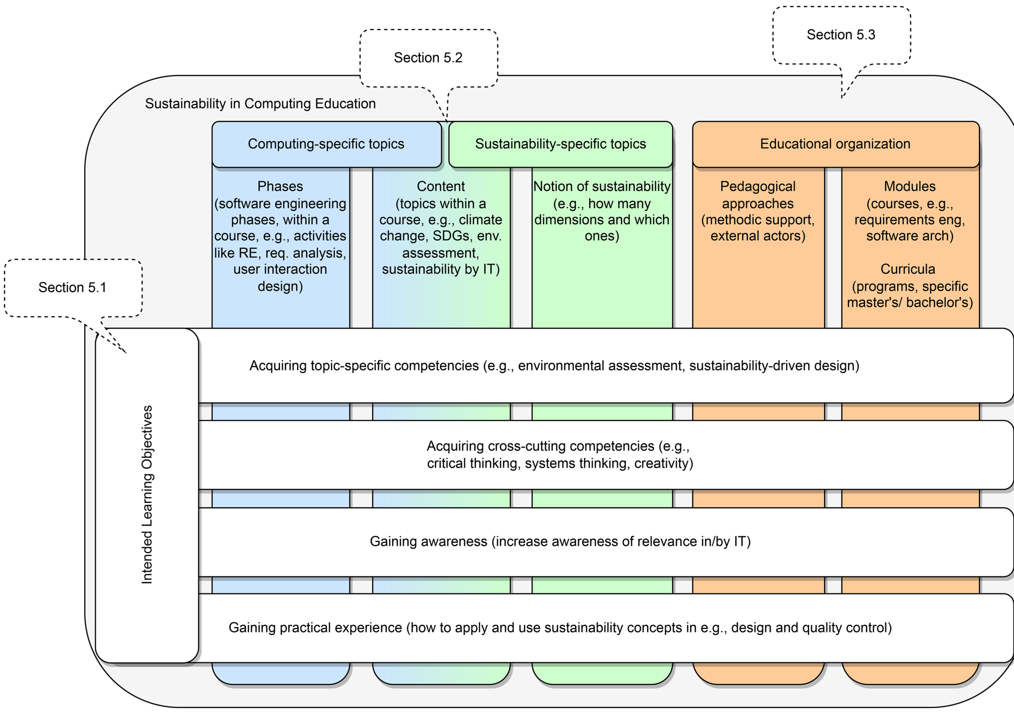

Fig. 3. An overview of the different educational components in education for sustainability in computing.

descriptors in educational frameworks especially, but not exclusively, in the European Union, we aim to ease their use.

Acquiring Topic-Specific Competencies. Topic-specific competencies are specific to the domain of computing and sustainability. In any educational component (module or curriculum), the intended learning objectives and the related topics are intertwined (as the second is instrumental to achieving the first). Therefore, the topics elicited from the studies are presented in Section 5.2. Depending on the types of competencies covered by the study, acquiring topic-specific competencies can be generally mapped on Dublin descriptors "Knowledge and understanding" and "Applying knowledge and understanding."

Acquiring Cross-Cutting Competencies. These competencies are relevant across applications and domains and allow people to act effectively in the target application or domain. Previous work has formulated such competencies in terms of "key sustainability competencies," which include, for example, systems thinking and integrative problem solving [201, 252]. We see reference to the work by Wiek et al. [252] in other works [27, 32, 32, 47, 49, 68, 86]. Mann et al. [42] link to *action competence*[4] in environmental education [171]. In the primary studies, we identified the following list of cross-cutting competencies:

— *Systems thinking*: Systems thinking is a holistic approach to thinking in systems and included in various ways and contexts: for climate change and gamification [15, 19], in general, to address sustainability in broad contexts [54, 84]; for problem solving in a systemic way

[4]In other words, an individual's capacity of critically selecting and conducting possible actions that may solve societal problems through democratic mechanisms (https://wikieducator.org/Learning_and_Teaching_in_Practice/Action_competence).

[39, 89], to include environmental friendliness in computing processes [81]; and for balancing ICT, economics, and sustainability [38, 52, 84]. In addition, systems thinking is mentioned as an instrument to acquire a reflective, holistic way of thinking [73]. Easterbrook [13] proposes it in the form of a Toolkit with a Domain Ontology for Sustainability Thinking, Theories of Change, and Tools for Critical Analysis. Huber and Hilty [23] conclude that "[T]eaching systems thinking . . . plays an important role in teaching sustainability, in particular when the fields of ICT and Sustainable Development (SD) are to be combined." Specifically the "rebound effect," which can be used as a potential introductory example to systems thinking, provoked students to think about technical efficiency in a new way.

— *Multi-perspective thinking*: Multi-perspective thinking uses systems thinking to consider the concerns of various parties. For example, Krogstie and Krogstie [32] promote it as a way to address the concerns of individuals versus those of social communities, for example, by using personas and associated scenarios to explore different needs.
— *Transformation mindset*: Acquiring a transformation mindset is proposed as "a way of thinking that leads to transformational acts resulting in socio-ecological restoration" [41].
— *Judgments*: Making judgments is another frequently mentioned cross-cutting skill for many sustainability-related purposes: we make judgments in ethics [35]; we make judgments on the societal role of informatics in shaping the future, and in doing so we assume an active role as software professionals [37]; and we use judgments to reflect on (i) ethical and sustainability aspects of software systems, and (ii) choices in terms of both product impacts and processes [6]. We also use judgments for critical thinking (e.g., for exploring the use of technology to protect the environment [11], and for learning and reflectivity [86]).
— *Creativity*: Creativity is reported as a key competence in software engineering for sustainability [89], for which it found as especially necessary "for developing new insight, making new connections, and identifying new solutions."
— *Communication*: Sustainability in given subjects requires communication skills, included in primary studies [6, 11] as a skill to report orally and/or in writing. One paper uses academic writing to communicate basic tenets of sustainability and IT in society, the responsibilities of IT professionals, and the effects that a particular IT system has from a systems perspective [37].
— *Ecological approach*: The ability to apply an ecological approach to computing is proposed by some studies as a learning objective instrumental, for example, to the creation, research, and exploitation of ICT [81]; to create eco-friendly technology and processes [87]; and in general to develop STEM reasoning skills in sociotechnical areas [52]. A special angle is addressed by Qureshi [68] to develop the knowledge of how to develop and improve sustainable living (where ICT is a supporting instrument).
— *Meta-learning*: "Learning to learn" is a skill to "support students' development in a range of analytical, communication, and learning skills appropriate to the subject matter and level of the course" [11].
— *Research methods*: Research methods that specifically benefit ICT for Development (ICT4D) and the SDGs are taught to the students. For example, Lago and de Boer [35] propose Green Labs and ICT4D Field Work in their preview of a master's program geared around Digital Society and Sustainability. Müller et al. [50] propose a model combining education on sustainability with thorough training in scientific research methods, including example projects from an existing social science curriculum and its integration into a real-world laboratory on sustainable energy use.
— *Critical thinking*: The concept of critical thinking goes back to the American philosopher John Dewey (1910), who defined it as "active, persistent, and careful consideration of any

belief or supposed form of knowledge in the light of the grounds that support it, and the further conclusions to which it tends" [140]. Critical thinking methods are important for all students such that "the next generation of professionals may be more likely to give consideration to issues (e.g., the environment, social equity, biodiversity) that they otherwise would have ignored" [24]. Critical thinking methods have gained popularity [17, 18, 35]. Another example of critical thinking is proposed by Lopez et al. [39], who use Felber's model for the common good matrix to help elicit values in an engineering project.

Depending on the types of competencies covered by the study, Acquiring cross-cutting competencies can be generally mapped on Dublin descriptors "Make judgment," "Learning skills," and "Communication."

Gaining Awareness. The need to create awareness, among the students and various stakeholders, of the role of software (and ICT in general) for sustainability is common to many studies. Awareness is often mentioned with a broad connotation, as stimulating the reflection on the role of software [1, 5, 44, 80]; the role of informatics in society, legal issues, and ethical professional responsibility [8]; the role of ICT industry and its societal and environmental implications [38]; or the conceptual understanding and awareness of environmental issues [69]. Lopez et al. [39] propose a framework to help the students think about the sustainability of their own thesis project.

Further, many studies aim at creating awareness of the specific types of effects. For example, the mentioned enabling effects (i.e., software engineering for sustainability) include the impact of ICT on society [35] and case study specific ICT impact on sustainability [61]. Studies that explicitly target both direct (e.g., software energy footprint) and enabling effects include, for example, user participation and inclusivity [84]; creation of ICT solutions in resource-scarce contexts [35]; the reflection on ethical aspects of the profession [6]; green and sustainable software engineering [80]; and the environmental impact of software, networks; and services [30]. Some studies add the sustainability of the software engineering process [47, 65–67, 87].

Gaining awareness can be generally mapped onto the Dublin descriptor "Knowledge and understanding" [158].

Gaining Practical Experience. A significant number of studies propose letting the students gain practical experience in various forms: by means of integrative and transformative projects [7], by facilitating integrative learning through reflective writing [74], and by exploring different ICT perspectives [65–67]. More traditional approaches include project-centered learning [49, 89]; case-based learning [61]; practical student assignments [84]; and using real-world sustainability problems, hard data, and technical methods [36].

Depending on the education level covered by the study, gaining practical experience can be generally mapped on Dublin descriptors "Applying knowledge and understanding" and "Communication."

5.2 Topics Being Taught (SRQ 2.1)

The topics being taught refer to the context of computing and sustainability. In particular, we observe that teaching topics may be a collection, or even a combination, of computing-specific topics and sustainability-specific ones. Accordingly, computing and sustainability provide the context in which teaching topics are organized.

Following this line of thought, the *computing-specific topics* identified from the studies entail the phases (i.e., from the perspective of time, e.g., the software lifecycle, like requirements elicitation) and the contents (i.e., from the perspective of the artifacts created over time, e.g., software models) specifically related to the computing field. Both phases and content are important and complementary: phases-wise, we may follow different techniques to transform a software design into a specific technical implementation; content-wise, the software design can be represented in specific modeling notations, and the technical implementation can be realized by using different programming languages.

Sustainability-specific topics, in turn, entail notions of sustainability and in particular how it is being considered in a given educational setting (see Section 4 for different conceptualizations). Finally, we have also identified a third type of somehow-hybrid topics, which stem from the combination of computing and sustainability and as such do not belong to one or the other but lie in their intersection (e.g., green computing techniques). We call these *combined computing-sustainability topics*. The following reports on the primary studies addressing these three types of topics.

Computing-Specific Topics. These most prominently regard the focus in a given module, specifically on software development project management [1], user experience/human-computer interaction (UX/HCI) [84], or measuring the energy footprint of ICT [81].

Sustainability-Specific Topics. We use the PESTLE classification as a general mapping of how the topic of sustainability is being understood in learning objectives.[5] Accordingly, we identified studies that are specific to various notions of sustainability: the environmental [11, 81, 87], the social (social relevance of programming [76]), and the sociotechnical (the impact of inclusive HCI [76] or social learning [86]). Some others are all encompassing, by addressing dimensions from the whole PESTLE classification (e.g., [6, 12]) to sustainability in general (e.g., [14]). In addition, under this umbrella, we identified the following topics:

— *Climate change*: This content topic is addressed in many universities, some of them more in-depth using systems thinking approaches [13, 15, 32], and some of them more exploratory in projects [36, 70]. The main teaching point is that climate change is present, complex, and immediate. Krogstie and Krogstie [32] include sustainability content in assignments, such as by means of including personas with differing views on the climate measures.
— *Sustainable development concepts and the SDGs*: Several studies used the SDGs as a source of inspiration to choose projects for students to work on, or contextualize, the application of IT in a meaningful way. Argento et al. [3] found projects on campus related to SDGs. Crompton et al. [11] helped students understand how the use of technology to meet the material needs of humans contributes to environmental effects. Stone [75] created introductory programming projects focused on sustainability topics such that students were exposed to the general concepts and terminology involved. This is expanded in the work of Stone and Cruz [76] with reflective writing. Koniukhov and Osadcha [31] implemented ESD (UNESCO) principles in the process of training future software engineers.
— *Ethics and social good*: Several studies mentioned the importance of including ethics and social good as context for IT projects. For example, Goldweber et al. [21] report on 14 introductory projects in that context, from radioactive mice to water pollution to voting simulation. Polmear et al. [64] compare macroethics in teaching across cultures that can be drawn from. Eriksson and Pargman [17] see students as becoming ambassadors for change.

Combined Computing-Sustainability Topics. Some studies report on combined contents providing competencies like green computing techniques [7], technology assessment to analyze technological developments and their consequences [45], and how to help minimize the energy footprint of software solutions [30], or how to work in interdisciplinary settings [62] while fostering creativity [89]. Under this umbrella, we identified the following topics:

— *Environmental assessment, lifecycle assessment, and technology assessment*: These topics entail standards as well as concepts for environmental assessment, lifecycle assessment, design for

[5]PESTLE stands for Political, Economic, Social, Technological, Legal, and Environmental. A PESTLE analysis aims to identify potential threats and weaknesses from the perspective of the preceding six factors (https://doi.org/10.1002/joe.21935).

environment, and environmental decision making [78]. These topics include systems and sustainability perspectives, systems performance analysis, and economic decision-making tools as well as project evaluation. Furthermore, industrial ecology contributes to the lens of Earth systems engineering and management, supplemented by lifecycle assessment and material flow analysis [85]. Technology assessment considers how to evaluate the outcomes and impacts of large-scale complex engineering systems from a decision maker's perspective. There are legal, political, economic, environmental, and social frameworks that can be used to assess technology and its impacts [45].

— *Green IT and sustainable computing*: Green IT is the study and practice of designing, manufacturing, using, and disposing efficiently of computers, servers, and associated subsystems like monitors, networking, and communications systems [28] (see also the incremental perspective in Section 4.2). This topic area includes energy-aware services, investments in green IT, measurements of energy efficiency and software qualities, and "Green Labs" [34]. It can be expanded toward a circular economy and smart systems, as well as Quality of Service and environmental requirements and contracts [30].
— *Sustainability in/by IT*: This topic area covers the three perspectives described in Section 4.2. For Sustainability in and by IT, Hilty and Aebischer [163] define three impact dimensions of ICT (first-, second-, and third-order effects). These impact dimensions are used in several publications to explain the connection between ICT and sustainability [40, 54].

  The biggest potential to motivate students to engage with the topic, according to Huber and Hilty [23], is an understanding that ICT is part of the problem and the solution. They give examples for recycling of ICT, using ICT to reduce greenhouse gas emissions, seemingly dematerialized economies, and rebound effects that lead to increasing demand for goods or services.

  Penzenstadler and Fleischmann [60] argue for making the link between IT and sustainability explicit, and offer ways of how to teach about it. In addition, Penzenstadler et al. [61, 62] show examples of how to design the requirements for a system such that they address the impact of sustainability requirements on IT (i.e., requirement analysis).

5.3 Educational Organization (SRQ 2.2)

In the following, we present "how" sustainability education in computing is being implemented in terms of two elements: (i) pedagogical approaches, or the teaching methods that are used to realize the learning objectives described before, and (ii) the "building blocks" in which sustainability education is organized (i.e., modules and curricula).

5.3.1 Pedagogical Approaches. We could trace two aspects in the presentation of pedagogical approaches: (i) practices to integrate different fields of knowledge and (ii) pedagogical methods in sustainability education. They are described in the following.

Practices to Integrate Different Fields of Knowledge. Several of the primary studies include reflections on pedagogical approaches to integrate different fields of knowledge [1, 8, 17, 38, 42, 45, 46, 59, 64, 78, 82, 84, 85]. Multiple papers argue that the students' discipline needs to be combined with domain knowledge of the various dimensions of sustainability [64, 78, 85], and that, specifically, ethics [8, 42, 78] or other subjects from the humanities [46] are central to the integration of holistic perspectives on engineering and management. Two such approaches emerged from our analysis:

— *Multidisciplinary student groups*: This approach is about the composition of student groups. Multidisciplinary groups of students are advocated, allowing for a more holistic understanding of sustainability issues [45, 84]. One example is a collaboration between IT and Material

& Earth Sciences [6]. Another one [70] uses a question-based approach to select topics that then require looking into different disciplines.
- *Engaging external actors*: Several of the studies report on the value of engaging external actors [6, 10, 24, 30, 34, 48, 54, 61, 79, 84]. Collaboration with external stakeholders is either reported as being done through entrepreneurial approaches [6], through cooperation with the industry or public sector [10, 30, 48, 84], or through the local community [6, 79]. Representatives from these sectors can give guest lectures, such as industry representatives in the work of Porras et al. [67]. Students become active agents of change in the local community when working with external stakeholders, such as expressed in the following: "Entrepreneurial experiences is an educational framework encouraging students to have the competencies to make a positive change in their own context, the ability to assess opportunities and resources for making a difference, and the courage to act accordingly" [6].

Pedagogical Methods in Sustainability Education. The primary studies report on different methods—that is, different ways of engaging students in learning activities and promoting skills, attitudes, and behaviors assumed to be associated with learning for sustainability:

- *General learning approaches*: These are meant to help students become active participants in their modules, which are not necessarily specific to learning for sustainable development. In this category, the studies report on using student-centered active learning [24], discussions and reflections [54, 67, 68, 84], preparation and classification of ready-made project ideas on computing for the social good [21], experiential and reflective learning activity and reflective reports [59], a "Sustainable programming pedagogical model" with reflections [74], and a flipped classroom for critical thinking.
- *Games, simulations, or role-playing exercises*: Such exercises for sustainability were described in five studies [15, 19, 37, 45, 58]. Some use custom board games designed to build experiences related to understanding norms, values, or complex systems [37, 58], some use simpler playbook formats featuring smaller exercises fit for classroom use [15, 19], and one reports on role-playing and "structured academic controversy forum" [45]. Eriksson et al. [15] use in their CS module the systems thinking games Living Loop and Harvest from the "The Systems Thinking Playbook for Climate Change" [237], to let students experience the concepts detailed in the preceding lectures. Easterbrook [13] reports on a seminar series where the students "collectively tease out the systems concepts exhibited by the game, along with their own reactions to the overall behavior of the system."
- *Problem-based learning, course projects, and hands-on experience*: These pedagogical methods were described in 15 of the primary studies [6, 17, 24, 26, 40, 46, 48, 52, 54, 55, 62, 67, 70, 79, 85]. In these methods, the students engage with and take responsibility for real-world issues; they also take responsibility for their own learning while working on the issues. Miñano Rubio et al. [46] describe course projects as an "important leverage point for the integration of sustainability." The projects are contextualized in different ways—for example, as a part of a longer education and vertically integrated through longer periods of studies [52], or integrated with other disciplines in interdisciplinary projects [62, 70]. The concept "learning by doing" is used and extended into "learning by living." The students apply and learn about software technology in specific applications, such as gardening (growing your own food) [62]. In one example, students changed lifestyles for a shorter period of time and reflected on the outcome—that is, the students explored the notion of sustainable living in their everyday life and experienced firsthand the related choices and challenges [68]. In addition, connecting computing to social sustainability can bring sustainability to life [21, 73]. Mann [40]

proposes an educational model for transformative action so that students act consciously and responsibly within their professional practice.

5.3.2 Building Blocks: Modules and Curricula. The realization of sustainability in computing education is discussed in terms of the changes required to modules or curricula. Some authors aspire for radical change [40, 54] and propose to rethink education as a whole, as "the solution is not to try and cram more material into an already crowded curriculum but rather to see sustainability as the context, a basis for deeper learning, or even a reason for learning" [40], and therefore "rather than carefully aligning sustainability with the discipline, we need to be pointing out how much change is required" [40]. Teaching in ways that allow for and encourage activism, also expressed as "development activism," may be one approach to achieving radical change through education, such as in "Dissent 101" [166]. The scope of the studies varies from individual modules to the design of full curricula.

Modules. The primary studies report on specific modules through which sustainability education is implemented, such as teaching general sustainability competencies [59] or cross-cutting skills like systems thinking [13]. The studies provide guidance for module design—for instance, thesis projects about sustainable engineering [39]. Even though many of the primary studies do not inform about the curricular level in which their proposal is being taught, most works seem to focus on the BSc and master levels. The extent to which the integration of sustainability was performed varies. In a lighter mode, we found efforts to teach sustainability in IT via one or several workshops [10] or seminars [7, 59, 80], assignments [84], or projects [36, 40, 46, 75], or through modules in modules [61, 69, 74, 76, 80]. Penzenstadler and Fleischmann [60] describe how integrating sustainability can be achieved through minor changes (e.g., in seminars) and how those minor changes can be a seed for promoting the value of sustainability to students, which might lead to more transformational changes of computing education later on. Easterbrook [13] informs about their determination to educate all their MSc and BSc students about sustainability and reports on how they increase sustainability-related aspects in different modules, particularly in those of their Human-Technology Interaction MSc program.

A few primary studies propose whole new modules, such as a module on green computing [7, 11, 15, 16, 19, 28, 55, 56, 79, 82], introductory modules on software and sustainable development [5, 18, 57, 78], a final-year project module on sustainability [39], "software engineering sustainability" [37, 81], and ethics [8]. Easterbrook [13] proposes three modules: on climate informatics, on the social and environmental impacts of the internet, and on systems thinking for global problems.

Curricula. Curricula embed sustainability either as a central focus (e.g., [35]) or as general design guidelines (e.g., [83, 87]). The level of the curricula at which sustainability in computing education is implemented varies from K-12 [10] to BSc and MSc [13] to Ph.D. degrees [12]. Several primary studies report on how sustainability is being implemented across the curriculum or program [1, 13, 24, 33, 38, 46, 48, 49, 83, 85, 87]. Examples include the integration of "Sustainability and Social Commitment" skills (SSC) in different degree modules in a 4-year Computing Engineering degree [38, 61, 67], "greenifying curricula" [3, 30, 34, 47, 64, 73, 87], a 1-year IS Master program "with a special focus on the Digital Society and Sustainability" [35], or the blueprint of the Erasmus Mundus Joint Master Degree in Pervasive Computing and Communications for Sustainable Development [66, 67]. Miñano Rubio et al. [46] propose a model for the holistic and systematic integration of sustainability competencies into engineering curricula that can serve as guidance.

Finally, Mann et al. [44] develop recommendations for policies that can catalyze the integration of sustainability in all computing programs across institutions. The vision of this work is to create

Table 3. Achieved Learning Objectives Mapped on the Pillars of Figure 3 and General Themes

Pillar	Theme (achieved learning objectives)	Meaning of the category Adding sustainability to education . . .	Primary studies
Gain awareness	Increased awareness	. . . improved the awareness among students of the global sustainability issues the world faces.	[1, 7, 11, 25, 36, 37, 56, 59, 69, 71, 75, 76, 88]
Gain awareness, Acquire cross-cutting competencies	Restlessness	. . . led students to express deep concerns, even anxiety, about the current (lack of) sustainability of the global trends.	[8, 56, 57]
Acquire cross-cutting competencies	Mindset change	. . . led students to radically change their perspective about sustainability, its causes, or potential solutions.	[8, 25, 36, 37, 56, 71, 88]
Acquire cross-cutting competencies	Increased motivation	. . . led students to express their willingness to adopt a more sustainable practice or attitude.	[7, 25, 56, 75, 76, 88]
Acquire cross-cutting competencies	Multidimensionality of the problem	. . . led sustainability to be recognized as a multidimensional problem, and one whose dimensions are often in conflict.	[56, 57, 88]
Acquire cross-cutting competencies	Negative impact of ICT systems	. . . linked to the computing discipline and its impact on climate change and other sustainability challenges. Students understand how computing can harm sustainability.	[1, 16, 25, 37, 68]
Acquire topic-specific competencies, Gain practical experience	Positive impact of ICT systems	. . . showed the potential of computing for addressing sustainability challenges. Students understand how computing and their computing skills can contribute to improving sustainability.	[1, 7, 9, 16, 25, 32, 36, 37, 68, 71, 76]
Gain practical experience	Lifestyle change	. . . made students change their personal, or their community's, practices and attitudes into more sustainable ones.	[11, 16, 68, 76]

"a philosophy of Computer Education for Sustainability" that "will be enhanced if undertaken within a context of institutional operational practice" [44, p. 191].

5.4 Effects of Sustainability in Computing Education (SRQ 2.3)

The effects of teaching sustainability have been studied from two different perspectives: (i) what researchers/educators reported that their students demonstrated to have learned (i.e., the achieved learning outcomes), and (ii) other effects that were reported as a consequence of implementing their pedagogical initiatives.

5.4.1 The Achieved Learning Outcomes. The achieved learning outcomes were categorized in the themes shown in Table 3 together with a description of their meanings and the primary studies in which they were witnessed. For each theme of learning outcomes, the first column (and the descriptions that follow) refers to the categories of learning objectives that they respond to (see horizontal pillars in Figure 3). Following the principle of constructive alignment [113], our aim is to help educators align the *intended* learning objectives and the *achieved* learning outcomes. (See also the discussion in Section 5.4.)

Achieved Cross-Cutting Competencies. The primary studies report on the achieved learning outcomes that can be interpreted as cross-cutting competencies:

— *Increased awareness*: The most documented effect of sustainability in computing education is an increased awareness of what sustainability is and the sustainability issues humanity is facing. For example, Stone reveals that "a majority of participating students reported that the course and its assignments helped them have a greater understanding and appreciation for sustainability" [75], an observation similarly made in other works [25, 37, 76]. Furthermore, Leifler [36] reports that one student "claimed not to have understood the full implications and scope of climate change before, and said that his understanding had improved much." The students seemed surprised at how much they learned and how little they knew before [88]. Students also enter and select sustainability education with an awareness and desire to learn and care for the environment and state they become even more aware during the education [11]. In the work of Pargman and Eriksson [56], one can read how some students went from doubting climate change to expressing deep concerns for the future of mankind.

— *Restlessness*: Teaching sustainability was sometimes reported as raising in students an overall feeling of restlessness [8, 56, 57]. Students expressed deep concerns, anxiety, and fear about our global future. Concrete evidence suggests that being thoroughly exposed to real-world sustainability issues can lead to uncertainty on whether it will be possible to address those issues: "The revelations have made me more anxious about life and our future. It's good stuff but I would probably be happier without it. Not knowing is bliss" [57]. Further evidence reports even more profound impacts, where several students have expressed feeling almost depressed halfway through the course: "The course can give a feeling of hopelessness" [56]. As discussed in the work of Pargman and Eriksson [56], this effect suggests that the students were emotionally highly engaged in the sustainability topic.

— *Mindset change*: In addition to an increased awareness of the topic of sustainability, the primary studies present a change in the mindset of the students as a learning effect [8, 25, 36, 56, 88]. Issa et al. [25] received formal and informal feedback from their students and concluded that their unit shifted students' mindsets. The students recognized the potential damage of IT systems and were oriented to "using IT wisely," including minimizing IT usage. In the work of Casañ et al. [8], one can find direct feedback from students that sustainability education has changed their view of the field of Informatics and made them reason about aspects that never crossed their minds. Similarly, one student admitted to thinking about the people talking about climate change as extremists before taking the course—a vision that changed after taking it [36]. When asked to write a newspaper headline that would reflect any change in their thinking about sustainability as a result of attending the course, the students described in the work of Zeegers and Clark [88] submitted headlines that reflect how confronting the course was for some of them—a concrete example being "I am Lost!!—Please Show Me the Way to Sustainability."

— *Increased motivation*: Students have demonstrated an increased motivation to adopt a more sustainable practice or attitude as an effect of sustainability education [7, 25, 56, 76, 88]. We find expressive statements such as the "most significant [change this course has brought] has been the reawakening of an ambition to make a difference" [88]. The increase in motivation expressed by students also encompasses their professional practice: students who concluded a course on green computing mentioned a strong enthusiasm for green computing as something they will apply in their profession [7]. Finally, one student stated, "I was interested in marketing and stuff like that before the course, but now I feel like doing something that is more beneficial to humanity" [56].

— *Multidimensionality of the problem*: One of the challenges of addressing sustainability is that it entails multiple dimensions that need to be addressed in a holistic way. One of the reported effects of teaching sustainability was that students learned the multidimensionality of the problem at hand [56, 57, 88]. In fact, besides understanding the multiple dimensions of sustainability, students have also been shown to understand that the different dimensions are often in conflict with each other, specifically with the economic dimension.

Topic-Specific Competencies. The primary studies reported that the students learned about the following topics:

— *Negative impact of ICT systems (or the use thereof)*: The instructors of a master's degree course on sustainability and green IT describe that "Students were stunned by the damages of information technology usage locally and globally" [25]. Similarly, having analyzed the answers of the retrospective survey of a course addressing sustainability for media technology students, the authors acknowledge that they were successful in explaining the connection between ICT and climate change [16]. Furthermore, in another retrospective survey, students assessed the statement "Information Technology . . . causes new problems to arise that must be addressed" with an average of 4.62 on a 1-to-5 Likert scale [1]. Finally, in their reflections on the post-course feedback provided by students, the instructors in the work of Qureshi [68] note that, even if reported in limited cases, students demonstrate having understood that the convenience provided by technology can lead to unsustainable habits—one clear example being online food ordering systems.

— *Positive impact of ICT systems*: We have also found numerous examples that show that students learned about the potential positive impact of ICT systems—that is, about the potential contributions that these can have to address sustainability issues [1, 7, 16, 25, 32, 36, 37, 68, 76]. Concrete feedback from students includes "This unit is very important for future students to make the changes in the IT world" [25] and that the use of climate models provided them with new perspectives on what their contribution as future engineers can be [36]. Similarly, we observed that students acknowledged that sustainability is a concern for both the consumers and the designers of IT systems [37]. The majority of respondents on a retrospective survey also agreed to strongly agreed that thanks to the course, they understand the applicability of programming to solve complex social problems [76]. Concurrently, students strongly agreed that "IT makes potential solutions to the problems of sustainability available" [1]. The use of technology has also been described by students as a way to assist them in living more sustainably, namely by using mobile applications that track their traveling carbon footprint [68].

Practical Experience in the Form of Lifestyle Change. The primary studies report that the students learn about and test concrete lifestyle changes [11, 16, 68, 76]. This could be interpreted as the cross-cutting competence of "gaining practical experience." Interestingly, while the education was focused on the relationship between computing and sustainability, the changes most often refer to daily activities and/or community practices instead. In the work of Crompton et al. [11], one can find various concrete statements along these lines, particularly regarding the following:

— *Travel patterns*: "I now cycle to work," "Cut down on unnecessary journeys," "Have scrapped our second vehicle and use public transport or walk instead," and even "Moved house to reduce travel to and from work."

— *Consumption of energy, materials, and food*: "We now recycle cardboard and plastic as well as glass and cans. We shop for food now with an awareness of 'food miles' and unnecessary packaging and what's in-season," and "Buy only two newspapers per week . . . compost all relevant household waste, change all lighting to low energy." Concurrent observations in consumption patterns can also be found in other works [16, 76]. Further evidence of improved practices can be found in Qureshi [68], most of which reflect incremental (instead of radical) changes. We should mention that lifestyle changes are sometimes acknowledged as not being easy to achieve: Qureshi [68] describes situations in which students admitted to struggling to adjust to new lifestyle choices, but eventually persisted on them and were successful in taking (self-admitted) small steps. Finally, the majority of respondents of a survey in a study that used sustainability-themed projects in introductory programming modules have also agreed/strongly agreed that they can now see the potential application of sustainability practices in their own communities that was facilitated by the assignments and activities of the module [76].

Table 4. Other Effects Mapped on General Themes

Pillar	**Theme**	**Meaning of the category**	**Examples of primary studies**
(educational organization)	(achieved learning objectives)	Adding sustainability to education . . .	
Pedagogical approaches	Changing student demographics	. . . attracts new types of students and may change the demographics of the student groups.	[66, 75]
	New career opportunities	. . . provides new opportunities in work life.	[17, 29, 66, 67]
Modules	New proposals and openings	. . . will eventually lead to new modules, curricula, and even policies.	[38, 43, 44, 46, 48, 52, 54, 66, 67, 80]

5.4.2 Other Effects. The effects we describe in this section are effects that we extracted from the primary studies but go beyond the intended or achieved learning outcomes. Similarly to Table 3, we extracted and classified such effects into general themes (Table 4) described in the following.

Changing Student Demographics. Integrating sustainability into computing education makes computing education attractive to very diverse groups of prospective students. For example, while computing disciplines have traditionally been rather male dominated, this is changing when sustainability-related contents are emphasized [66]. Stone [75] reports that "the inclusion of socially-relevant projects and course themes has been shown to assist in attracting students to Computer and Information Science, and practical, problem-based applications have also been shown to attract females and under-represented groups to the discipline."

New Career Opportunities. The integration of sustainability in computing subjects has been shown to provide students with new skills and competencies [35, 49, 82]. As such, they also create new career opportunities as shown in other works [66, 67]. These new careers can be linked with the general evolution of society under the Sustainable Development Challenges and Climate Change in addition to required 21st-century skills [35].

New Proposals and Openings. The successful integration of sustainability into a subset of computing courses can eventually lead to new proposals and openings that may change a discipline. An example can be found in the evolution of the Educational framework for the Information Sciences master programs, which was revised in 2016 to include sustainability [241]. In some of the primary studies, the proposals focus on identifying elements needed for a core sustainability course (e.g., [54]), curricula structure or content [46, 48, 52], or even a policy/approach for including sustainability into education [43, 44].

5.5 Takeaways for RQ 2

In this section, we presented a *Framework for Implementing Educational Components for Sustainability* (see Figure 3). It consists of horizontal pillars (intended learning objectives) and vertical pillars (topics pertaining to sustainability and computing, and the educational organization). This framework with its pillars can inspire educators and prompt them with questions to consider. The vertical pillars about the educational organization, for example, raise questions about the scope of the education modules that should address sustainability or the pedagogical approaches to teaching sustainability. The horizontal pillars can remind educators about the different types of learning objectives.

Once an educational activity is being conducted, we can assess the achieved learning outcomes by evaluating the coverage of the various pillars. We can also use the framework to reflect on the implementation of education in a larger sense, such as reflecting on what modules are missing or the pedagogical approaches that are lacking. Such a framework could also be an instrument to accommodate change in the way we design and run education.

The preceding took prominently the perspective of educators, and, as has been pointed out in Section 4.3, the existing work dominantly views education as training. This implies that we have little insight into how education as emancipation can be implemented. The perspective of the learners is of course extremely interesting and relevant too. The learners may be increasingly diverse, considering ongoing efforts to develop education for lifelong learning, where practitioners (next to full-time students) and organizations need to acquire sustainability mindsets and competencies. In this direction, we might argue that the framework proposed here could be used as a "stepping stone" to (i) create a catalog that describes an educational offer in terms of the competencies and skills aspired by prospective students, and (ii) allow them composing their student journey and personalized growth where the atomic unit is not the module but the individual lecture within and across modules. Some initiatives are already emerging to support such an emancipatory view of personalized journeys—for example, by issuing digital certificates for so-called *micro-credentials*.[6] This is an interesting direction for future work.

In the discussion in Section 7.1, we add some additional discussion about the modules that are or should be taught in computing and sustainability education as well as the dominant types of building blocks used in teaching experiences. We relate the curricula and the pedagogical approaches required to increase the recognition of sustainability in computing education.

6 RESEARCH DESIGN (RQ 3)

In this section, we answer *RQ 3: What type of research design has been conducted on sustainability in computing education?* A study's research design provides the blueprint for the collection, measurement, and analysis of data, and aims to reduce the bias and increase the trust and reliability in the accuracy of the data collected for the research phenomenon or problem under investigation [123]. In RQ 3, we investigated the research design being conducted by the community against the proposed ACM empirical standards [214] guidelines with respect to the overall research design including the following subresearch questions: (i) the epistemological stance underpinning the research design; (ii) the research method(s) used and to what extent the method(s) included core attributes of the approach; and (iii) what threats to validity were considered, which potentially jeopardize the reliability of the results and the confidence in the conclusions that can be drawn.

6.1 Epistemology (SRQ 3.1) and Threats to Validity (SRQ 3.3)

First, we discuss what epistemological stance has been adopted as part of the research design (SRQ 3.1). Based on the results of our analysis, we consider these two subresearch questions together rather than separately as a result of the brevity of the data that was identified. SRQ 3.1 investigated the epistemological stance adopted in the selected research literature. Epistemology is the "theory of knowledge" and influences how that knowledge is collected and from which sources" [137]. In research terms, it is argued that the philosophical standpoint should be made clear from the beginning, as a researcher's view of the world and knowledge strongly influences the choice of methodology and methods and interpretation of data [174]. Within epistemology, there are several approaches and branches, such as positivism and interpretivism, which are diametrically opposed. A thorough treatment of the relationship between ontology, epistemology, methodology, and methods is beyond the scope of this work, and readers are referred to the work of Bridges [120] for a more in-depth discussion of the relationship and importance of epistemological stance and research design. During the analysis, we found no studies that [explicitly] stated an epistemological stance, which is considered a key founding principle in guiding research in education, underpinning the consequences for knowledge construction within the research community [147]. This

[6]Edu Badges: never stop learning https://edubadges.nl

Table 5. Number and Type of Studies Classified According to ACM Empirical Standards [214]

Type of empirical study	No. of studies	No. of essential attributes
General standard	58	16
Systematic review	2	13
Questionnaire survey	11	18
Interview study	5	10
Case study	13	12

leads to the question of whether it is possible to derive an implicit epistemological stance through a reverse mapping between method and epistemology; however, that is beyond the scope of this already extensive work. The absence of an [explicit] epistemological stance raises important questions regarding research design overall, and the reliability and generalizability of the results as it is concerned with all aspects of the validity, scope, and methods of acquiring knowledge. In addition, it influences how researchers frame their research in their attempts to discover knowledge and the extent to which its transferability can be assessed.

SRQ 3.3 investigated the threats to validity in the identified research literature. Threats to validity refer to specific reasons as to why researchers can draw incorrect conclusions when they make an inference in an experiment because of covariance, causation constructs, or whether the causal relationship holds over variations in persons, settings, treatments, and outcomes [135]. While the concept of threats to validity has evolved over the years from the initial discussions by Campbell and Stanley [121], Shadish et al. [228] identified the potential threats to validity, and the statistical procedures of educational experiments, that are generally considered in modern-day research including statistical conclusion validity, construct validity, internal validity, and external validity. From an educational research perspective, Creswell and Creswell [134] consider two primary threats critical to consider: internal validity and external validity, where internal threats relate to drawing appropriate inferences to the actual design and procedures used in an experiment, whereas threats to external validity are problems that threaten a researcher's ability to draw correct inferences from the sample data to other persons, settings, treatment variables, and measures. According to the work of Cook [125], three threats may affect this generalizability: the interaction of selection and treatment, the interaction of setting and treatment, and the interaction of history and treatment. During the analysis, we found only six studies that considered threats to validity in their research design, which are considered key characteristics of experimental research in education [135]. The general absence of threats to validity raises important questions regarding the research design overall and the reliability and generalizability of the results.

6.2 Methods (SRQ 3.2)

SRQ 3.2 investigated the methods adopted in the primary studies, and to what extent they aligned with the essential attributes characterizing each type of empirical study. Table 5 shows the number of studies that belonged to each type of empirical study and the number of essential attributes[7] we used to evaluate the quality of each paper. We used the classification from the ACM [214] to categorize the type of empirical studies as shown in Table 5.

General Standard. This general standard applies to all studies that collect and analyze data. The results of our analysis identified that the majority of the studies were classified into the

[7] https://acmsigsoft.github.io/EmpiricalStandards/docs/

general standard category as reported in Table 5. Focusing on the research type of the papers within the category, we classified them into the following subcategories: (i) a vision/proposal paper describing an educational plan for the future, (ii) a position paper recommending a course of action, (iii) an experience report, and (iv) a proposal of something already happening. From our analysis, we found that the majority of the studies classified in this general category can be considered "Experience reports" [7, 15, 59, 65, 72] or "Proposals" [10, 83, 84]. A small number of papers were classified as "Vision" papers (e.g., [57, 89]). With regard to the attributes that describe the purpose and objective of the research questions, we found some diversity. For example, in the experience papers, the studies report that the most common problems belong to the following topics: (i) studying the impact of sustainability software engineering education [52, 59, 66]; (ii) developing green computer courses [7, 34, 79]; (iii) studies suggesting system thinking games, creativity, and practical assignments to introduce sustainability [15, 61]; and (iv) curriculum design to introduce sustainability competencies in software engineering or CS courses [24, 43]. For proposal papers, we also found similar topics to that of the experience report papers, such as assignments related to various sustainability topics (e.g., [84]), curriculum design and competencies (e.g., [83]) as well as proposals suggesting how to teach sustainability and social skills (e.g., [38]), green computing models for sustainable development [28, 34, 87], and introducing sustainability into bachelor courses [41, 54, 60]. The vision paper [57] discussed future ways to teach sustainability based on an introductory course in sustainability and ICT, whereas another vision paper [63] describes an educational plan of sustainability in computing for the future.

Another essential attribute we analyzed was whether the methodology was appropriate for the goal or problem stated. A significant number of studies did not clearly report the methods used for experience report papers [15, 43] or were "not applicable" in the case of position papers [65, 83]. The reason is that we noted that some vision or proposal papers under this category did not carry out any research, and consequently including a research method does not make sense. Other papers partially report the methods used somewhere in the paper [7, 59], but there is no explicit methodology section that describes the methods employed for data collection and analysis. Finally, there is a set of papers that clearly include a clear methodology section used in the studies [30, 52, 61, 68].

With regard to the what, where, when, and how data were collected, only some studies in this category indicated fully or partially how and where the data was collected [7, 15, 30, 35, 43, 59], whereas the others did not provide such information or were "not applicable" according to the study. In addition, many of the studies provided the number of subjects who participated in the experiments or surveys ranging from a low number of participants (e.g., 16 in the work of Klimova et al. [30] or 20 in the work of Penzenstadler and Bauer [59]) to a huge number of participants (e.g., 1,270 in the work of Porras et al. [66] or 2,420 in the work of Zalewski and Sybramanian [87]). Other studies did not indicate the number of subjects. Surprisingly, for the rest of the 11 essential attributes defined for this category (e.g., discuss threats to validity, clarify the role of the researchers, innovate the research methodology, or discuss statistical power or saturation), in the majority of the papers analyzed we could not find this information or this attribute was "not applicable" based on the type of study being reported (e.g., experience).

Systematic Review. In this category, we defined 13 essential attributes but we only found two studies [26, 29]. The study of Ramoz et al. [26] is an SLR that investigates research trends on sustainable development for training software engineers on sustainable principles, whereas the work of Klimova and Rondeau [29] is a survey that provides an educational landscape of green ICT and sustainable computing. Both studies partially describe the problem objective or research question, and both outline an appropriate methodology. Only the work of Klimova and Rondeau [29] provides the information regarding data collection. The rest of the essential attributes defined in the

ACM standard have not been included in the work of Ramoz et al. [26]. However, in the case of Klimova and Rondeau [29], the authors mention the detailed steps and replication package of the process, the inclusion and exclusion criteria, and the data extracted from the primary studies.

Questionnaire Survey. In this category, we classified eight studies where open-ended questions are systematically analyzed. Several types of goals are investigated. For instance, Polmear et al. [64] mix a questionnaire survey with qualitative questions about ethical aspects that include sustainability. Ethical aspects are also investigated in the work of Bielefeldt et al. [4] to illustrate how sustainability practices include ethics in teaching. The study uses open-ended questions to extract additional thoughts from the participants. In the work of Mann et al. [44], a survey compares the understandings of sustainability using different benchmarks and discusses the attitudes of the participants toward integrating sustainability in computing. Another work [71] investigates the use of green computing techniques and how green IT topics are taught in CS courses. About the rest of the essential attributes that characterize this category, only Mann et al. [44] did not include the research questions, whereas other works [4, 42, 44, 64, 80] included these. Additionally, all of the studies indicated an appropriate research methodology, described how and where the data was collected, and noted how the data was analyzed (except the work of Mann et al. [44]). We did not find evidence for the rest of the essential attributes (e.g., how responses were monitored or managed, analysis of response rates, or measuring the constructs using validated scales). Only some of the studies partially indicated that, for instance, the threats to validity [64], described systematically the replication of the study [44], or described how the participants were recruited [4]. Only two studies [44, 80] detailed how the questionnaire instrument was created.

Interview Study. In this category, we only found two studies [69, 73]. The first study reports semistructured interviews from program leaders and teachers about how social sustainability can be integrated and taught, whereas the second combines quantitative and qualitative analysis to explore the awareness and conceptual understanding of environmental issues in students enrolled in an introductory computing course. The interview study investigated how social sustainability is operationalized in engineering programs and the resources needed to support social sustainability educators as a learning objective. In this second study, two groups of 137 CS/IT students were asked about 20 questions on student computer use and green computing. Both studies indicated the research questions and the methodology while partially indicating the details of the data analysis process and the selection process of the interviewees. Only Robila [69] described the demographics of the participants, whereas Skogh et al. [73] included the experience of the subjects. Finally, none of the studies discussed how saturation was achieved or included the threats to validity. Notwithstanding, in the work of Robila [69], we found some discussion around the possible biases reflected by the researchers.

Case Study. In this last category, we found 11 studies that cover different topics. For instance, the work of Stone [75] is a 2-year case study aimed at creating introductory courses focused on sustainability topics, whereas Watson et al. [85] use a tool to assess universities' curricula in sustainability development, and two surveys were conducted to investigate the results of the assessment of sustainability courses in environmental engineering curriculum at a university in the United States and the student's perceptions of the contribution of such courses to sustainability. Other studies analyze the effect of teaching sustainability topics in regular courses, such as the work of Tam [78], which reports the results of a sustainability course taught over 3 years and the effectiveness of teaching sustainability, whereas Rubio et al. [46] analyze the learning guidelines (i.e., a document that describes the course details) of degree programs in informatics and industrial engineering in 25 Spanish universities and proposes a curriculum model to embed sustainability into engineering education. Other studies like that of Cico et al. [9] analyze 45 project proposals to identify social and technical sustainability aspects and how sustainability topics are introduced in customers' project descriptions.

From our analysis of the rest of the essential attributes characterizing case studies, we found that 3 out of 11 studies [23, 75, 88] included the research questions, but none of the studies provided examples for the questions investigated (three paper categories, i.e., questionnaire surveys, interview studies, and case studies, include adding examples of the research questions as an essential attribute). Conversely, all of the studies indicate, fully or partially, a proper research method for each case study, and all except two [1, 78] indicated how and where the data was collected. Compared to the other categories, the studies indicated in most cases that the rest of the essential attributes were covered or partially covered except in some case studies that did not include some of these attributes. For instance, studies like that of Penzenstadler et al. [62] did not include the demographics of the participants, and the study of Huber and Hilty [23] did not describe the site in rich detail. Others (e.g., [46, 78]) did not justify the selection of the case study, whereas only three studies [23, 62, 75] included some description for the threats to validity. For the rest of the studies, most of the essential attributes were detailed.

Summary. Less than half of the papers we analyzed actually present empirical research. It is challenging to summarize the quality of the studies for each category and for many different essential attributes that should characterize each of the studies. Apart from five papers that could belong to two different categories, we found some common patterns in our analysis revealing the quality of the studies analyzed. There is a significant number of studies that, according to ACM guidelines [214], do not describe the majority of the essential attributes. This is especially bad in the general standard and questionnaire survey categories. However, we cannot provide significant conclusions for systematic reviews and interview studies, as we only found a small number of papers in these two categories. Yet, the case study category exhibits good results for the papers classified. We found that most of them describe the majority of the essential attributes, so it seems more easy to classify papers under this category than for the others. In Figure 4, we statistically summarize our findings attending to the quality of the studies and the number of essential attributes supported and not supported. It should be noted that we did not include in the count the attributes labeled as "not applicable." In addition, in the left side of Figure 4, we show the ratio of attributes supported per study type with respect to the number of papers for each category.

6.3 Takeaway Lessons (RQ 3)

This section provides an analysis of the types of studies that have been conducted with an emphasis on the specific design of the research including the procedures involved in them, such as sampling, data collection instruments, and protocols. In the absence of any generally agreed standard for evaluating the quality of the research design, we classified each study using the ACM Empirical Standards [214] as a framework to aid in the identification of the essential, desirable, and extraordinary attributes for empirical research for a particular method. Alternative perspectives on evaluating the quality of research have been proposed by Lincoln [184], Tuckman [243], Richardson and St. Pierre [218], and Creswell and Miller [136]. In combination, they offer philosophical, procedural, and reflexive criteria to use in evaluating research design. However, Creswell [133] argues that as a result of the fundamental differences between methodological approaches to research, each merits its own criteria for evaluation. Because of diversity in the various approaches and subject areas, there is no single gold standard for determining the quality of research design, but there is a clear need for the research community in this area to consider moving toward adopting or developing a common standard by which research output can be transparently and consistently evaluated against. Our analysis highlights that the majority of studies published are experience reports that incorporate a range of different methods. These studies are underpinned by a

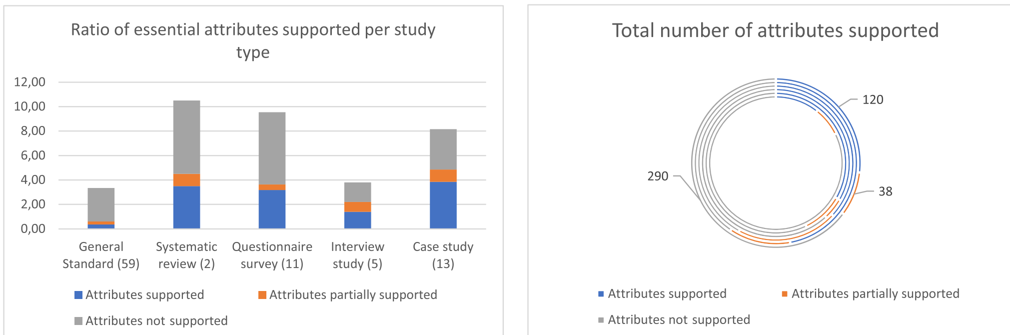

Fig. 4. The number of essential attributes covered for the different types of research methods. On the left side, we show the ratio of attributes supported per study type with respect to the number of papers for each category. On the right side, the quality of the studies and the number of essential attributes supported and not supported, for example, whether the data reported on (e.g., a survey or a detailed SLR protocol) is available.

pragmatic and ad-hoc approach rather than a theoretically pure and rigorous approach to research design. As a result, the published output exhibits a similar alignment of shortcomings in research design to those reported by Hall et al. [159]. While the papers do not follow a rigorous approach to the design of the research from a theoretical perspective, the results provide insight into how sustainability can be integrated into the computing curricula at different levels of granularity. As a result, it is strongly recommended that researchers investigating sustainability in computing education adopt a more meticulous and repeatable approach to the quality of the research being conducted. This is imperative if any improvements or recommendations on educational practice, the quality of policy debates on educational provision, and the advancement of knowledge in the field are to be achieved that are supported by sound empirical evidence. To improve the overall quality of the research design and the validity and reliability of data-gathering procedures, we strongly recommend the following: clearly stating an explicit epistemological stance, adopting a research design appropriate to address the problem under investigation, clearly describing the data-gathering methods and adopting an appropriate sampling strategy where applicable, using appropriate methods to analyze data, explicitly stating assumptions, and framing the limitations of the study around threats to validity.

We provide additional discussion at the end of Section 7.1 by comparing our analysis of the empirical standards used to other research methods regarding its quality and the research instruments.

7 DISCUSSION

This study provides an understanding of existing work on sustainability in computing education and its limitations. The review from 2019 by Pollock et al. [213] suggests that sustainability or climate change has been incorporated into computing education primarily at an "aspirational level, without any tangible results to date" (p. 16). In the present systematic review, spanning a wider set of digital libraries, we did in fact find 89 primary studies (compared to 11 papers in the work of Pollock et al. [213]). Together, the articles present different perspectives on how sustainability education can be, or already is, implemented and researched on different scales (seminars, courses, programs) and on different levels (K-12 to Ph.D. education).

We have focused on capturing and presenting the various ways in which sustainability in computing education is conceived of and implemented within the collection of papers rather than in the individual papers. Except for the analysis to answer RQ 3 about the research on sustainability in computing education, we have done a qualitative and not a quantitative analysis. Capturing the papers that discussed the themes we identified and presented, we can only see whether or not a theme has been discussed frequently or less frequently. Future analysis of the state of the art could include more quantitative analyses.

7.1 Limitations of Existing Research on Sustainability in Computing Education and Directions for Future Work

In the following, we describe and discuss limitations or gaps in the current literature and how they could be addressed in future research.

7.1.1 The Research in the Light of the Severity of Challenges and Demands for Unprecedented Change. Much more work is needed engaging with the role of computing education for urgent, unprecedented system change. Stein et al. [234] argue that education needs to be disruptive, and it needs to be about "growing up" and showing up differently, facing the "impossibility of sustaining our contemporary modern-colonial habits of being, which are underwritten by racial, colonial, and ecological violence" (p. 275). We did identify work that engages with conceptions of computing as disruptive (Section 4.2) and have also pointed to studies that argue for radical changes to computing education. As discussed in the work of Eriksson and Pargman [16], approaches for curriculum change vary from the incremental and integrated to the transformative and critical. Such transformative changes rely on the idea that promoting a just and sustainable society must be the goal, not computing itself [235]. We find that the majority of studies present smaller and incremental changes to a curriculum to include sustainability rather than a fundamental redesign of education (Section 5.3). We also found that existing work is anthropocentric, motivating sustainability for human well-being (Section 4.1).

Education is dominantly conceived of as training predefined knowledge, skills, or competencies (Section 4.3). We have identified an alternative understanding of education, which we termed *emancipatory education*, inspired by previous research. Viewing education as training has been argued to be too limited. It renders education into an instrument to bring about certain competencies that are decided upon by the few, in the current unsustainable system. It locks education to being about training certain competencies thereby reducing the possibilities for alternative futures to emerge in education and limiting the potential of education for change [149, 164]. The potential of education for alternative futures and radical change has been argued to lie in being a space for reflection, experimentation, and creativity, allowing for the possibility of the impossible, not yet imagined [197]. Education could be a place in which new ideas, understandings, and ways of being in the world evolve, drawing on and taking into account the diverse experiences that all involved parties may bring (students, teachers, others outside school or universities) [149, 164, 197]. It would require to make space for the individual learner's experiences and meanings. Such education has the purpose of "subjectification" [112]. Ideas of education for radical change and sustainability stand in contrast to dominant framings of contemporary education. Education has increasingly become oriented toward producing certain disciplinary outcomes in an effective way and has become instrumentalized to achieve economic goals [91, 101, 189]. In education for radical change, concrete learning objectives may still be important, but they may be used in new ways, exploring change and the potential of education as a part of transforming society. Importantly, learning outcomes should not only be defined on the grounds of pre-existing occupational profiles and businesses or economic agendas but rather help explore novel and potentially disruptive profiles.

Among the work that embraces the need for radical change analyzed here, we find the argument that education should play a more activistic role considering the change that is needed [40]. In light of the literature on the role of education, we should be cautious not to turn education into an instrument for activism as it is perceived by certain people. This would go against the idea of education as emancipatory. However, education might involve activism or direct actions as a means for learning and acquiring competencies. If students are to take part in making and unmaking futures, they need to be emancipated. Students need to be given opportunities for deep reflections on the root causes of the current crisis to contribute to a social and political movement for a fundamentally different society [173]. As a part of this, students need not only cognitive but also action capabilities—they need to engage with values and emotions.

Engaging with our predicaments likely evokes unpleasant emotions [93]. Emotions have gained increasing attention in the past years in the education for sustainability literature, albeit less so in computing education. However, the effects of sustainability education identified in this work point to emotions (Section 5.4): students become more aware, and they become "deeply concerned," anxious, and restless . Existing research suggests that young people today are already very concerned and even pessimistic about the state of the world. The described outcomes of education may therefore not necessarily be the effect of the education but may describe the students' general state. An important question therefore is how education should engage with emotions—for example, emotions from anticipating different futures, anxious and desirable futures [107]. A recent review by Pihkala [211] collects ways to address climate anxiety in education. It has inspired a recent intervention study in a sustainability course for media technology students [90]. More than addressing negative emotions, education should also promote "critical hope" [93] or "active hope" [185]. Ojala [93] reviews the role of education in promoting hope and points out that hope is a contested concept as it can be based on denial or de-emphasizing the severity of sustainability issues. Hope, however, is argued to be an "existential must" or an ontological necessity [154]. As humans, we tend to only take action when motivated—for example, if discomfort arises. It is therefore important for students in computing to engage and deal with emotions. We pose the open question of how such engagement with emotions can become more common, considering dominant norms and values in computing that suggest computing is a rational, value-neutral endeavor, which is discussed in the following.

7.1.2 Connections to Research on Equality, Justice, Norms, Values, and Power. Critical research on norms, values, or the culture of computing or computing education has been conducted for decades. Much of this work has been conducted by gender researchers or with a focus on gender, aiming to understand and address the under-representation of women [94, 188, 199, 200, 207, 208, 216]. This research repeatedly concludes computing is socially (re)produced or positioned as purely rational, technical or nonhuman, abstract, and reductionist. Reductionism is not only understood in terms of reducing complex problems to smaller parts but also avoiding engaging with problems in their complexity, approaching all problems with mathematical and technical methods, and valuing rationality. This culture is argued to be aligned to, or "co-produced with," (hegemonic) masculinity. It excludes women and puts them off [225]. The culture of computing education is also argued to simply be disengaging, privileging the already passionate students, mostly male, and stereotypical ways of engaging in computing [122, 199].

Recent work in computing education emphasizes the need for broader discourses of equality and justice. This body of work engages with various forms of inequalities, discrimination, exploitation, and colonization, including environmental degradation. A recent special issue on justice-centered computing education [180, 223] even asks, poignantly, "Why computing education?" (in contrast to other work to help people affected by the pandemic of climate disasters), and "Why broadening participation?" (in contrast to questioning value systems that reproduce discrimination). Such questions are asked in light of the fundamental injustices and problems facing disenfranchised groups, and the structural issues that underpin such injustices, which also are maintained by the existing education system. A theme in this work is establishing counter-hegemonic practices in computing education, building on and acknowledging marginalized knowledge in computing, such as indigenous knowledge [145]. A focus here is moving from a critique of hegemonic practices to integrating different knowledge traditions and practices.

Work on sustainability in computing education should connect to and build on this work on equality and justice. A recent review of work on climate mitigation [236] has drawn a similar conclusion: an important step is to connect the work on equality and climate change, which has so far hardly happened. They find that the reasons for our collective failures to address climate change are a "narrow-techno-economic mindset" and failures of education to open vistas for imagining fair and sustainable societies. Narrow techno-mindsets are also problematized in the literature as an equality, which highlights the overlap of these areas of work.

Norms and values are being discussed in the articles we reviewed here, and those discussions could be improved by connecting to the body of work on equality or justice and power. For example, Easterbrook [13] criticized computational thinking as the focus in computing education and suggests systems thinking as a necessary competence to work for sustainability (see also Section 5.1 on learning objectives). Computational thinking is reductionist, and the work on gender and equality helps in understanding why and how reductionist framings are maintained. Another example is the work by Samuel Mann, who argues that students should become change agents promoting strong sustainability, which "will be at odds with other, less forceful sustainability perspectives" [57]. He suggests: "In the best of all possible worlds, we would like them to act as insiders who are part of the dominant culture, but who at the same time try to change the system they are part of from within" [57, p. 19]. There is a lot of gender research on cultures of computing, science, and engineering, as well as education in these fields that help understand cultures and how they are maintained. Connecting critical research on equality, justice, or power and sustainability research seems important to engage with the complexity of the sustainability challenges and develop education for system change.

7.1.3 Implications of Current Approaches to Curriculum Development and Directions for Future Work. In light of the dominant framings of sustainability in computing education as training in separate modules, we raise concerns about *student well-being*. What happens to students if they learn about the great challenges we are facing in a module on sustainability, with the outcomes of being restless and very concerned, feeling discomforting emotions? They may have gotten support to deal with emotions during the sustainability module but might need to suppress anxiety or grief in the rest of education, as it lies outside the norm. Suppressing uncomfortable emotions is one unsustainable way of handling them, which can lead to depression and stress [211]. This is another reason sustainability cannot be left to a course or a few shorter modules only. Addressing these concerns, emotions, and well-being is important for all courses. There is evidence that computer workers and their products can significantly benefit from well-being practices [206] that can be taught to computing students. If computing is to contribute to the well-being of others, humans, and other species or the planet, then the discipline needs to evolve as a discipline going beyond the understanding of technology as a purely rational means of interaction.

In light of all this, we ask the question of how to proceed with curricula and pedagogical approaches for sustainability in computing education. On the one hand, we might have reached a critical mass of work that could be used to define standards and curricula. It could increase the recognition of sustainability in computing education and hence promote change of norms. It may also help to push or even "enforce" sustainability education, making sure all students get a chance to learn about and engage with different aspects of sustainability. The learning objectives described in the literature reviewed could inform such a step. On the other hand, we have identified that more encompassing views of education, which we chose to call *emancipatory education* in line with the literature on education for sustainability (Section 4.3), are mostly absent from the material reviewed. This implies that we should develop education in other ways that grant freedom and trust, allowing creativity and diverse individuals to develop and contribute to knowledge and change in "their ways."

The review results are limited in terms of more specific topics within computing and sustainability, such as on software architecture or software testing and sustainability. This may be due to our search query that looked for papers within computing and sustainability. Our SLR could hence be extended to cover these computing-specific education papers.

To find other holes and get a more "complete" picture of what sustainability in computing education can entail, our findings could be mapped to other existing standards, such as to the Dublin descriptors like, for instance, "making judgments," which emerged as especially important for sustainability in computing education, for its intrinsic need of a holistic discourse. If such mapping would be present when combining computing and sustainability topics in the design of new courses (or redesign of existing ones), educators could use the mapping to reflect on which learning objectives (e.g., "making judgments") should be achieved with a true combination of computing-sustainability topics, like architecture assessment methods that embed sustainability dimensions, and which would instead be achieved by separate sustainability and computing specific topics that are orthogonal and strengthen one another (like architecture quality assessment methods on the one side and sustainability theories on the other side). They are the European Union standard classification used in educational frameworks for curricula development and accreditation. As such, they should serve well for the purpose of integrating sustainability into computing curricula. However, they have received criticism for not addressing attitudes and competencies as, for example, proposed by Frezza et al. [155]. In addition, covering the relationship between existing computing topics and what is generally understood about the societal transformations needed may be missing the point, as the changes needed are claimed to be emancipatory or require an openness when working with sustainability competencies. Key sustainability competencies were only found based on the work by Wiek et al. [252] from 2011 (see Section 5.1). However, these have been updated since [201].

It is our hope that the present work will lead to further developments of existing frameworks for computing curricula. A first scan of the ACM/IEEE curriculum published in 2020 [153] shows, for example, that indirect impacts or rebound effects of computing systems are not mentioned.

One question for the development of computing curricula is how to make space for sustainability education. We see that existing computing curricula such as the ACM/IEEE curriculum [153] get expanded item by item [107]. Sustainability is one of many items being added or injected into the curriculum, just as other items. It is next to impossible to discard any items because they all still seem relevant to some degree. As argued by Klotz [177], humans have a tendency to solve challenges by adding things and making things more complex—rarely do we manage to simplify and subtract. Computing is a young discipline, so it should be easier, compared to other subjects, to fundamentally rethink the curriculum. Getting rid of mandatory curricula rather than creating ever more might be a preferable approach to engage with sustainability, especially as "sustainability add-ons" risk being seen as less relevant to core technical topics as long as a techno-centric computing culture persists. Such an idea is well aligned with the view of education as emancipatory. It would require a broad and critical introduction to technology and our current predicaments, a change of computing culture that orients students to abstract, reductionist technical competence. Embracing the idea of education as emancipatory (see Section 5.3), as something that goes beyond training that which we already know, implies that we open up education and leave space for concerns and development that is not determined by the educator or other people in power. This could mean leaving spaces in the curriculum for students to define, or even moving away from the idea of designing education based on curricula.

All of these points raised in the discussion should be investigated focusing on different education levels. Progression in learner development has hardly surfaced in the results presented here.

7.1.4 Limitations of Existing Research and Outlook. Our analysis reveals that a large number of the articles are experience reports rather than thorough research studies. The current state of research on sustainability in computing education reflects the state of computing education in 2004. Most of the papers then were classified as "Marco-Polo papers" [92], work of the nature "I went there [e.g., programming education, here computing education for sustainability] and I saw this" [e.g., the students liked it]. Such work is of value for sharing experiences among educators. Conducting more rigorous research could possibly increase the value of the research by providing more trustworthy evidence. Setting up standards for research could help but also limit creativity and experimentation. As argued before when discussing curricula for education, standards for research could also lock research to our contemporary system and ideas of how to conduct relevant research. In any case, more empirical research is needed, using a variety of empirical research methods. Funding for such research is necessary. Section 6 provides quality attributes from the ACM standard. For the experience report, the standard is less applicable so developing standards for this kind of publication might be useful. A new standard for research on educational experiments and interventions that assures quality and grants freedom could also be valuable.

With an understanding of education as emancipatory (see Section 4.3), the role of research could be to capture personal growth or novel, more sustainable ways of living, understanding, or relating to the world. Research here might be more agile, adapting methods and theories to what emerges from education practices. Creative empirical methods (e.g., [172]) might be a source of inspiration. Another step forward to new ways of doing research could be the collaboration with like-minded people from other disciplines and external stakeholders, which is already used as a pedagogical approach (Section 5.3). As many have argued, we need to cross disciplines and benefit from interrelationships rather than sticking to silo thinking.

7.2 Threats to Validity

For this section, we considered various classic sources (e.g., [176, 254]; however, as observed by Ampatzoglou et al. [100], there is no standard way of writing about the threats to validity, in general and specifically for SLRs, but it is common to include construct validity, reliability, internal validity, and external validity, according to the guideline proposed in other works [222, 255], which we adopted in the following.

Overall, this work is a result of a long collaboration. All of the authors participated in this work of reviewing the literature and writing this article from the start to the end, a process that lasted 22 months until we submitted the first draft for review. During those 22 months, we met regularly every week to work together and discuss our findings and writings. We also engaged in vivid discussions of what this review should include and not include, and how this and other research should be conducted.

Construct Validity. This concerns the correct data collection and the correct measurement of the theoretical concepts [144]. The authors have different expertise within computing, education, and sustainability, and the long duration of collaboration allowed us to bring together our different experiences and relevant prior research we found relevant. While we built on our background knowledge to shape the study design (and this might have introduced strong biases), we also defined an explicit protocol following the guidelines in the field and refined it in a number of iterations to ensure a thorough research process.

Reliability. This concerns whether the study is replicable and extensible by other researchers. We carefully documented the overall structure of our study in an explicit protocol, including the research questions, criteria for inclusion/exclusion, the search string, and the snowball process. In particular, the inclusion and exclusion of primary studies are essential components of our research protocol. Therefore, we assigned two researchers to look at each paper; each gave a relevance score independently. In the case of disagreement, a third researcher looked at the paper so that consensus could be achieved. Finally, the whole group did the snowballing. For each paper, one group member identified the relevant papers. Then, a different member analyzed the accepted papers, validating their relevance according to the inclusion and exclusion criteria. Concerning the analysis, we recognize that a more explicit description of the procedure in the iterative thematic analysis and documentation of results per paper would increase replicability, hence validity. To mitigate this limitation, we shared at least early results from analyzing each paper in the replication package.

Internal Validity. This concerns whether researchers interpret the data correctly. Accordingly, one possible threat is misinterpretations of terms used in papers that were collected. To mitigate it, we discussed each finding in groups of researchers and had weekly meetings for discussion during the past 2 years, in which we discussed in subgroups and the whole group. We have a strong background in this domain, coming from five different European countries and nine different universities and having different experiences within the fields of sustainability, computing, and education.

External Validity. This concerns how well the study is generalizable. Since SLRs collect papers based on a search string, any papers that meet the search string are included; bias can pertain to the search string itself and the snowball activity. We discussed the search string among all authors to mitigate this threat. After several interactions of rectifying to include as many relevant papers as possible and avoid biases like culture and sex, we have obtained the status quo regarding sustainability in computing education. We also knew papers that we expected to find in the search results, which allowed us to evaluate our search strategy. This was one of the reasons we also included the education workshop ICT4S, as that contained papers that we did not find in the four databases but that we saw as relevant to our study. It is possible that we have overseen papers in the snowball process, given that it was done manually. However, we tried to avoid this from happening as much as possible by having a rigorous process.

8 CONCLUSION

This article presented the state of the art on conceptions, implementations, and research on sustainability in computing education. Educators and researchers can use them to position their own work—for example, on how they conceive of sustainability as well as computing and education for sustainability in the context of computing education. The framework presented in Section 5 captures different aspects of current implementations, such as learning objectives and outcomes as well as pedagogical approaches. We found some evidence that sustainability education is appreciated by the students—they become aware, concerned, and gain competencies. We were able to map observed learning outcomes to the identified learning objectives. We also described other outcomes, suggesting that sustainability education is about more than learning but change, such as computing and education practices.

We found 89 articles describing sustainability in computing education, but the work that engages with the severity and complexity of challenges and the dysfunction and violence of our current system or ways of organizing life is rather scarce. Adding sustainability as a topic as other topics is inappropriate in our view. We need to transform education and explore the potential of education and computing in a process in which new practices and processes evolve. Developing sustainability in computing education needs to take inspiration from various fields of knowledge, especially critical studies of technology and education. Education should not be reduced to acquiring competence but can be seen to be about contributing to democratic change and learning as a part of the process.

A condition for an education that takes responsibility is a caring orientation to the world and the future. This would mean challenging and changing norms and values in computing education that encourage individuals to engage in computing as a purely technical, abstract, and rational undertaking. Although understanding technical underpinnings and development trajectories of computing are relevant, reproducing or continuing on them might not be. We are missing a connection to previous work on gender and under-representation that helps to understand how norms and values are reproduced in power structures. Arguing for the potential of education for novelty and hope, we pose the open question of how computing education can orient itself more toward emancipation, based on care, experimentation, critical thinking, and reflection.

Our times are characterized by trouble, and equally "by ingenuity and exploration, by invention and reinvention of old ideas" [150]. We are living in exciting times [195], in which we must accomplish unprecedented change, setting stop not only to emissions but to violence that is built into our modern ways of being. Sustainability education still is somewhat of a niche activity within computing education, which urgently needs to change. This review shows that concepts and experiences with sustainability in computing education do exist that can be grown through various types of collaborations, with actors from within computing and academia, as well as outside.

APPENDIX

Table 6. Number of Papers Excluded by Different Criteria D, duplicate; L, language; A, accessibility; S, short paper; N, non-academic; C, content

		Exclusion by EC1–6					Exclusion by not fulfilling IC1–2	
Database	Total found	D	L	A	S	N	C	Final inclusion
WoS	34	5	0	1	1	0	23	4
Scopus	14	1	0	0	4	0	8	1
IEEE	199	2	0	0	0	23	174	18
ACM	86	0	0	0	1	0	76	9
IJHSE	140	0	0	0	2	0	128	10
CompSusEd	4	0	0	0	0	0	1	3

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