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A systematic review of the top-50 most-cited articles on socio-scientific issues in K-12 education

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Abstract

Socio-scientific issues (SSI) has been shown to serve as a useful learning context in K-12 education, not only to help students improve their scientific literacy and develop 21st century skills such as argumentative and decision-making but also to promote students' sense of self-efficacy and civic responsibility. From the perspective of highly cited papers, combined with the relevance model of science education, this review conducted a systematic review of the top-50 most-cited articles in SSI in K-12 research in the Web of Science database and made a diagnostic evaluation of them according to the relevance model of science education. The results showed that the effects of teaching intervention on the nature of science is the most emphasized theme. High school students are the most focused demographic, and energy is the most highlighted topic. The relevance model of science education shows imbalances in dimensions, imbalances between present and future, and imbalances between intrinsic and extrinsic factors. This review thematically illustrates what is known and what needs to be known for future research of SSI in K-12 education. On this basis, the research trend and future education measures of SSI in K-12 education are put forward, and the further integration of SSI into school education is proposed.

Keywords: socio-scientific issues, K-12 education, relevance model of science education, systematic review

INTRODUCTION

Socio-scientific issues (SSI) denote significant societal concerns inherently linked with scientific aspects. These intricate and multifaceted issues are likely to be encountered by individuals, notably K-12 students, in their daily experiences (Kolstø, 2001). The integration of SSI stands as the cornerstone of contemporary social science education within classrooms (Driver et al., 2000; Hazelkorn et al., 2015; Sadler et al., 2007). Over the last two decades, a burgeoning body of research has demonstrated that SSI can serve as a valuable framework and investigative tool for enhancing scientific comprehension, understanding the nature of science (NoS) (Dawson & Schibeci, 2003; Khishfe & Lederman, 2006; Sadler et al., 2004), improving argumentation and decision-making proficiencies (Osborne et al., 2004; Sadler & Donnelly, 2006), fostering increased interest and motivation toward learning science (Albe, 2008; Bulte et al., 2006; Harris & Ratcliffe, 2005; Parchmann et al., 2006), and bolstering student self-efficacy (Sadler & Zeidler, 2005).

Numerous studies have highlighted that students in K-12 education often lack interest in science, particularly in physics and chemistry, viewing science as distant and disconnected from their lives and society (Avargil et al., 2020; Gilbert, 2006; Hofstein et al., 2011). Furthermore, science appears to garner even less enthusiasm among male students (Avargil et al., 2020). SSI endeavors to stimulate students' interest and engagement in science, rendering science education more pertinent (Calik & Wiyarsi, 2021; Stuckey et al., 2013). Notably, in the United States (USA), a compelling survey revealed strong advocacy among a considerable percentage of science teachers for incorporating more real-world issues into the classroom to enhance the relevance of science education (Luft et al., 2009). Stuckey et al. introduced the relevance model of science education, encompassing three dimensions (individual, societal, and vocational) along with present-future and intrinsic-

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Contribution to the literature

- This paper contributes to the literature by conducting a thorough analysis of the top 50 most-cited articles on Socio-Scientific Issues (SSI) in K-12 education from the Web of Science database, utilizing a comprehensive scientific relevance model.
- The findings highlight the primary focus of SSI research, particularly in exploring the impact of teaching interventions on the nature of science among high school students, with a predominant focus on energy-related topics.
- Furthermore, the study identifies key authors and suggests future directions for expanding SSI application in education, emphasizing the development of 21st-century skills and the need for balanced integration of the relevance model in K-12 schooling.

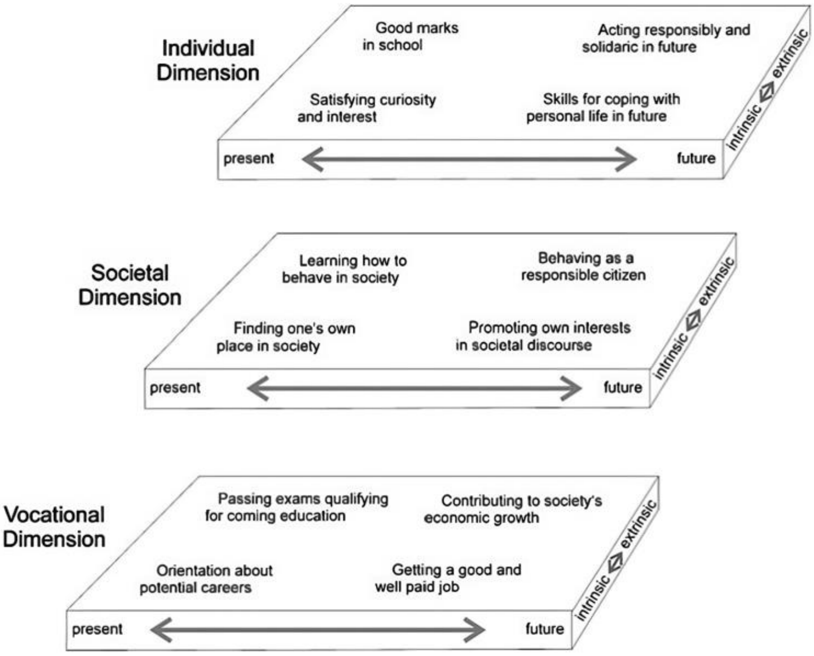

Figure 1. Relevance model of science education (Stuckey et al., 2013)

extrinsic components (refer to **Figure 1**), illustrating the suitability of SSI within this model (Stuckey et al., 2013). Guided by the relevance model of science education, the renewed emphasis on SSI curriculum development enables a more precise delineation of focus, ensuring a balanced approach across all facets of SSI curriculum development (Stuckey et al., 2013). Simultaneously, this model's application is pivotal for course developers, offering substantial benefits for science/SSI teachers in terms of classroom management and practice (Calik & Wiyarsi, 2021).

The integration of SSI within K-12 education, alongside the relevance model of science education, aims to cultivate K-12 students' interest in science and elevate their motivation and attitudes toward scientific learning (Calik & Wiyarsi, 2021; Eilks et al., 2018; Stuckey & Eilks, 2014). Consequently, a systematic literature review (SLR) is imperative to consolidate research articles focused on SSI in K-12 education and assess their alignment with the relevance model of science education. The choice of an SLR was based on two fundamental reasons. Firstly, the utilization of SLR aligns with an evidence-based approach, widely applied across disciplines such as management, marketing, human resources, tourism, economics, operations, and education (Brereton et al., 2007; Calma & Davies, 2016; Chan et al., 2012; Hoepner et al., 2012; Jeung et al., 2011; Tranfield et al., 2003). Bennett et al. (2005) argue that SLR represents a rigorous method for examining literature in science education. Secondly, compared to traditional literature reviews, SLRs are characterized by transparency, replicability, and adherence to scientific processes concerning article search strategies, inclusion and exclusion criteria, data entry, and coding. Consequently, they can yield impartial and equitable results (Ahmad et al., 2020; Asatullaeva et al., 2021; Bennett et al., 2005; Tranfield et al., 2003).

The concept of the journal impact factor originated in the late 1950s and early 1960s as a measure to gauge the frequency of citations particular journals receive in articles (Blessinger & Hrycaj, 2010). Researchers tend to select high-quality, indicative, and peer-reviewed papers when reading and citing literature, typically associated with a high citation count (Lai, 2020; Mohr et

Table 1. Inclusion & exclusion criteria

Inclusion	Exclusion
-Must involve socio-scientific issues in formal or informal learning with clear descriptions of practical applications -Theme samples must be K-12 students	-Editorials, reviews, correction notes, & early-access articles -Not related to SSIs in K-12 education -Not written in English -Not in the top-50 most-cited articles

al., 2017). Such articles not only signify substantial influence within the research field but also encapsulate classical research topics and valuable research queries within the domain (Flores et al., 1999; Fu & Ho, 2018). Consequently, a literature review containing a compilation of highly cited articles can aid novices in identifying pivotal research advancements and significant topics that scholars frequently prioritize. Moreover, it can effectively facilitate the development of their research initiatives (Blessinger & Hrycaj, 2010; Kinshuk et al., 2013; Lin et al., 2014; Tang et al., 2016).

A systematic review is a type of review that employs a more rigorous approach to research and writing compared to other types of reviews (Siddaway et al., 2019). Systematic reviews involve precise and comprehensive searches, and further refine suitable articles by determining inclusion and exclusion criteria. They link theory to evidence and evidence to theory, presenting the results and discussions of studies in a more accessible manner. Using citation counts as inclusion or exclusion criteria in systematic reviews is a common practice, often applied when there is a large body of literature in the field (Aylward et al., 2008, p. 1976-2006; Lee et al., 2009). This approach helps identify the most noteworthy studies in the field to address the research question of the systematic review. According to surveys, the total number of papers included in each literature review ranges from 14 to 200 papers (Asatullaeva et al., 2021). Some systematic reviews select the top-50 most cited papers as inclusion criteria (Ahmad et al., 2020; Asatullaeva et al., 2021; Chu et al., 2022).

This systematic review focuses on SSI in K-12 education to determine the research focus of this field to date. Additionally, it provides statistical analysis and discussion on purposes, variables, samples, the topic of SSI, dimensions of SSI, authors' productivity, and model of science education. This is something previous systematic reviews have not accomplished, as they mostly focused on a specific area without analyzing the issue from a broader perspective. The research aimed to conduct a thematic synthesis of the top-50 publications on SSI in K-12 education citation index of the Web of Science (WoS) database. Subsequently, an inferential evaluation was undertaken to assess their alignment with the relevance model of science education. Consequently, the review sought answers to the following research questions:

1. What thematic codes do the top-50 most-cited articles related to SSI in K-12 education show?
2. Who are the top-10 most productive authors of the top-50 cited articles?
3. How do the top-50 most-cited articles related to SSI in K-12 education reflect the relevance model of science education?

METHODS

To perform this systematic review, the principles and guidelines of PRISMA were adopted in this study (Moher et al., 2009).

Process of Data Searching & Collection

WoS database was selected for the search because of its reliability and authority. Articles in WoS database demonstrate higher quality consistency due to strict peer review and objective evaluation processes (Braun et al., 2000; Wohlin, 2007). Moreover, WoS database is the most important and commonly used source database for bibliometric studies in various research fields (Gil-Montoya et al., 2006; Kinshuk et al., 2013; Lee et al., 2009; Tan et al., 2014). The selection of articles from WoS database, including SSCI, SCI-EXPANDED, and ESCI indices, was based on their ease of retrieval for all SSCI and other important indexed journals (Akcayir & Akcayir, 2018; Arici et al., 2019).

Based on Hooshyar et al. (2020) and Zawacki-Richter et al. (2019), we conducted the search process in WoS database and reviewed the bibliographies of all relevant articles. Finally, those articles that investigated SSI in K-12 education were selected. To optimize the relevance, this study used various keyword groups to search for SSI in K-12 education articles in the "education/educational research category" in WoS database: socio-scientific issues ("socio-scientific" or "socio-scientific" or "socio-scientific issues" or "socio-scientific issues" or "controversial issues" or "societal issues") and K-12 education("education" or "class*" or "learn*" or "K-12*" or "elementary" or "middle school*" or "high school*" or "secondary school*"). A total of 1,129 SSCI articles were obtained on May 12, 2023. To be included in this systematic review, each study had to meet the criteria indicated in **Table 1**.

Figure 2 illustrates the article selection process adhering to PRISMA guidelines (Page et al., 2021). Initially, editorials, reviews, correction notes, and early access articles were excluded, alongside non-English language publications and those unrelated to education, resulting in 652 articles for further review. Subsequently, a meticulous manual review scrutinized each article's

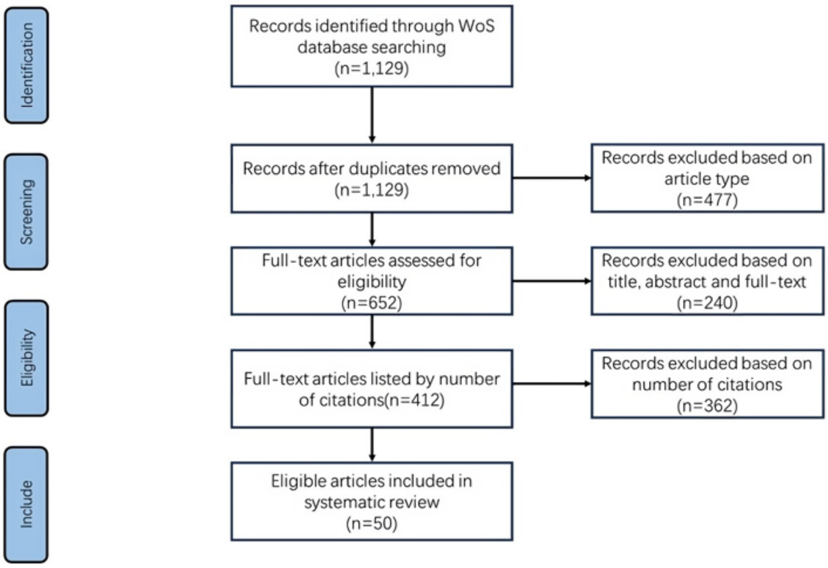

Figure 2. PRISMA flow diagram (Source: Authors' own elaboration)

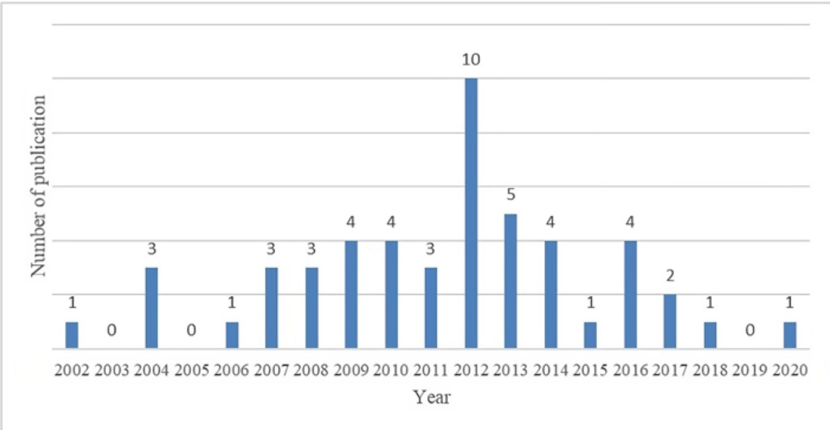

Figure 3. Distribution of frequently cited research on SSI in K-12 education (Source: Authors' own elaboration)

title, abstract, and full text against predefined inclusion and exclusion criteria, yielding 412 articles for detailed examination. Finally, the top-50 most cited articles were included in this systematic review.

Data Distribution

Figure 3 illustrates the distribution of the top-50 most-cited SSI in K-12 education articles. These articles span publication years from 2002 to 2020, indicating the temporal scope of the top-50 most-cited articles addressing SSI in K-12 education studies, dating back to 2002.

The earliest paper, authored by Jimenez-Aleixandre (Jimenez-Aleixandre, 2002), delves into the examination of knowledge and skills crucial for navigating SSI and identifying them within classroom discourse. Notably, over half of the highly cited articles surfaced between 2007 and 2014, signifying the burgeoning popularity and emergence of significant research topics and findings in SSI studies during that period. This trend might be attributed to the prevalent perspective among educators advocating for an in-depth exploration of SSI as a foundational aspect of contemporary scientific literacy and an indispensable component within present-day science classrooms (Driver et al., 2000; Hughes, 2000; Zeidler et al., 2002).

Data Coding & Analysis

During the categorization of the top-50 most-cited articles on SSI in K-12 education, two distinct research types emerged: Intervention research, incorporating experimental designs and/or treatments, and Descriptive research, encompassing exploratory and/or empirical studies examining K-12 students' perspectives, values, argumentation skills, conceptual understanding, NoS, decision-making processes, and learning outcomes related to SSI. To present a comprehensive SLR, we employed and adapted a matrix (Calik et al., 2005; Lin et al., 2014). The matrix coding encompassed thematic purposes, variables, samples, specific SSI, thematic codes (used in this review), authors' productivity, and inferential components aligned with the relevance model of science education. Two researchers conducted the coding, which was later

Table 2. Frequencies (f) & percentages (p) of thematic codes at theme purposes

Codes	Research IDs*	f	p (%)
Using SSI as a driving factor to explore relevant competencies (argumentation skills, decision-making skills, motivation, and socio-scientific reasoning skills)	D1-D4, D7-D8, D10, D12-D21, D23-D24, & D27	20	40.0
Investigating the effect(s) of SSI on related variables (e.g., nature of science, morality, and conceptual understanding)	I1-I23	23	46.0
Designing lesson/curriculum plans using	D5, D9, D11, & D22	4	8.0
Developing measurement tools/instruments regarding SSI	D6 & D25-D26	3	6.0
Total		50	100

Note. I: Intervention & D: Descriptive

confirmed by a third party, achieving a coding consistency marked by a kappa value of 0.87. Furthermore, to identify the 'relevance' components within research articles, a comprehensive analysis was performed by thoroughly reviewing the full articles. In addition, the research author' productivity is necessary for a novice to understand, research, and learn to design relevant studies and experiments in the field of study (Chu et al., 2022; Lin et al., 2014). Howard et al.'s (1987) formula to quantitatively analyze authors' contribution is adopted for each or multiple researcher's contribution to be analyzed. This formula, considered public, was adopted for its widespread acceptance (Chu et al., 2022; Flores et al., 1999; Lin et al., 2014). Following this formula, we identified the number of citations, the total number of authors (n), and the order of a specific author (i) within each paper, ultimately calculating the scores for each author. For instance, the author contribution scores for Sadler, T. D., Barab, S. A., and Scott, B. were determined as 0.47, 0.32, and 0.21, respectively. Notably, in Sadler et al.'s (2007) study, where the number of citations amounted to 292, the contribution scores for the aforementioned three authors totaled 137.24, 93.44, and 61.32, respectively. Consequently, this study utilized Eq. (1) to compute the scores for all researchers involved:

$$Score\ (i) = Numberof\ citations \times \frac{(1.5^{n-i})}{\sum_{k=1}^{n} 1.5^{n-k}}. \qquad (1)$$

For the codes, the description is in **Appendix A**, **Appendix B**, and **Appendix C**.

RESULTS AND DISCUSSION

Theme Purposes

Table 2 lists the top-50 most-cited articles on SSI in K-12 education, providing frequencies (f) and percentages (p) of thematic codes corresponding to various theme purposes. As depicted in **Table 1**, the purposes outlined in these research articles encompass four distinct codes, with their percentages ranging from six to 46. The prevailing frequency in these codes often relates to common variables within SSI inquiries, such as the nature of science, morality, and conceptual understanding (Eastwood et al., 2012; Fowler et al., 2009; Varma & Linn, 2012). These articles, serving as evidence, increasingly suggest that SSI can serve as effective research tools influencing the quality of science education. Notably, SSI inherently represent controversial issues (Sadler & Zeidler, 2005). The secondary code likely emanates from the characteristic nature of SSI, prompting competencies like argumentation skills, decision-making skills, motivation, and socio-scientific reasoning abilities (Christenson et al., 2012; Dawson & Venville, 2009; Evagorou et al., 2012; Jimenez-Aleixandre, 2002; Lin & Mintzes, 2010). The third code, centered on using SSI to design learning frameworks, curricula, and after-school science programs emphasizing student-centered inquiry pedagogy, appears to have effectively stimulated K-12 students' interest in science education (Birmingham & Barton, 2014; Evagorou et al., 2012; Grace, 2009). A lower frequency observed for the final code indicates a lesser focus on developing new methodologies to trigger or influence competencies related to argumentation and decision-making within SSI (Rudsberg et al., 2013; Sakschewski et al., 2014).

Theme Variables

Table 3 delineates that 23 research articles incorporate teaching interventions as independent variables. These independent variables encompass student-centered inquiry pedagogy, argument-based learning, web-based learning, and online learning environments, which appear to be influenced by constructivist learning theory and educational technology. Notably, students' construction of meaning concerning SSI in information and communication technology-mediated settings seems to catalyze their engagement in 'doing science' activities (Furberg & Ludvigsen, 2008). In other words, researchers and teachers aim to integrate the concepts of 'education through science' and 'education in science' (Holbrook & Rannikmae, 2007).

Among the top-50 most-cited articles on SSI in K-12 education, the dependent variables encompass diverse aspects: NoS (f=8), argumentation (f=6), conceptual understanding (f=4), informal reasoning skills (f=2), and decision-making skills (f=2). These articles seem to emphasize the cultivation of 21st century skills. Additionally, other dependent variables concentrate on cognitive and affective learning domains, encompassing moral (f=2), character (f=1), values (f=1), emotions (f=1),

Table 3. Frequencies (f) & percentages (p) of thematic codes at theme variables

Themes	Codes	Research IDs*	f	p (%)
Independent variable	Teaching intervention (student-centered inquiry pedagogy, web-based learning, online learning environment, & argument-based learning)	I1-I23	23	27.1
Dependent variable	Nature of science	I1, I4, I8, I9, I11, I14, I19, & I22	8	9.4
	Argumentation	I2, I4, I5, I11, I14, & I22	6	7.1
	Conceptual understanding	I2, I16, I17, & I18	4	4.7
	Content knowledge	I6, I15, & I16	3	3.5
	Moral	I7 & I20	2	2.4
	Informal reasoning skills	I2 & I12	2	2.4
	Decision making skills	I9 & I18	2	2.4
	Reflective judgement	I3	1	1.2
	Character	I10	1	1.2
	Values	I10	1	1.2
	Epistemological beliefs	I12	1	1.2
	Future thinking	I13	1	1.2
	Emotions	I21	1	1.2
	Compassion	I23	1	1.2
	Intent	I23	1	1.2
Not applicable		D1-D27	27	31.8
Total			85	100

Note. I: Intervention; D: Descriptive; & Some research articles may contain more than one dimensions of SSI

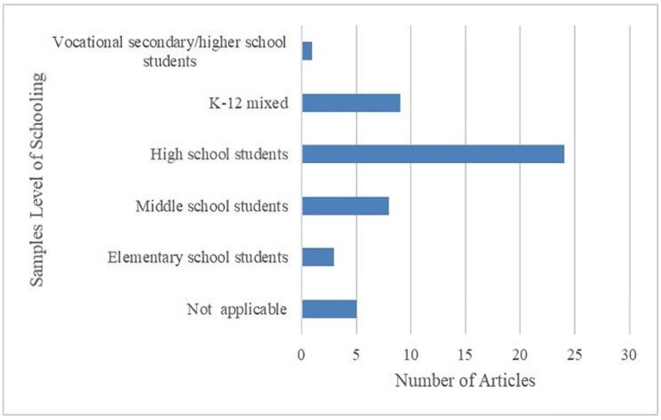

Figure 4. Distribution of thematic codes at theme samples (Source: Authors' own elaboration)

and epistemological beliefs (f=1). This aligns with the developmental psychology framework underlying the application of SSI, addressing moral, ethical issues, and the development of students' character information (Zeidler et al., 2009). Notably, all eight papers place emphasis on NoS as the dependent variable, while none focus on other dimensions of scientific literacy (such as scientific habits of mind, scientific attitudes, and awareness of the intricate relationship between science, technology, and society). This corroborates findings from prior studies (Calik & Wiyarsi, 2021; Holbrook & Rannikmae, 2007; Zeidler et al., 2009).

Theme Samples

Figure 4 depicts the distribution of the top-50 most-cited articles on SSI in K-12 education across various student samples: higher school students (n=24, 48.0%), K-12 mixed (n=9, 18.0%), middle school students (n=8, 16.0%), not applicable (n=5, 10.0%), elementary school students (n=3, 6.0%), and vocational school students (n=1, 2.0%). Although SSI is not typically tied to a specific age or educational level, nearly 50.0% of the articles specifically examined students from distinct educational levels, predominantly focusing on high school students. This emphasis on high school students may derive from the pervasive notion that 'lower and upper secondary schools significantly influence students' personal, societal, and vocational development.' High school students often serve as appropriate samples for descriptive and intervention research concerning SSI due to the tentative, creative, culturally embedded nature of SSI discourses (Zeidler et al., 2009). For instance, (Khishfe et al., 2017) delved into high school students' understanding of NoS and their arguments within contexts like global warming, genetically modified food, acid rain, and human cloning. Moreover, the limited representation of vocational school students in only one article might be attributed to the reluctance of vocational science researchers and teachers to engage in teaching SSI (Albe, 2008).

Theme Socio-Scientific Issues

The researcher categorized SSI discussed in the top-50 most-cited articles on SSI in K-12 education across eleven aspects, as illustrated in **Table 4**. Among these articles, energy was the most extensively explored (f=14, 19.2%), followed by genetically modified foods, crops, and technology (f=13, 17.8%), climate change (f=10, 13.7%), cloning and genetic technology (f=10, 13.7%), local issues (f=6, 8.2%), medicine and diseases (f=7, 9.6%), environmental management and pollution (f=3, 4.1%), food additives and safety (f=3, 4.1%), sustainable

Table 4. Frequencies (f) & percentages (p) of thematic codes at theme SSI

Codes	Research IDs*	f	p (%)
Energy (e.g., nuclear energy usage, water usage, & safety)	D1, D4, D6, I11, I12, I14, D11, D12, D22, D23, D24, I18, D26, & I21	14	19.2
Genetically modified foods, crops, & technology	I4, D7, D8, I9, I10, I13, I14, D20, D21, D23, D24, I19, & I22	13	17.8
Climate change (e.g., global warming, greenhouse effect, & carbon cycles on a global scale)	I1, I6, D14, I16, D23, I17, D24, I20, I22, & D27	10	13.7
Clone and gene test	I2, I3, D7, I7, D8, I9, D15, D21, I19, & I22	10	13.7
Local issues (e.g., competition for space between rabbits & puffins, competition between African elephants & local farmers, establishment of Ma-Guo National Park)	D2, I5, D9, D10, D16, & I23	6	8.2
Medicine & diseases (e.g. stem cell research, scarce medical resources, & flu)	D2, D4, I8, I15, D13, D19, & D21	7	9.6
Environmental management & pollution (e.g., wetland & acid rain)	D3, I19, & I22	3	4.1
Food additive and safety	D2, I3, & I13	3	4.1
Others (e.g., what students do to make world a better place, mobile phones either are dangerous or not dangerous for human health)	D2, D5, & D18	3	4.1
Sustainable development	D17 & D25	2	2.7
Consumption	D23& D24	2	2.7
Total		73	100

Note. I: Intervention; D: Descriptive; & Some research articles may contain more than one dimensions of SSI

Table 5. Frequencies (f) & percentages (p) of thematic codes at theme dimensions of SSI

Codes	Research IDs*	f	p (%)
Sociology/culture	D2, D13, & I23	3	2.9
Economy	D1, D2, I2, D3, D14, D16, D22, D23, & D24	9	8.7
Environment/ecology	D1, D2, I1, D3, I5, I6, D10, I11, I12, I13, D11, D14, I16, D16, D18, D21, D22, D23, I17, D24, D25, I18, I19, D26, I20, I21, I22, D27, & I23	29	27.9
Health	D1, D2, I3, D4, I4, D5, I7, D8, I8, I9, I11, I13, I14, I15, D12, D19, D21, I19, & I22	19	18.3
Technology/science	D1, D2, I2, I3, D3, I4, D6, D7, I7, D8, I8, I9, I10, I12, I13, I14, D11, I15, D15, D20, D21, D23, D24, I19, D26, I20, I21, I22, & I23	29	27.9
Ethics/morality	D2, I2, I3, I7, D8, I9, D13, D15, D17, D25, & I22	11	10.6
Policy	D2, I5, D9, & D16	4	3.8
Total		104	100

Note. I: Intervention; D: Descriptive; & Some research articles may contain more than one dimensions of SSI

development (f=2, 2.7%), consumption (f=2, 2.7%), and others (f=3, 4.1%). Notably, cloning, stem cells, genome projects, global warming, and nuclear energy have become common elements in the national vocabulary and political discourse, emphasizing the prominence of these SSI in present and future contexts.

Students' experiences and knowledge significantly influenced argumentation concerning SSI. Interestingly, researchers identified local issues (e.g., establishing Ma-Guo National Park) as SSI, where students' experiences appeared to mediate their knowledge. In contrast, in articles focusing on global issues (e.g., global warming), students tended to prioritize scientific knowledge, excluding personal experiences (Christenson et al., 2012; S. Lin & Mintzes, 2010; Sadler, 2004). Employing local SSI as contexts can render science more relevant to students' lives, while utilizing global SSI as pedagogical strategies helps K-12 students envision connections between broader global issues and themselves. This approach aids students in integrating classroom science experiences with their personal lives (Cajas, 1999; Pedretti & Hodson, 1995; Sadler, 2004).

Theme Dimensions of Socio-Scientific Issues

The authors edited and adapted six subject areas of SEE-SEP model proposed by (Chang Rundgren & Rundgren, 2010) to provide a detailed and comprehensive understanding of the dimensions of SSI. **Table 5** illustrates the dimensions of SSI in the top-50 most-cited articles on SSI in K-12 education. The primary dimensions were environment (f=29, 27.9%) and technology (f=29, 27.9%), followed by health (f=19, 18.3%), ethics (f=11, 10.6%), and economy (f=9, 8.7%), while dimensions related to policy and sociology ranged from 2.9% to 3.8%. K-12 students were predominantly involved in generating the three main dimensions of environment, technology, and health as samples for studying SSI. For instance, the technology dimension encompasses genetically modified organisms, an area, where high school students exhibit knowledge of

Table 6. Comparisons of the top-10 author productivity of the top-50 most-cited articles

R	Authors	Country	Scores	n	Most frequently cited article
1	Sadler	USA	262.69	7	What do students gain by engaging in socio-scientific inquiry? (D1)*
2	Zeidler	USA	245.09	7	Advancing reflective judgment through socio-scientific issues (I3)
3	Khishfe	Lebanon	211.78	4	Nature of science and decision-making (I9)
4	Venville	Australia	181.60	3	The impact of a classroom intervention on grade 10 students' argumentation skills, informal reasoning, and conceptual understanding of science (I2)
5	Jimenez-Aleixandre	Spain	177.32	2	Knowledge producers or knowledge consumers? Argumentation and decision making about environmental management (D3)
6	Kolsto	Norway	144.00	1	Patterns in students' argumentation confronted with a risk-focused socio-scientific issue (D4)
7	Dawson	Australia	133.20	2	Teaching strategies for developing students' argumentation skills about socio-scientific issues in high school genetics (D7)
8	Able	France	116.00	1	When scientific knowledge, daily life experience, epistemological and social considerations intersect: Students' argumentation in group discussions on a socio-scientific issue (D5)
9	Osborne	USA	105.74	3	Exploring young students' collaborative argumentation within a socio-scientific issue (I5)
10	Evagorou	Cyprus	105.32	2	Exploring young students' collaborative argumentation within a socio-scientific issue (I5)

Note. I: Intervention; D: Descriptive; R: Rank; & n: Numberof articles

genetics across various countries/regions (e.g., USA, Korea, Taiwan China, Australia) (Dawson & Venville, 2010; Lee et al., 2013; Sadler et al., 2016). Conversely, the limited focus on the policy dimension in only four articles might stem from a perception that 'political issues are not easily amenable to change or that politicians are not readily accessible' (Evagorou et al., 2012; Evagorou & Osborne, 2013; Lin & Mintzes, 2010; von Aufschnaiter et al., 2008).

Authors' Productivity

The analysis of authors' productivity for the top-50 most-cited articles revealed contributions from 91 researchers between 2002 and 2022.

Table 6 details the top-10 most productive authors based on their contribution scores. Predominantly, researchers contributing to SSI in K-12 education research hail from countries such as USA, Australia, Lebanon, Spain, Norway, France, and Cyprus. Among these top-10 researchers, a cumulative total of 23 articles were published, which contrasts with the sum of 32 articles noted in **Table 6**. This is because there were authors who participated together in nine of these articles, suggesting a tendency for productive scholars to engage in collaboration when producing academic papers (Lin et al., 2014). For instance, 'Exploring young students' collaborative argumentation within a socio-scientific issue' authored by Osborne, J. was a collaborative effort with (Evagorou & Osborne, 2013). Among the nine most frequently cited articles, there were five descriptive articles (D1, D3, D4, D5, and D7) and four intervention articles (I2, I3, I5, and I9), with a relatively balanced ratio between the two. The intervention articles (I3, I9, and I5) focused on reflective judgment, NoS, argumentation, while the I2 article centered on argumentation, conceptual understanding, and informal reasoning. Regarding the theme 'SSI' in these articles, clone and gene testing (D7, I2, I3, and I9) received the most attention, followed by energy (D1), environmental management, pollution (D3), local issues (I5), medicine, diseases (D4), and other issues (D5). These findings deviate from those presented in the top-50 most-cited articles on SSI in K-12 education. However, the outcomes of the 23 articles authored by the top-10 productive authors align closely with those of the top-50 most-cited articles (Lin et al., 2014).

Inferential Components for Relevance Model of Science Education

Table 7 displays that all of the top-50 most-cited articles on SSI in K-12 education addressed the present-intrinsic component of the individual dimension and the future-intrinsic component of the societal dimension. Moreover, a significant majority of the research articles delved into the future-intrinsic and extrinsic components of the individual dimension (f=48, 96.0%), along with the future-extrinsic component of the societal dimension (f=48, 96.0%). SSI inherently encapsulate various socially relevant questions, such as 'Are mobile phones potentially harmful to human health?' These issues pose considerable intellectual challenges, especially for younger or less experienced students (Marks & Eilks, 2009). The articles employing SSI in K-12 education aim to equip students with personal and societal life skills (e.g., argumentation skills, informal reasoning, and decision-making) and cater to their individual learning curiosity and interests in the present (Feierabend & Eilks, 2011; Stuckey et al., 2013). Nevertheless, engaging with SSI in education presupposes that K-12 students will not only grasp the

Table 7. Frequencies (f) & percentages (p) of inferential components for relevance model

Relevance model of SE			Research ID*	f	p (%)
Individual dimension	Present	Intrinsic	D1-D27, I1-I23	50	100
		Extrinsic	I1-I2, I4-I16, I18-I19, I22-I23, D6-D10, D15-D17, D20, & D22-D27	34	68.0
	Future	Intrinsic	I1-I6, I9-I23, & D1-D27	48	96.0
		Extrinsic	I1-I11, I13-I23, D1-D14, & D16-D27	48	96.0
Societal dimension	Present	Intrinsic	I1-I3, I5-I10, I13, I16-I18, I20, I22-I23, D1-D11, D13-D14, D16-D18, D20, D22-D23, & D25-D27	38	76.0
		Extrinsic	I1-I14, I16-I18, I20-I23, D1-D11, D13-D14, D16-D18, D20-D23, & D25-D27	43	86.0
	Future	Intrinsic	I1-I23 & D1-D27	50	100
		Extrinsic	I1-I11, I13-I23, D1-D14, & D16-D27	48	96.0
Vocational dimension	Present	Intrinsic	I5, I9-I10, D5, D9-D13, D18, & D20	11	22.0
		Extrinsic	I10, I12-I15, I17, I20, I22-I23, D13-D18, D20, & D22-D27	22	44.0
	Future	Intrinsic		0	0.0
		Extrinsic	D1, D3-D4, D11, D14, & D18	6	12.0

Note. I: Intervention; D: Descriptive; & SE: Science education

fundamental scientific facts and concepts underlying these issues but also prepare to actively participate in future societal discourse and assume responsibility as citizens (Sadler, 2011). In essence, the incorporation of SSI within science education in K-12 settings significantly influences both individual and societal dimensions, profoundly impacting basic science education (Calik & Wiyarsi, 2021).

Compared with the present-intrinsic components of individual and societal dimensions (f=34, 68.0%; f=38, 76.0%), the present-extrinsic component of the societal dimension (f=43, 86.0%), the treatment of vocational dimensions in the research articles was notably low. This indicates a challenge in integrating the vocational dimension and its related components into science education based on the top-50 most-cited research articles on SSI in K-12 education. Within the vocational dimension, the present-intrinsic and extrinsic components (f=11, 22.0%; f=22, 44.0%) were more prevalent than the future-oriented components (f=0, 0.0%; f=6, 12.0%). This discrepancy could stem from the focus on K-12 students in the sampled articles, where knowledge and life skills in science may hold greater importance than vocational aspects (Atasoy et al., 2020; Avargil et al., 2020). Alternatively, researchers might have considered these present components more feasible and research-friendly than future-oriented ones, leading to a limited exploration of future components within SSI context (Jones et al., 2012). Anticipatory objectives such as 'securing a good and well-paid job' or 'contributing to society's economic growth' often require prolonged examination, potentially leading to their implicit treatment within SSI contexts. However, research articles might have shed light specifically on the present-intrinsic component of the vocational dimension.

The role-play method is a prominent SSI-based teaching approach in science education. Employing the role-play method can effectively stimulate students' interest and orientation towards science careers, particularly regarding the 'orientation about potential careers' in the present-intrinsic component. For instance, when addressing the contemporary issue of the impact of mobile phone use on health, secondary vocational school students engage in role-playing scenarios as judges, defendants, plaintiffs, defense lawyers, and experts. This engagement enhances students' argumentation skills while fostering a deeper understanding of various professional roles. Simultaneously, a positive and comfortable experience in science learning during SSI processes can potentially encourage students to pursue science-related careers in the future (Albe, 2008; Hind et al., 2001).

CONCLUSIONS & IMPLICATIONS

This study involved screening, coding, and analyzing the top-50 most-cited articles on SSI in K-12 education retrieved from WoS database. The comprehensive assessment combined the scientific relevance model. The systematic review revealed several key findings:

(a) the primary focus of SSI in K-12 education centers on investigating the impact of SSI on related variables, particularly exploring the effects of teaching intervention on NoS,

(b) high school students were the most common sample group,

(c) energy emerged as the most frequently studied SSI topic, predominantly within the environment/ecology dimension,

(d) the top-10 authors were identified based on their productivity scores, shedding light on the researchers' primary focuses, which is clone and gene testing, and

(e) components for the relevance model of science education exhibit imbalances, including imbalances in dimensions, imbalances between present and future, and imbalances between intrinsic and extrinsic factors.

This is particularly evident in the lack of a vocational dimension. SSI significantly contributes to improving

21st century skills like NoS, argumentation, and informal reasoning. Hence, we propose further promotion and expansion of SSI within K-12 education, extending its application to early childhood, higher education, and special education. The interdisciplinary nature of SSI encourages the development of specific, controversial science questions tied to local contexts, appealing to K-12 students and fostering their enthusiasm for science exploration. We urge SSI researchers and educators to explore collaborative studies that potentially yield synergistic results. Future SSI research in K-12 education should explore and measure its impact on students' career choices. Developing reliable tools to predict K-12 students' inclination toward potential science careers is also imperative. Additionally, further research should illustrate how to integrate all components of the 'relevance' model into K-12 schooling in a balanced manner.

It is crucial to acknowledge certain limitations in this study. Firstly, the scope of SSI study was confined to K-12 education. Secondly, the analysis was limited to the top-50 most-cited studies on SSI in K-12 education within WoS database. Finally, the study solely utilized one relevance model of SSI in K-12 education for the analysis.

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APPENDIX A

Table A1. Basic information of articles

RID	Reference	C/R	Journal name
D1	Sadler et al. (2007)	USA	Research in Science Education
D2	von Aufschnaiter et al. (2008)	Germany	Journal of Research in Science Teaching
I1	Sadler et al. (2004)	USA	International Journal of Science Education
I2	Venville and Dawson (2010)	Australia	Journal of Research in Science Teaching
I3	Zeidler et al. (2009)	USA	Journal of Research in Science Teaching
D3	Jimenez-Aleixandre (2002)	Spain	International Journal of Science Education
D4	Kolstø (2006)	Norway	International Journal of Science Education
I4	Walker and Zeidler (2007)	USA	International Journal of Science Education
D5	Able (2008)	France	Research in Science Education
I5	Evagorou and Osborne (2013)	Cyprus	Journal of Research in Science Teaching
D6	Wu and Tsai (2007)	China Taiwan	International Journal of Science Education
D7	Dawson and Venville (2010)	Australia	Research in Science Education
I6	Klosterman and Sadler (2010)	USA	International Journal of Science Education
I7	Fowler et al. (2009)	USA	International Journal of Science Education
D8	Dawson and Venville (2009)	Australia	International Journal of Science Education
I8	Eastwood et al. (2012)	USA	International Journal of Science Education
D9	Evagorou et al. (2012)	Cyprus	International Journal of Science Education
I9	Khishfe (2012a)	Lebanon	International Journal of Science Education
D10	Grace (2009)	UK	International Journal of Science Education
I10	Lee et al. (2013)	Korea	International Journal of Science Education
I11	Khishfe (2014)	Lebanon	International Journal of Science Education
I12	Wu and Tsai (2011)	China Taiwan	International Journal of Science Education
I13	Jones et al. (2012)	New Zealand	Research in Science Education
I14	Khishfe (2012b)	Lebanon	Journal of Research in Science Teaching
D11	Birmingham and Barton (2014)	USA	Journal of Research in Science Teaching
I15	Sadler et al. (2016)	USA	International Journal of Science Education
D12	Bencze et al. (2012)	Canada	Research in Science Education
D13	Zeidler et al. (2013)	USA	Journal of Research in Science Teaching
D14	Herman (2015)	USA	Science Education
D15	Furberg and Ludvigsen (2008)	Norway	International Journal of Science Education
I16	Zangori et al. (2017)	USA	Journal of Research in Science Teaching
D16	Lin and Mintzes (2010)	China Taiwan	International Journal of Science and Mathematics Education
D17	Gresch et al. (2013)	Germany	Journal of Science Education and Technology
D18	Vesterinen et al. (2016)	Sweden	Journal of Science Education and Technology
D19	Lee and Grace (2012)	Hong Kong China	Science Education
D20	Chung et al. (2016)	Korea	International Journal of Science and Mathematics Education
D21	Yoon (2011)	USA	Journal of the Learning Sciences
D22	Rose and Barton (2012)	USA	Journal of Research in Science Teaching
D23	Christenson et al. (2012)	Sweden	Journal of Science Education and Technology
I17	Varma and Linn (2012)	USA	Journal of Science Education and Technology
D24	Christenson et al. (2014)	Sweden	Research in Science Education
D25	Rudsberg et al. (2013)	Sweden	Science Education
I18	Yang and Yang (2004)	Taiwan, China	International Journal of Science Education
I19	Reis and Galvão (2004)	Portugal	International Journal of Science Education
D26	Sakschewski et al. (2014)	Germany	International Journal of Science Education
I20	Sternäng and Lundholm (2011)	Sweden	International Journal of Science Education
I21	Tomas et al. (2016)	Australia	Journal of Research in Science Teaching
I22	Khishfe et al. (2017)	Lebanon	International Journal of Science Education
D27	Dawson and Carson (2020)	Australia	Research in Science Education
I23	Herman (2018)	USA	Journal of Research in Science Teaching

Note. RID: Research ID & C/R: Country/region

APPENDIX B

Table B1. Variables, samples, SSI, & dimensions of SSI

RID	Variables		n	SSI	DSSI
	Independent	Dependent			
D1	/	/	3	Pollution & water quality	2,345
D2	/	/	4	Funding a zoo phases of moon blood pressure diet substances	1,234,567
I1	SSI-based science brief	NoS	5	Global warming	3
I2	SSI-based instruction	Argumentation skills, informal reasoning, & conceptual understanding of genetics	5	Designer babies	256
I3	SSI driven curriculum	Reflective judgement	5	Related to chemical additives in food, religion & science, & genetic determination of alcoholism	456
D3	/	/	5	Wetland environmental management	235
D4	/	/	1	Local construction of new power lines & possible increased risk of childhood leukemia	4
I4	A web-based learning activity embedded in SSI	NoS, argumentation, & discourse	6	Genetically modified foods	45
D5	/	/	7	Mobile phones either are dangerous or not dangerous for human health	4
I5	An online learning environment-argue-WISE	Collaborative argumentation	NA	Whether UK government should kill gray squirrels to save indigenous red	37
D6	/	/	5	Nuclear energy usage	5
D7	/	/	5	A genetically modified tomato & prenatal genetic testing for cystic fibrosis	5
I6	SSI-based instruction	Science content knowledge	5	Global warming & greenhouse effect	3
I7	SSI-based instruction	Moral sensitivity	5	Genetic modification & reproductive cloning	456
D8	/	/	6	biotechnology, cloning, genetic testing for diseases, paternity and forensics, and the production and consumption of genetically modified food crops	456
I8	SSI-based instruction	nature of science (NOS)	5	stem cell research	45
D9	/	/	1	Whether they agree with UK government's decision to kill grey squirrels to save indigenous red	7
I9	NoS instruction	NoS understandings, students' DM, & students' DM factors	5	Cloning & genetically modified food	456
D10	/	/	1	Competition for space between rabbits & puffins, competition between African elephants & local farmers	3
I10	SSI program	Character & values	4	genetically modified (GM) technology	5
I11	SSI-based argumentation instruction	Understandings of NoS aspects & argumentation components	4	Water usage & safety	34
I12	SSI-based instruction	SEBs (as well as their cognitive structures) & informal reasoning	5	Nuclear power usage	35
I13	Student-centered inquiry pedagogy conceptual framework	Future thinking	6	A dairy farm, future food, & GM foods	345
I14	SSI-based instruction	NoS aspects & argumentation skills	5	Genetically modified food & water fluoridation	45
D11	/	/	6	Green energy	35
I15	SSI-based instruction	Biological content knowledge	5	Use of biotechnology for identifying & treating sexually transmitted diseases	45
D12	/	/	5	Water quality	4

Table B1. Variables, samples, SSI, & dimensions of SSI

RID	Variables		n	SSI	DSSI
	Independent	Dependent			
D13	/	/	5	Scarce medical resources	16
D14	/	/	6	Global warming (GW) science & willingness to mitigate GW	23
D15	/	/	6	Gene technology	56
I16	Model-oriented SSI teaching	Carbon cycling & reasoning about relationships between carbon cycling & climate change	5	Carbon cycles on a global scale	3
D16	/	/	3	Establishment of Ma Guo National Park	237
D17	/	/	5	Sustainable development	6
D18	/	/	1	What students do to make world a better place?	3
D19	/	/	4	Avian flu	4
D20	/	/	4	GM technology	5
D21	/	/	4	Cloning, genetic engineering & medicine, & genetically modified crops	345
D22	/	/	6	Whether their city should build a new hybrid power plant	23
D23	/	/	5	GW, genetically modified organisms (GMO), nuclear power, & consumption	235
I17	Technology-enhanced learning environment featuring virtual experiments	Characterize students' understanding	3	Greenhouse effect & global warming change	3
D24	/	/	5	GW, GMO, nuclear power, & consumer consumption	235
D25	/	/	5	Sustainable development	36
I18	Science, technology, & society-oriented instruction	Conceptual knowledge & reasoning mode	5	Use of underground water	3
I19	SSI-based instruction	NoS	5	Cloning, treating toxic waste, & consuming genetically modified foods	3,456
D26			6	Generating electric power from wind, energy storage, & energy usage	35
I20	SSI-based instruction	Moral considerations & reasoning	4	Climate change	35
I21	SSI-based instruction	Emotions	4	Australia's current sources of energy & energy consumption, & role that renewable energy sources might play in future	35
I22	SSI-based instruction	NoS understandings & arguments	5	GW, genetically modified food, acid rain, & human cloning	3456
D27			5	Climate change	3
I23	Place-based SSI instruction	NoS, views, compassion toward those impacted by contentious environmental issues, & pro-environmental intent	6	Wolf reintroduction in Greater Yellowstone Area	135

Note. RID: Research ID; n: Number of samples/participants; & DSSI: Dimensions of SSI

APPENDIX C

Table C1. Inferential components for relevance model

RID	Inferential components for relevance model											
	Individual (Pre)		Individual (Fut)		Societal (Pre)		Societal (Fut)		Vocational (Pre)		Vocational (Fut)	
	I	E	I	E	I	E	I	E	I	E	I	E
D1	+		+	+	+	+	+	+				+
D2	+		+	+	+	+	+	+				
I1	+	+	+	+	+	+	+	+				
I2	+	+	+	+	+	+	+	+				
I3	+		+	+	+	+	+	+				
D3	+		+	+	+	+	+	+				+
D4	+		+	+	+	+	+	+				+
I4	+	+	+	+		+	+	+				
D5	+		+	+	+	+	+	+	+			
I5	+	+	+	+	+	+	+	+	+			
D6	+	+	+	+	+	+	+	+				
D7	+	+	+	+	+	+	+	+				
I6	+	+	+	+	+	+	+	+				
I7	+	+		+	+	+	+	+				
D8	+	+	+	+	+	+	+	+				
I8	+	+		+	+	+	+	+				
D9	+	+	+	+	+	+	+	+	+			
I9	+	+	+	+	+	+	+	+	+			
D10	+	+	+	+	+	+	+	+	+			
I10	+	+	+	+	+	+	+	+	+	+		
I11	+	+	+	+		+	+	+				
I12	+	+	+	+		+	+			+		
I13	+	+	+	+	+	+	+	+		+		
I14	+	+	+	+		+	+	+		+		
D11	+		+	+	+	+	+	+	+			+
I15	+	+	+	+			+	+		+		
D12	+		+	+			+	+	+			
D13	+		+	+	+	+	+	+	+	+		
D14	+		+	+	+	+	+	+		+		+
D15	+	+	+	+			+	+		+		
I16	+	+	+	+	+	+	+	+		+		
D16	+	+	+	+	+	+	+	+		+		
D17	+	+	+	+	+	+	+	+		+		
D18	+		+	+	+	+	+	+	+	+		+
D19	+		+	+			+	+				
D20	+	+	+	+	+	+	+	+	+	+		
D21	+		+	+		+	+	+				
D22	+	+	+	+	+	+	+	+		+		
D23	+	+	+	+	+	+	+	+		+		
I17	+		+	+	+	+	+	+		+		
D24	+	+	+	+			+	+		+		
D25	+	+	+	+	+	+	+	+		+		
I18	+	+	+	+	+	+	+	+		+		
I19	+	+	+	+			+	+				
D26	+	+	+	+	+	+	+	+		+		
I20	+		+	+	+	+	+	+		+		
I21	+		+	+		+	+	+				
I22	+	+	+	+	+	+	+	+		+		
D27	+	+	+	+	+	+	+	+		+		
I23	+	+	+	+	+	+	+	+		+		