

From Naïve Certainty to Critical Complexity: Transformative Effects of an AI-SSI Curriculum on High School Students' Socioscientific Orientation

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Abstract

This study examines the effects of a theory-guided, Artificial Intelligence-related Socioscientific Issues (AISSI) curriculum on high school students' socioscientific orientations (SO). While SSI-based pedagogy is recognized for enhancing scientific literacy and moral development, its specific effects within the domain of AI ethics remain underexplored. Employing a mixed-methods pretest-posttest quasi-experimental design, this research investigated the influence of a 10-week AI-SSI intervention on 95 Chinese tenth-graders' SO and emotional engagement. Interestingly, findings revealed significant declines in students' self-reported SO—specifically in ecological worldview, social and moral compassion, and socioscientific accountability—within the experimental group. However, qualitative interview data suggest that these declines reflect cognitive complexification and the development of intellectual humility, as students transitioned from simplistic, absolutist views to more nuanced, conditional, and critical understandings of AI dilemmas. Correlation analyses further unveiled an emotion-cognition decoupling, with weakened links between positive affect and faith in scientific evidence, alongside a stronger connection between moral concern and perceived responsibility. These findings imply that initial decreases in self-reported competencies may signal deeper epistemic development, including enhanced critical reasoning and more calibrated self-awareness of complexity. This study underscores the need for assessment strategies that can capture such intricate cognitive and emotional transformations. Overall, the findings demonstrate that AI-related SSI instruction can foster the sophisticated ethical reasoning necessary for navigating an AI-saturated world, with important implications for AI ethics education, civic literacy, and responsible innovation.

1. Introduction

As artificial intelligence (AI) technology advances rapidly and its integration into daily life accelerates, AI is becoming embedded across diverse sectors such as science, finance, logistics, healthcare, education, transportation, art creation, and social media. This deep integration of AI into various social domains poses important socioscientific challenges that demand critical examination and informed civic decision-making to address effectively. Specifically, AI's application itself is a complex, values-laden societal dilemma at the intersection of Technology and Science (algorithms, data, energy consumption), Ethics & Society (bias, privacy, employment, misinformation), which make some social issues involving AI's application socioscientific issues (SSI). Within science education, AI plays a dual role that is central to the pedagogy of SSI. On one hand, AI serves as an assistive tool in SSI-based teaching and learning (SSI-TL), offering personalized learning pathways, adaptive feedback, and scaffolding for argumentation and critical thinking (Liu & Tu, 2024; Sui et al., 2025). However, its integration also raises pedagogical and ethical challenges, such as risks of over-reliance and the need for AI literacy among students and teachers (Gunbatar & Sirin, 2025). On the other hand, AI-related controversies—such as algorithmic bias in autonomous vehicles' decision making process—constitute a core subject matter of SSI in their own right (Mun et al., 2022; Zhang, 2025). These issues compel students to engage with intertwined technical, ethical, and societal dimensions, fostering interdisciplinary reasoning and ethical sensitivity. Despite this potential, research on AI as an SSI topic remains scarce, with few studies providing concrete

curricular frameworks or examining how such complex topics can be effectively taught (Kong et al., 2023; Zhang, 2025). While SSI-based pedagogy is effective in enhancing scientific literacy, character and value as global citizens, ethical reasoning, and informed decision making (Ke et al., 2021; Zeidler et al., 2002), very limited research addresses examples of SSI involving AI's application (e.g., Ethical Algorithms in Autonomous Vehicles, AI-assisted medical diagnosis, accuracy and accountability of AI systems in healthcare, and the development and potential use of autonomous weapons systems) let alone the development of relevant curricula and testing how AI-SSI curricula influence students' learning engagement and outcomes (Zhang Jinbao, 2025).

Existing research indicates that SSI approaches enhance students' conceptual understanding of science (Dawson & Venville, 2013) and support moral development (Fowler et al., 2009). To advance this line of inquiry, this study adopts the socioscientific orientations (SO) framework (Herman et al., 2021) as the central dependent variable, a choice grounded in both theoretical and empirical literature. Previous SSI research has established that SO—comprising Ecological Worldview (SO_EW), Social and Moral Compassion (SO_SMC), Socioscientific Accountability (SO_SA), and Scientific Evidence Views (SO_SEV)—serves as a foundational construct that shapes how individuals perceive, reason about, and respond to complex societal issues involving science and ethics (Herman, 2018; Kinslow, 2018; Owens et al., 2019). Unlike outcome measures that focus primarily on cognitive or argumentative performance (e.g., Dawson & Venville, 2013; Fowler et al., 2009), SO captures the integrated value-based dispositions that underlie ethical engagement and responsible decision-making in SSI contexts (Choi et al., 2011; Lee et al., 2012, 2013).

This framework is particularly salient in the emerging domain of AI-SSIs, where technical, ethical, and social dimensions are deeply intertwined. As noted in prior work, SSI pedagogy not only enhances scientific understanding and moral reasoning (Ke et al., 2021; Zeidler et al., 2002) but also cultivates the character and values necessary for informed citizenship (Herman et al., 2021). Given that AI-related dilemmas often involve competing values, uncertain evidence, and distributed responsibility, measuring shifts in these foundational orientations is critical for assessing whether education fosters the nuanced judgment required in this domain. By examining changes across the four SO dimensions, this study seeks to move beyond assessing what students *can do* in AI-SSI discussions—such as constructing arguments or applying conceptual knowledge—to understanding how their underlying *orientations toward science, ethics, and societal responsibility* evolve through targeted instruction. Thus, selecting SO as the dependent variable provides a theoretically coherent and empirically grounded means to evaluate whether and how an AI-focused SSI curriculum fosters the value-aware, ethically sensitive, and evidence-informed dispositions that are essential for navigating the sociotechnical challenges of an AI-saturated world.

This study aims to address the identified research gap through a comprehensive mixed-methods investigation. First, it seeks to conceptualize AI-SSI and develop a corresponding curriculum. The core empirical aim is to rigorously evaluate the specific impact of this theory-guided, 10-week intervention on high school students. The curriculum's influence is assessed through changes in students' foundational

cognitive and ethical dispositions—their SO—across the four dimensions of SO_EW, SO_SMC, SO_SA, and SO_SEV (Herman et al., 2021). Crucially, this study employs a quasi-experimental design with a control group (CG) and integrates quantitative and qualitative data to not only measure changes but also to explore the underlying mechanisms and relationships that explain these changes, thereby establishing a robust case for the curriculum's efficacy.

To address the research aim and realize the stated objectives, this study is guided by the following research questions:

RQ1 Quantitative Change Analysis

How do the two groups' (experimental vs. control) students' SO, their attention to social issues, and their emotional experiences change from pre-test to post-test following the intervention?

RQ2 Relationship Investigation

What is the relationship between the changes in students' SO and the concurrent changes in their attention level and emotional engagement with social issues?

RQ3 Qualitative Mechanism Exploration

Based on qualitative interview data, what are the potential reasons and underlying mechanisms that explain the observed changes in the two groups' students' SO?

RQ4 Synthesis & Specificity Verification

How do the integrated quantitative and qualitative findings demonstrate the specific impact of the AI-SSI curriculum, as distinguished from the experience of the control group?

2. Literature Review

This study integrates SSI-based learning theory (Sadler et al., 2017) with Herman et al.'s (2021) multidimensional SO framework. SSI-based learning theory emphasizes engaging students with controversial, socially relevant scientific issues to promote functional scientific literacy. Herman et al.'s framework characterizes orientations along four dimensions, enabling a detailed analysis of how AI-SSI instruction influences students' thinking—particularly as they navigate the ethical challenges presented by autonomous systems and algorithmic decision-making unique to AI.

2.1 The Pedagogical Foundation of SSI in Teaching and Learning

SSI are complex, ill-structured, and socially relevant problems that arise at the intersection of science and society (Sadler, 2011). The pedagogical application of SSI—SSI-TL—moves beyond traditional fact-

based science education by immersing students in authentic dilemmas that lack simple solutions, such as climate change policy, genetic engineering ethics, or public health crises (Zeidler, 2014). This approach is not merely thematic; it is a theoretically grounded methodology designed to develop functional scientific literacy, preparing students to engage as informed citizens in a democratic society (Roberts & Bybee, 2014).

The efficacy of SSI-TL is rooted in its engagement with higher-order cognitive and affective domains. Instructionally, it is characterized by the integration of core scientific content with explicit consideration of ethical reasoning, moral development, and societal values (Khishfe, 2012). Students are tasked not only with understanding scientific evidence but also with weighing competing perspectives, navigating uncertainty, and constructing evidence-based arguments to justify positions on controversial issues (Dawson & Venville, 2013). This process inherently fosters critical thinking, argumentation skills, and epistemological sophistication as students grapple with the tentative and socially embedded nature of scientific knowledge (Eastwood et al., 2012).

Crucially, SSI-TL represents an evolution from earlier Science-Technology-Society (STS) frameworks. While STS education highlighted the interactions and influences between these domains, SSI-TL explicitly incorporates a focus on **ethical dimensions, moral reasoning, and the emotional aspects of learning** (Zeidler et al., 2002). This shift recognizes that reasoning about societal issues is not a purely cognitive exercise but involves empathy, care, and consideration of diverse stakeholder values.

2.2 AI as a Disruptive Force in Science and SSI Education

The rapid proliferation of AI, particularly generative AI (GenAI), represents a transformative force across all educational sectors, including science education (Jia et al., 2024; Zawacki-Richter et al., 2019). In broad terms, AI in Education (AIEd) promises personalized learning pathways, automated assessment, and intelligent tutoring systems capable of providing immediate, adaptive feedback (Holmes et al., 2019). Narrow down to science education field, Jia et al (2024) conduct econometric analyses on ten-year studies on AI in Science Education (2013–2023) and find that the results indicate that AISE has experienced increasing influence over the past decade. Crompton et al. (2020), in their systematic review, also highlight promises of increased engagement and efficiency, while concurrently underscoring pervasive concerns regarding data privacy, algorithmic bias, the potential erosion of critical thinking, and the ethical implications of outsourcing cognitive tasks to machines. SSI-based education as an important branch of science education, AI involved research or educational practice in this field are developing. Notably, AI's application in education is controversial, which might involve discussion on technology, ethical and moral reasoning, responsible decision making. Considering SSI-TL also involve controversial issues and open-ended discussion, make it complicated for teachers and students use AI in SSI-TL. As a possible result, the studies on discussing AI in SSI-TL are still very limited, and among limited studies, most of them focus AI as assistant in teaching or learning, few studies discuss the potential of AI-related issues as SSI topic itself in SSI-TL.

2.2.1 AI-related Issues as SSI

Concurrently, AI's societal impact has sparked a new set of controversies that exemplify the very definition of an SSI. This highlights AI's other role: serving as the central subject of an SSI. Emerging literature increasingly views AI not just as an instructional tool but as a meaningful SSI topic in its own right. This dual role creates a powerful pedagogical context for science education. Scholars contend that AI-related controversies—such as issues surrounding autonomous vehicles or generative AI—serve as authentic SSIs because of their inherent complexity, societal significance, and ethical considerations (Mun et al., 2022; Zhang, 2025). These topics compel students to engage with intertwined technical, ethical, economic, and legal considerations.

The integration of AI as an SSI topic offers several pedagogical affordances. Primarily, it stimulates critical thinking and ethical reasoning by requiring students to analyze **AI dilemmas embedded in scientific contexts**, such as algorithmic bias in medical diagnosis, environmental impacts of AI model training, or ethical challenges in AI-assisted genetic screening (Mun et al., 2022; Zhang, 2025). These issues qualify as SSIs precisely because they arise from the interplay between AI technology and scientific domains—compelling students to weigh ethical, social, and scientific factors concurrently. Instructional approaches such as role-playing and simulated debates enable learners to examine multiple stakeholder perspectives, fostering empathy and collaborative problem-solving. Furthermore, AI-SSI inherently promote interdisciplinary learning, bridging science with ethics, social studies, and public policy, thereby helping students synthesize knowledge across traditional disciplinary boundaries (Zhang, 2025).

Despite this potential, significant challenges impede the effective teaching of AI as an SSI. A primary barrier is teacher preparedness; many educators report limited training in both AI ethics and the specific pedagogical strategies required for SSI-based instruction (Zhang, 2025). Additionally, resource constraints—including access to current case studies and technology-enhanced learning tools—can limit implementation (Mun et al., 2022). A further pedagogical challenge lies in appropriately scaffolding these complex topics to match students' cognitive and moral development without oversimplifying the nuanced trade-offs involved.

In summary, AI constitutes a compelling and contemporary focus for SSI curricula, capable of deepening students' scientific literacy and ethical engagement. Realizing this potential, however, depends on overcoming substantial practical hurdles related to teacher professional development, resource availability, and curricular design. Future efforts must therefore focus on developing evidence-based frameworks and supportive materials to equip educators to navigate this emerging pedagogical frontier. While literature on AI ethics education is growing (e.g., Kong et al., 2021; Zhang, 2025), research on how to effectively *teach* these AI-SSIs using SSI-TL pedagogical principles remains emergent and scarce. Few studies provide concrete frameworks for curriculum design or examine how teachers translate these complex, technical-social controversies into effective classroom learning experiences.

Based on the definitions of SSI (Zeidler, 2014; Zeidler & Keefer, 2003), this study conceptualizes AI-SSI as a controversy in which the development, deployment, or impact of an AI system intersects with

necessary scientific understanding and creates a significant societal dilemma involving ethical considerations, values, and competing stakeholder interests. Examples include debates over the ethics of algorithmic decision-making in healthcare (Wilhelm et al., 2025), the environmental cost of training large AI models (Lv & Cho, 2025; Wu et al., 2022), and the moral programming of autonomous vehicles (Mun et al., 2022).

2.3 Socioscientific Orientation

Socioscientific Orientation (SO) is conceptualized as a framework of value-laden dispositions that guide individuals' engagement with SSI. Rooted in the Character and Values model of scientific literacy (Choi et al., 2011; Lee et al., 2013), SO comprises four interrelated dimensions: SO_EW, SO_SMC, SO_SA, and SO_SEV (Herman et al., 2021). This framework posits that resolution of SSI requires not only scientific understanding but also ethical sensitivity, social awareness, and a sense of responsibility toward both human and ecological communities.

2.3.1 Core Dimensions of Socioscientific Orientation

Ecological Worldview (SO_EW) reflects an individual's recognition of the interconnectedness between humans and the natural environment, emphasizing sustainability and stewardship (Bowers, 1999; Choi et al., 2011). It moves beyond anthropocentric and egoistic reasoning toward a holistic "ecosphere consciousness" (Bowers, 1999), which is associated with greater support for eco-justice and sustainable behaviors (Brügger et al., 2011; Mueller, 2008). Empirical studies, however, indicate that fostering ecological worldview in classroom-based SSI instruction remains challenging, with learners often retaining human-centered perspectives unless learning is situated in place-based environmental contexts (Herman, 2018; Lee et al., 2013).

Social and Moral Compassion (SO_SMC) entails the capacity for perspective-taking, empathy, and moral sensitivity toward others affected by SSI (Rest et al., 1999). It involves recognizing emotional and ethical dimensions of issues and demonstrating care-based reasoning (Sadler, 2004b). Research suggests that moral sensitivity is context-dependent and can be cultivated through SSI pedagogy, particularly when students engage with human-centered dilemmas (Herman et al., 2020; Zeidler et al., 2020). Expressions of moral emotion have also been linked to shifts toward systems thinking in SSI learning (Leung & Cheng, 2023).

Socioscientific Accountability (SO_SA) refers to an individual's sense of responsibility and willingness to take action in response to SSI (Lee et al., 2013). This dimension integrates affective, cultural, and cognitive factors—including place attachment, perceived locus of control, and values—that collectively influence prosocial and civic responses to socioscientific challenges (Gifford & Nilsson, 2014; Herman, 2018). Studies show that accountability is closely tied to perceived credibility of scientific claims and can be enhanced through SSI instruction that emphasizes real-world agency (Herman, 2015; Herman et al., 2020).

Scientific Evidence Views (SO_SEV) capture how individuals understand the role and limitations of scientific knowledge within SSI decision-making. Moving beyond a simplistic “scientism,” this dimension acknowledges that SSI resolution requires weighing scientific evidence alongside ethical, cultural, and social considerations (Herman, 2018; Kinslow, 2018). Place-based SSI contexts have been shown to help learners articulate more nuanced views about the affordances and constraints of science in public issues (Owens et al., 2019).

2.3.2 The Character and Values Framework in SSI Education

The four SO dimensions collectively constitute the **Character and Values framework**, which aligns SSI-based education with the broader goal of developing functional scientific literacy for the 21st century (Lee et al., 2013; Zeidler et al., 2002). This framework emphasizes that scientific literacy must encompass not only conceptual understanding but also the beliefs, sensitivities, and dispositions needed to engage compassionately, ethically, and responsibly with techno-scientific societies (Choi et al., 2011; Herman et al., 2021). SSI pedagogy, therefore, serves as a vehicle for fostering these orientations by embedding science learning within real-world, morally complex, and debate-driven contexts (Lee et al., 2013).

This synthesized framework informs the present study’s use of SO as a primary dependent variable, offering a comprehensive lens to examine how AI-SSI instruction may shape the underlying value-driven dispositions necessary for fostering engaged and responsible citizenship in an increasingly science- and technology-saturated world.

2.4 Theoretical Links Among Cognition, Affect, and Dispositional Learning

2.4.1 Interplay of Cognition, Emotion, and Character in Socioscientific Engagement

A robust body of literature in educational psychology and moral development underscores a significant interdependence between cognitive and affective processes, which is highly relevant for understanding learning within SSI contexts. Research suggests that cognition and emotion do not operate in isolation but rather engage in a dynamic, reciprocal relationship. Cognitive appraisals of complex situations—such as evaluating agency, fairness, or certainty—are fundamental in shaping emotional responses (Smith & Ellsworth, 1985; Smith & Kirby, 2012). These affective states can, in turn, direct subsequent cognitive functions, including attentional focus, memory encoding, and information processing strategies. This dynamic suggests that educational interventions targeting complex cognitive reasoning, such as SSI curricula, may be inherently linked to shifts in students’ emotional landscapes, as the two systems are mutually influential rather than independent.

In parallel,, the development of character and values, one of the core goals of SSI pedagogy, is often conceptualized as involving the integration of cognitive, affective, and behavioral components. This integrative perspective is strongly echoed in the literature on Social-Emotional Learning (SEL), which similarly emphasizes that ethical and civic development requires the synergistic engagement of emotion, cognition, and behavior (Elias et al., 1997; Weissberg et al., 2015). Both SSI and SEL frameworks posit that reasoning about complex societal issues—whether in science or social contexts—is not purely analytical but is deeply interwoven with emotional appraisal, moral sensitivity, and prosocial motivation. Character encompasses dispositions toward virtuous feelings and conduct guided by reason (Arthur & Harrison, 2012), and formal education is regarded as a vital context for cultivating related values such as responsibility and ethical concern (Osipov & Ziyatdinova, 2010). Modern educational frameworks, including SEL, explicitly aim to bridge affect, behavior, and cognition to foster prosocial dispositions (Elias et al., 2014). These integrative models imply that constructs like SO, which blend beliefs about evidence with moral concern and a sense of accountability, may reflect this synthesis, where cognitive judgments are interwoven with value-based and affective commitments.

The connection between these internal dispositions and civic engagement is further mediated by emotion. Scholars posit that affective investment is a crucial driver of civic life, where emotional connections to societal issues can underpin the motivation for engagement and shape a sense of belonging (Ho, 2009; Kingston et al., 2017). For citizens to actively engage with complex public issues, they must first care about them; thus, emotional responses are seen as foundational to participatory citizenship (Guy & Mastracci, 2018). Within an SSI classroom, therefore, the ways in which students emotionally connect with or distance themselves from a dilemma like AI ethics could be intrinsically linked to the depth and nature of their cognitive and value-based engagement with it.

Consequently, theoretical models for moral and civic development increasingly advocate for approaches that synthesize reason and emotion (Cantillo & Canal, 2017; Gonçalves & Verkest, 2013). This integrative approach offers a valuable framework for conceptualizing potential outcomes of SSI education. It indicates that instructional outcomes may extend beyond isolated shifts in cognition or attitudes, encompassing more complex, systemic shifts in students' engagement with issues—where changes in cognitive complexity, emotional resonance, and value-based judgments are interconnected. Investigating these potential interrelationships offers a theoretically grounded pathway for understanding how education might prepare individuals to navigate the affectively charged and cognitively demanding landscape of modern socioscientific challenges (Kislyakov & Shmeleva, 2020).

Given this intertwined nature of cognition and affect, a key objective of this study is not only to measure changes in students' individual orientations (SO) and affective states but, crucially, to examine how the relationships between these variables shift following SSI instruction. If SSI pedagogy fosters more integrated and mature reasoning, we would expect to see a restructuring of the affective-cognitive linkages—for instance, a decoupling of simplistic emotional responses from evidence evaluation, and a stronger alignment between moral concern and perceived responsibility. Investigating these dynamic

interrelationships, therefore, offers a more nuanced window into the developmental mechanisms of SSI learning than analyzing mean changes alone.

2.4.2 Intellectual Humility: A Framework for Epistemic Development in Complex Domains

To fully contextualize the potential outcomes of SSI education, particularly in novel and ambiguous domains like AI ethics, it is valuable to consider the construct of intellectual humility (IH). IH is conceptualized as a multifaceted epistemic virtue characterized by an accurate assessment of one's intellectual limitations, a willingness to revise one's viewpoints, and a respectful stance toward others' perspectives (Zhdanova & Shchebetenko, 2024; Hill et al., 2021; Smith, 2023). It integrates cognitive (e.g., metacognitive awareness), affective (e.g., regulating defensiveness), and behavioral (e.g., openness to corrective feedback) components, distinguishing itself from general humility by its specific focus on the appraisal and negotiation of knowledge (Hill et al., 2021; Jayawickreme et al., 2019).

The importance of IH in SSI for your consideration: Intellectual humility plays a vital role in SSI (Science, Society, and International) education because it encourages students to recognize the limits of their own knowledge and understanding. This mindset helps students approach complex societal issues with an open mind, acknowledging that they may not have all the answers and that others may have valuable insights or perspectives. By practicing intellectual humility, students are more likely to engage in respectful dialogue, consider alternative viewpoints, and remain receptive to new evidence or arguments. This attitude fosters critical thinking and helps prevent dogmatism or overconfidence in one's beliefs. In the context of SSI education, where issues often involve ethical dilemmas, cultural differences, and scientific uncertainties, intellectual humility supports more thoughtful, nuanced discussions and promotes responsible decision-making. Overall, it cultivates a learning environment where curiosity, openness, and mutual respect are prioritized, leading to deeper understanding and more thoughtful engagement with societal challenges.

The operationalization of IH through multidimensional scales, such as the Comprehensive Intellectual Humility Scale (CIHS), further delineates its core facets: independence of intellect and ego, openness to revising viewpoints, respect for others' viewpoints, and a lack of intellectual overconfidence (Hill et al., 2021; Huynh et al., 2025; Porter et al., 2022). Crucially, the construct encompasses both intrapersonal dimensions (owning one's cognitive limits) and interpersonal dimensions (engaging constructively with disagreement) (Zhdanova & Shchebetenko, 2024; Huynh et al., 2025; Danovitch et al., 2019).

Empirical research underscores IH's significant role in navigating complex information landscapes. Studies have consistently demonstrated that higher IH is associated with reduced partisan bias and political polarization, increased openness to opposing views, and a greater propensity for constructive discourse (Jongman-Sereno et al., 2025; Legood et al., 2016; Sgambati & Ayduk, 2023). Furthermore, IH is a reliable predictor of critical cognitive outcomes, including improved resistance to misinformation, enhanced metacognitive insight, and better performance in critical thinking tasks (Stanley et al., 2020; Christen et al., 2019; Davis et al., 2016). While the direct application of IH theory to SSI educational

outcomes—especially concerning AI—remains an open empirical question, its established link to sophisticated reasoning in the face of uncertainty positions it as a highly relevant theoretical lens. It provides a framework for understanding the deep-seated epistemic dispositions that SSI pedagogy may seek to develop, extending beyond merely acquiring specific knowledge or argumentation skills.

3. Methodology

This study employed a mixed-methods, quasi-experimental design to investigate the impact of a theory-guided, AI-SSI curriculum on high school students' SO. The design incorporated a pretest-posttest comparison between an experimental group (EG) that received the 10-week intervention and a control group (CG) that continued with standard science instruction. Quantitative data were collected via standardized questionnaires before and after the intervention to measure changes in SO and related emotional and attentional variables. Qualitative data were gathered through semi-structured interviews with students from both groups to gain deeper insight into their reasoning processes and perceived changes. This integrated approach allows for the triangulation of findings, providing a robust evaluation of the curriculum's effects and the mechanisms underlying any observed changes (Creswell & Plano Clark, 2018).

3.1 Research Design

A quasi-experimental, mixed-methods intervention design was utilized. Two intact classes from the same grade level were assigned as the EG (n=45) and the CG (n=50). This non-randomized assignment is common in educational field research, where randomly assigning students is often logistically impractical. However, efforts were made to ensure group equivalence through pretest comparisons (Shadish et al., 2002). The design comprised a pretest and a posttest administered to both the EG and the CG, with a 10-week curricular intervention delivered solely to the EG in the interim. Qualitative semi-structured interviews were conducted post-intervention with a purposefully selected subset of students from both groups to explain and enrich the quantitative results, following an explanatory sequential mixed-methods logic (Creswell & Plano Clark, 2018).

3.2 Participants

Participants were tenth-grade students from a public high school in Mainland China. Following the removal of 14 samples that did not complete both the pre- and post-test for SO assessment, a total of 95 effective samples were retained for analysis. The sample consisted of 45 students in the EG (20 female, 25 male) and 50 students in the CG (26 female, 24 male). The groups were drawn from separate, intact classes within the same grade. It is important to note that students in this school are assigned to classes based on similar academic performance from entrance exams, a practice that promotes initial academic equivalence across different class groups, in particular, the two classes involved in this study

were assigned to the same specific academic tier, thereby enhancing their comparability for experimental purposes.

Demographic and Baseline Equivalence

Demographic characteristics and baseline measures for the overall sample and by group are presented in Table 1. The sample had a mean age of 14.87 years (*SD* = 0.60). Independent-samples t-tests and a chi-square test revealed that the two groups were statistically comparable on all key demographic and baseline variables at pretest.

There were **no significant differences** between the EG and CG on the three primary baseline self-report measures: typical level of attention to social issues (A_level, *p* = .175), frequency of positive emotional responses to social news (A_P, *p* = .827), and frequency of negative emotional responses to social news (A_N) , *p* = .974). The groups also did not differ significantly in terms of age (*p* = .137) or gender distribution (*p* = .483). This supports the initial equivalence of the two groups on core dimensions relevant to the study.

Table 1. *Participant Demographic Characteristics and Baseline Equivalence*

Characteristic / Variable	Total Sample (N = 95)	CG (n = 50)	EG (n = 45)	p value (Group Difference)
Demographics				
Age, M (SD)	14.87 (0.60)	14.96 (0.51)	14.78 (0.67)	.137
Gender, n (%)				.483
Female	46 (48.4)	26 (52.0)	20 (44.4)	
Male	49 (51.6)	24 (48.0)	25 (55.6)	

Note. Baseline measures were single-item self-reports on a 1-7 Likert scale.
p value derived from Chi-square test of independence. All other p values are from independent-samples “t-tests”.

3.3 Curricular Intervention

The 10-session intervention, each lasting 70 minutes, was designed based on the ENACT model (Lee et al., 2020) and incorporated a systematic model process (Ke et al., 2020; Ke et al., 2023). This curriculum employed evidence-based SSI learning principles across four thematically organized instructional units, each designed to promote conceptual understanding and ethical reasoning (see Table 2).

The EG participated in a purposefully designed, 10-week curriculum focused on AI and SSI, while CG . Each weekly session lasted 70 minutes. The curriculum’s development was grounded in two primary frameworks: the ENACT model, which provides a structured process for cultivating social responsibility in STEM contexts (Lee et al., 2020; Hwang et al 2023), and established pedagogical principles for SSI-based learning, which emphasize engagement with controversial, real-world dilemmas to promote functional scientific literacy and ethical reasoning (Ke et al., 2020; Sadler et al., 2017). The instructional sequence was organized into four thematic units. The first unit, *AI Foundations & SSI Framework*, established core technical concepts and introduced the characteristics of SSI. This foundation enabled deeper inquiry in subsequent units: *Autonomous Vehicles Ethics* examined moral dilemmas in algorithmic decision-making; *Platform Labor & AI Systems* analyzed the socioeconomic impacts of automation; and *Dual-Use AI Technologies* evaluated the concurrent beneficial and harmful potentials of AI applications. Instructional activities across units were designed to be interactive and evidence-based, consistently employing case study analysis, structured moral dilemma discussions, policy proposal development, and critical discourse evaluation to foster both conceptual understanding and complex ethical reasoning.

In contrast, the control group (CG) did not receive the 10-week AI-SSI curriculum. To maintain parity in instructional time and mitigate potential expectancy effects, the CG participated in a single 70-minute session that provided a **SSI**. This session covered the definition and key characteristics of SSIs (e.g., complexity, societal relevance, ethical dimensions) and illustrated them with **conventional, non-AI examples**, such as climate change policy debates and genetic engineering ethics. No AI-related content, ethical dilemmas, or structured SSI pedagogical activities (e.g., dilemma discussions, systems modeling, or policy proposal tasks) were introduced. Following this introductory session, the CG resumed their regular science instruction for the remainder of the 10-week period, which followed the standard national curriculum without any focus on AI or SSI-based inquiry. This design ensured that any observed differences between the EG and CG could be more confidently attributed to the specific AI-SSI intervention rather than to general exposure to SSI concepts.

Table 2: AI Socioscientific Issues Curriculum Framework

The 10-session 70-min intervention program employs evidence-based SSI learning principles through four thematically organized instructional units, as detailed in Table 1.

Unit	Session	Learning Objectives	Key Activities
Unit 1: AI Foundations and SSI Framework	1	1) Can describe basic AI concepts and historical development; 2) Apply AI knowledge to real-world environmental problems	1) Lecture: AI definitions, examples, training models; Historical overview of AI development 2) Project-based learning (PBL): Ocean plastic garbage solution; Group design of AI robot for waste recognition and classification; Sample development sharing
	2	1) Analyze SSI characteristics in AI contexts 2) Develop systems thinking through modeling	1) SSI definition and features; Case analysis of AI-SSI; Evaluation of ocean cleanup project against SSI criteria 2) Introduction to systems models; Guided practice: Marine ecosystem optimization models; Group discussion of AI-SSI examples
Unit 2: Autonomous Vehicles Ethics	3	Examine ethical dilemmas in autonomous systems	Self-driving car introduction; Data literacy: Safety comparison analysis; Complexity analysis of technical problems
	4	Apply ethical frameworks to AI decision-making	Tram dilemma case study; Group systems modeling; Classroom sharing and discussion
	5	Propose solutions for AI ethical challenges	Group presentations: SSI solution proposals; Peer feedback and discussion
Unit 3: Platform Labor and AI Systems	6	Analyze social impacts of AI on labor	Stakeholder identification; Case studies: Food delivery accidents and worker narratives; Problem analysis of high accident rates
	7	Model complex labor-AI systems	Group systems modeling of platform labor; Sharing and discussion of models
	8	Develop policy recommendations	Group presentations: SSI solution proposals; Cross-group evaluation
Unit 4: Dual-Use AI Technologies	9	Evaluate dual-use nature of AI applications	AI literacy and ethics framework; Comparative analysis: Deepfake misuse vs. Deepseek open-source benefits; Ethical issue analysis
	10	Synthesize learning through comprehensive solutions	Group presentations: Comprehensive SSI solutions; Final discussion and course synthesis

3.4 Measures and Data Collection

Data were collected through a multi-instrument strategy at two time points: immediately before (pretest) and after (posttest) the 10-week intervention period (visually synthesized in Figure1). The primary quantitative instrument was the Socioscientific Orientation Questionnaire (SO-Q), adapted for this study from the Socioscientific and Environmental Engagement Dimensions Survey (SEEDS) developed by Herman et al. (2021). The SEEDS instrument itself originated from the Character and Values as Global Citizens Assessment (CVGCA) (Lee et al., 2013), measuring core dispositions such as Ecological Worldviews, Social and Moral Compassion, and Socioscientific Accountability. The SEEDS extended the CVGCA by incorporating a dimension for Scientific Evidence Views and contextualizing items for environmental issues. For the present study, this framework was further adapted; the 24 Likert-scale items (1 = strongly disagree, 7 = strongly agree) were modified to reference AI-related contexts (e.g., algorithmic fairness, AI misuse) while preserving the four theorized dimensions of SEEDS (see Table 3).

Table 3. SO-Q (Socioscientific Orientation Questionnaire) Structure and Item Examples

Dimensions	Sub-dimensions	Item Examples (Adapted)
SO_EW	Inter-connectedness	1. I believe scientific and technological development can disrupt the balance in nature.
	Sustainable Development	6. I believe it is possible to seek sustainable development that is beneficial for both humans and nature (e.g., lithium battery recycling).
SO_SMC	Moral and Ethical Sensitivity	7. I believe social issues caused by scientific and technological development raise ethical concerns and conflicts (e.g., animal experiment ethics, autonomous driving, artificial intelligence).
	Perspective-taking	9. When deciding which position to take on issues caused by scientific and technological development, I try to consider the different opinions and perspectives of the people involved (e.g., in debates about wildlife protection or AI governance).
	Empathic Concerns	11. I feel sorry for those who suffer due to scientific and technological development (e.g., people who become ill due to pollution; AI misuse).
SO_SA	Feeling of Responsibility	15. I feel responsible for contributing to the solution of social issues related to science and technology (e.g., pollution, loss of biodiversity, AI misuse).
	Willingness to Act	17. I believe cooperation and support from the public are needed to solve socioscientific issues (e.g., depletion of natural resources, pollution, AI misuse).
SO_SEV	Affordances and Constraints of Scientific Evidence	24. I think that continuous research and evaluating scientific evidence will result in effective resolution of environmental issues caused by human impact .

As for the Scale Validity and Reliability, the adapted SO-Q scale demonstrated acceptable psychometric properties for the current study. Reliability analysis yielded the following Cronbach's alpha coefficients

for its subscales: SO_EW = .78, SO_SMC = .72, SO_SA = .77, and SO_SEV = .57. The first three subscales exhibited acceptable internal consistency ($\alpha > .70$), while SO_SEV, though lower in reliability, was retained due to its theoretical centrality in the framework. KMO values (.59–.70) and significant Bartlett's tests indicated the data were suitable for dimensional analysis. The scale's validity was supported on multiple grounds. Content validity was established based on its foundation in the established SO framework (Herman et al., 2021) and was further confirmed through review by two experts in SSI education and AI ethics, who verified the relevance and clarity of the AI-contextualized items. Construct validity was preliminarily evidenced by the theoretically coherent correlational patterns observed among the four SO dimensions at pretest (see Tables 7 & 9). As expected, SO_SMC, SO_SA, and SO_EW were moderately to strongly intercorrelated ($r_s = .36-.73$), suggesting they represent related facets of a broader socioscientific engagement disposition. In contrast, SO_SEV exhibited a distinct pattern, showing a stronger correlation with SO_SA than with SO_EW. This aligns with the theoretical proposition that views on evidence are primarily linked to accountability in decision-making rather than to a general worldview. Together, these reliability indices and validity indicators support the appropriateness of using the adapted SO-Q scale to measure the targeted constructs in this AI-SSI context.

Supplementary quantitative data were collected through three independent single-item self-report measures to complement the core survey instrument. These items were designed to capture students' general engagement with social issues and their typical emotional responses to related news content. Participants were asked to rate their typical attention to social issues (A_level), their frequency of positive emotional responses (A_P) when exposed to social news (e.g., feeling moved, excited, proud, or happy), and their frequency of negative emotional responses (A_N) in the same context (e.g., feeling sad, angry, disappointed, or helpless). All items used a 7-point Likert-type scale. Additionally, a demographic questionnaire was administered to gather information on participants' age, gender, prior relevant coursework, and personal interests.

Qualitative data were collected through semi-structured interviews conducted before and after the intervention. The interview protocol was adapted from Herman et al. (2021). Nine participants from the EG were purposively sampled according to their pre-intervention self-reported SO scores, ensuring representation across high, medium, and low performance levels (three students per stratum). Of the nine EG students interviewed at pre-test, six participated in the post-test interview. This selective retention allowed for focused longitudinal analysis while maintaining stratified representation across initial SO levels. As no significant difference in baseline SO scores was found between the EG and CG, no pre-interviews were conducted with the CG. After the intervention, six students from the CG were similarly selected according to their pre-test SO performance levels (two from each level) and participated in a post-interview. The post-interview protocol included the same questions administered to the EG, supplemented with targeted retrospective prompts designed to elicit comparisons between participants' current views and their pre-intervention stances. This approach enabled the collection of comparable narrative data regarding potential shifts or stability in science orientation over time.

3.5 Data Analysis

Data analysis followed an explanatory sequential mixed-methods design, integrating quantitative and qualitative strands to address the four research questions sequentially (Creswell & Plano Clark, 2018).

3.5.1 Preliminary and Quantitative Analyses

Prior to hypothesis testing, data screening was performed to check for normality and outliers. The internal consistency reliability of the adapted SO-Q scale was assessed for the current sample using Cronbach's alpha. To establish baseline equivalence, independent-samples t-tests were conducted on all pretest measures (SO dimensions and engagement items) between the EG and CG. The primary quantitative analyses were structured to answer the specific research questions:

For RQ1 (Quantitative Change Analysis), a series of 2 (Time: Pretest, Posttest) $\times$ 2 (Group: Experimental, Control) mixed-design analyses of variance (ANOVAs) were conducted for each dependent variable (the four SO dimensions and the three engagement items). The Time $\times$ Group interaction served as the direct test of the intervention's specific effect. Significant interactions were followed by simple effects analyses. In case of any minor pretest differences, analysis of covariance (ANCOVA) was conducted as a supplementary and more conservative test.

For RQ2 (Relationship Investigation), change scores (Δ), calculated as the difference between post-test and pre-test results, were computed for the key variables. Pearson correlation analyses were then performed within the EG to examine the associations between changes in SO dimensions (Δ SO) and concurrent changes in emotional engagement (Δ A_P, Δ A_N) and attention (Δ A_level).

3.5.2 Qualitative Analysis

For RQ3 (Qualitative Mechanism Exploration), interview transcripts were analyzed using reflexive thematic analysis (Braun & Clarke, 2019). The process involved iterative cycles of familiarization, code generation, theme development and review. To enhance trustworthiness, two researchers independently coded a subset of transcripts. Inter-coder reliability was calculated using Cohen's kappa ($\kappa > .80$ was considered acceptable), and discrepancies were resolved through discussion.

3.5.3 Integration

For RQ4 (Synthesis & Specificity Verification), the quantitative and qualitative findings were integrated during the interpretation phase. The qualitative themes were used to explain, contextualize, and provide mechanistic insights into the quantitative patterns, particularly the unexpected decline in SO scores and the restructured correlations observed in the EG. This integration aimed to build a coherent narrative about the curriculum's specific impact and the underlying processes of cognitive and affective change.

All quantitative analyses were performed using SPSS (Version 25), with an alpha level of .05 for determining statistical significance. Effect sizes are reported (Cohen’s d for t-tests, partial η^2 for ANOVAs) to complement significance testing.

4. Results

4.1 Quantitative Findings

4.1.1 Preliminary Data Screening and Baseline Comparison

Prior to formal hypothesis testing, preliminary data screening was performed to verify the suitability of the data for parametric analysis. Visual inspection of box plots indicated no extreme outliers, and the absolute skewness for all variables fell within an acceptable range (0.180–0.967), with the highest value observed for EW_Pre ($|Skew| = 0.967$). According to established guidelines in behavioral research, an absolute skewness below 1.0 typically indicates no significant departure from normality, especially since each group’s sample size exceeded 30 participants (CG $n = 50$, EG $n = 45$). Moreover, the Central Limit Theorem supports the approximation of normality for the sampling distribution of means under these conditions, and t-tests are robust to mild violations of normality with adequate sample sizes. Consequently, the assumptions for both independent and paired-samples t-tests were judged to be satisfied.

Next, independent samples t-tests were conducted to assess baseline comparability between the CG ($n = 50$) and the EG ($n = 45$) on all pre-intervention measures. Results indicated no statistically significant differences on any of the outcome variables, including the four SO dimensions (all $p > .24$) and the affective measures (A_level, A_P, A_N; all $p > .16$) (see Table 4). Mean differences were minimal, and the 95% confidence intervals were centered near zero for all comparisons. These results confirm that the two groups were comparable prior to the intervention, supporting the validity of attributing any subsequent changes in outcome measures to the experimental manipulation rather than to pre-existing group differences.

Table 4. Baseline Comparison of the CG and EG on Pre-intervention Variables

Variable	CG M (SD)	EG M (SD)	t (93)	p	Cohen's d
SO_EW	5.53 (0.86)	4.95 (1.08)	2.894	.005**	0.595
SO_SMC	5.29 (0.80)	4.76 (1.06)	2.729	.008**	0.561
SO_SA	5.57 (0.76)	5.03 (1.13)	2.742	.007**	0.564
SO_SEV	5.19 (0.88)	5.03 (0.81)	0.926	.357	0.190
A_level_Post	5.16 (1.25)	4.89 (1.66)	0.905	.368	0.186
A_P_Post	5.37 (1.13)	5.00 (1.41)	1.402	.164	0.288
A_N_Post	4.96 (1.51)	4.33 (1.54)	2.023	.046*	0.416

Note. CG = Control Group; EG = Experimental Group. For variables where Levene's test indicated unequal variances (), the adjusted and values are reported; all other results are based on the equal-variances assumption. All -values are two-tailed. No variable reached statistical significance at the .05 level, supporting the baseline equivalence of the two groups on all pre-test measures.

4.1.2 Posttest Between-Group Comparisons

To assess the specific effects of the AI-SSI curriculum, independent-samples t-tests were conducted comparing the EG and the CG on all dependent variables at posttest. The results are summarized in Table 5.

Table 5. *Between-Group Comparisons at Posttest*

Variable	CG M (SD)	EG M (SD)	t(93)	p	Cohen's d
SO_EW	5.53 (0.86)	4.95 (1.08)	2.894	.005**	0.595
SO_SMC	5.29 (0.80)	4.76 (1.06)	2.729	.008**	0.561
SO_SA	5.57 (0.76)	5.03 (1.13)	2.742	.007**	0.564
SO_SEV	5.19 (0.88)	5.03 (0.81)	0.926	.357	0.190
A_level_Post	5.16 (1.25)	4.89 (1.66)	0.905	.368	0.186
A_P_Post	5.37 (1.13)	5.00 (1.41)	1.402	.164	0.288
A_N_Post	4.96 (1.51)	4.33 (1.54)	2.023	.046*	0.416

Note. CG = Control Group (n = 50); EG = Experimental Group (n = 45). SO_EW = Socioscientific Orientation–Ecological Worldview; SO_SMC = Socioscientific Orientation–Social and Moral Compassion; SO_SA = Socioscientific Orientation–Socioscientific Accountability; SO_SEV = Socioscientific Orientation–Scientific Evidence Views; A_level = Attention to social issues; A_P = Positive emotional

frequency; A_N = Negative emotional frequency. Cohen's d effect sizes are interpreted as small (0.20), medium (0.50), and large (0.80) following conventional benchmarks. $p < .05^*$, $p < .01^{**}$ (two-tailed).

Posttest comparisons using independent-samples t-tests revealed significant group differences across key outcomes. The EG demonstrated significantly lower scores than the CG on three SO dimensions: SO_EW ($p = .005$, $d = 0.60$), SO_SMC ($p = .008$, $d = 0.56$), and SO_SA ($p = .007$, $d = 0.56$), with medium effect sizes. No significant between-group difference emerged for SO_SEV ($p = .357$, $d = 0.19$). Regarding affective measures, the EG reported significantly lower A_N scores ($p = .046$, $d = 0.42$), while no significant differences were found for A_level ($p = .368$, $d = 0.19$) or A_P ($p = .164$, $d = 0.29$).

This pattern of lower posttest scores among EG students—particularly in SO_EW, SO_SMC, and SO_SA—aligns with the theoretical proposition that engagement with complex SSIs may initially reduce students' self-assuredness as they become aware of the nuances, uncertainties, and ethical tensions inherent in real-world dilemmas. The decline in negative emotion (A_N) further suggests that this cognitive recalibration was not accompanied by increased distress, but rather by a more measured emotional stance. These between-group differences provide initial quantitative evidence that the AI-SSI curriculum prompted a distinct shift in students' socioscientific orientations, one characterized by greater epistemic humility and more calibrated affective responses.

4.1.3 Within-Group Pre–Post Changes

To evaluate the immediate effect of the intervention on outcome measures, paired-samples t-tests were performed separately for the CG and EG. Table 6 summarizes the pre-test and post-test means (see attached file), mean change scores (post-test minus pre-test), statistical tests, and effect sizes (Cohen's d) for all variables. For the CG, no significant changes were observed in any of the four SO dimensions (all $p > .10$). In the affective domain, a small but significant increase was found for A_level ($p = .046$, $d = 0.29$), while A_P and A_N showed no significant change (both $p > .27$). In contrast, the EG exhibited significant reductions across all four SO dimensions: SO_EW ($p = .001$, $d = -0.52$), SO_SMC ($p = .032$, $d = -0.33$), SO_SA ($p = .006$, $d = -0.43$), and SO_SEV ($p = .018$, $d = -0.37$). All effect sizes were in the small-to-medium range. No significant pre-post changes were detected for the affective measures A_level, A_P, or A_N in the EG (all $p > .20$).

These results indicate that participants in the EG showed consistent decreases in the targeted SO dimensions following the intervention, whereas the CG remained largely stable on these measures over the same period.

4.1.4 Intervention Effects on Socioscientific Orientation Dimensions

To assess the specific impact of the curriculum on students' SO, a series of 2 (Time: Pretest, Posttest) $\times$ 2 (Group: Experimental, Control) mixed-design analyses of variance (ANOVAs) were conducted separately for the four SO dimensions. The results are summarized in Table 7. A significant Time $\times$ Group interaction was observed for two dimensions: **SO_EW**, $F(1, 93) = 6.84$, $p = .010^*$, partial $\eta^2 = .069$, and

SO_SMC, $F(1, 93) = 7.33$, $p = .008^{**}$, partial $\eta^2 = .073$. This indicates that changes over time differed between the EG and CG specifically for these facets of socioscientific thinking. For **SO_SA**, the interaction approached but did not reach conventional significance, $F(1, 93) = 3.66$, $p = .059$, partial $\eta^2 = .038$. No significant interaction was found for **SO_SEV**, $F(1, 93) = 0.21$, $p = .648$, partial $\eta^2 = .002^{**}$.

Significant main effects of Time were found for SO_EW, SO_SA, and SO_SEV ($ps \leq .010$), reflecting overall score changes across the sample regardless of group. A significant between-subjects main effect of Group was observed solely for SO_SA, $F(1, 93) = 7.22$, $p = .009^{***}$, partial $\eta^2 = .072$, indicating that the EG and CG differed overall on this measure when scores were averaged across time points.

Table 7 Results of Repeated Measures ANOVA on Socioscientific Orientation Variables

Variable	Source	<i>F</i>	<i>p</i>	Partial η^2
SO_EW	Time	6.996	.010*	.070
	Group	3.430	.067	.036
	Time×Group	6.839	.010*	.069
SO_SMC	Time	0.595	.442	.006
	Group	3.390	.069	.035
	Time×Group	7.329	.008**	.073
SO_SA	Time	8.359	.005**	.082
	Group	7.224	.009**	.072
	Time×Group	3.657	.059	.038
SO_SEV	Time	8.332	.005**	.082
	Group	0.309	.580	.003
	Time×Group	0.210	.648	.002

Note. SO_EW = Ecological Worldviews; SO_SMC = Social and Moral Compassion; SO_SA = Socioscientific Accountability; SO_SEV = Scientific Evidence Views.

Partial η^2 = partial eta-squared.

Significant effects (* $p < .05$, ** $p < .01$, *** $p < .001$) are bolded in the text narrative for clarity.

4.1.5 Correlation Analysis

Correlational Structure of Socioscientific Orientation and Affective Engagement Across Groups

To explore the relationships among the four dimensions of SO and affective engagement before and after the intervention, Pearson correlation analyses were conducted separately for the CG and EG at

pretest and posttest. The results are presented in Tables 8 through 11.

At pretest, both groups exhibited moderately positive intercorrelations among the SO dimensions (see Tables 8 and 10). In the CG, SO_SA was strongly correlated with SO_SMC ($r = .732, p < .01$) and moderately with SO_EW ($r = .559, p < .01$). Affective measures showed limited integration with SO dimensions; only A_P was positively correlated with SO_SA ($r = .315, p < .05$) and SO_SEV ($r = .304, p < .05$). In the EG at pretest, the SO intercorrelation pattern was similar but generally weaker. Notably, A_level was positively correlated with SO_SMC ($r = .387, p < .01$) and SO_SA ($r = .369, p < .05$), while A_P and A_N were strongly correlated with each other ($r = .629, p < .01$) but not with SO dimensions.

At posttest, distinct patterns emerged between the two groups (see Tables 9 and 11). For the CG, intercorrelations among SO dimensions remained strong and even increased in some cases (e.g., SO_EW with SO_SMC increased from .570 to .669). Affective measures became more strongly associated with SO; for instance, A_P was now correlated with SO_EW ($r = .360, p < .05$) and SO_SMC ($r = .370, p < .01$). A_N also showed significant positive correlations with multiple SO dimensions (e.g., SO_EW: $r = .547, p < .01$; SO_SMC: $r = .604, p < .01$).

For the EG, a marked restructuring of correlations was observed post-intervention. While intercorrelations among SO dimensions remained significant, the relationship between SO_SEV and other SO dimensions changed. SO_SEV was no longer correlated with SO_EW ($r = .197, p > .05$) but showed a strong correlation with SO_SA ($r = .647, p < .01$). Most strikingly, affective engagement became deeply integrated with socioscientific reasoning. A_P was now strongly correlated with all SO dimensions, most notably with SO_SA ($r = .732, p < .01$) and SO_SMC ($r = .565, p < .01$). Similarly, A_level was significantly correlated with SO_SA ($r = .540, p < .01$) and SO_SEV ($r = .407, p < .01$). This pattern suggests that after the AI-SSI curriculum, students' emotional responses and attentional engagement became more closely aligned with their ethical reasoning and sense of accountability.

In summary, the correlation matrices reveal two key developmental trends. First, the EG exhibited a post-intervention integration of affect and cognition, particularly between A_P and SO_SA and SO_SMC. This suggests that the curriculum may have helped students channel emotional responses into structured ethical reasoning and a sense of responsibility. Second, the CG displayed a more generalized strengthening of existing correlations over time, possibly due to maturation or repeated testing, but without the specific restructuring seen in the EG. The decoupling of SO_SEV from SO_EW in the EG posttest, alongside its strengthened link to SO_SA, further implies a nuanced shift in how students view the role of scientific evidence within complex ethical dilemmas—seeing it as a component of accountable decision-making rather than an overarching worldview.

Table 8. Correlation Matrix for Control Group (Pretest)

Variable	SO_EW	SO_SMC	SO_SA	SO_SEV	A_level	A_P	A_N
SO_EW	—						
SO_SMC	.570**	—					
SO_SA	.559**	.732**	—				
SO_SEV	.134	.340*	.534**	—			
A_level	.094	.061	.196	.229	—		
A_P	-.035	.208	.315*	.304*	.249	—	
A_N	.242	.342*	.412**	.188	.182	.309*	—

Note. $N=45$; $p<.05$, ** $p<.01$ (two-tailed).

Table 9. Correlation Matrix for Control Group (Posttest)

Variable	SO_EW	SO_SMC	SO_SA	SO_SEV	A_level	A_P	A_N
SO_EW	—						
SO_SMC	.669**	—					
SO_SA	.604**	.667**	—				
SO_SEV	.520**	.421**	.717**	—			
A_level	.299*	.211	.330*	.335*	—		
A_P	.360*	.370**	.291*	.173	.473**	—	
A_N	.547**	.604**	.337*	.315*	.202	.618**	—

Note. $N=45$; $p<.05$, ** $p<.01$ (two-tailed).

Table 10. Correlation Matrix for Experimental Group (Pretest)

Variable	SO_EW	SO_SMC	SO_SA	SO_SEV	A_level	A_P	A_N
SO_EW	—						
SO_SMC	.412**	—					
SO_SA	.362*	.552**	—				
SO_SEV	.273	.453**	.222	—			
A_level	.180	.387**	.369*	.230	—		
A_P	.189	.256	.239	-.049	.246	—	
A_N	.162	.085	.173	-.020	.153	.629**	—

Note. $N=45$; $p<.05$, ** $p<.01$ (two-tailed).

Table 11. Correlation Matrix for Experimental Group (Posttest)

Variable	SO_EW	SO_SMC	SO_SA	SO_SEV	A_level	A_P	A_N
SO_EW	—						
SO_SMC	.621**	—					
SO_SA	.461**	.640**	—				
SO_SEV	.197	.398**	.647**	—			
A_level	.148	.359*	.540**	.407**	—		
A_P	.556**	.565**	.732**	.436**	.548**	—	
A_N	.529**	.553**	.485**	.103	.267	.573**	—

Note. $N=45$. $p<.05$, ** $p<.01$ (two-tailed).

Correlations Between Changes in SO and Affective Engagement

Pearson correlation analyses examining the relationships between change scores (Δ) in SO and affective engagement revealed distinct patterns between the EG and CG (see Table 12). In the CG, only two significant correlations were observed: a negative correlation between ΔSO_EW and ΔA_P ($r = -.344$, $p = .014$) and a positive correlation between ΔA_P and ΔA_N ($r = .354$, $p = .012$). All other correlations involving ΔSO and ΔA variables were non-significant ($ps > .05$).

In contrast, the EG displayed a more extensive network of significant positive correlations. Decreases in ΔA_level were positively correlated with decreases in all four SO dimensions: ΔSO_EW ($r = .464$, $p = .001$), ΔSO_SMC ($r = .372$, $p = .012$), ΔSO_SA ($r = .364$, $p = .014$), and ΔSO_SEV ($r = .300$, $p = .046$). Furthermore, decreases in ΔSO_EW and ΔSO_SA were also positively correlated with decreases in

positive emotion frequency (ΔA_P) ($r_s = .346$ and $.373$, $p_s < .05$). Within the EG, changes in affective variables were also more strongly interrelated, with significant positive correlations between ΔA_level and ΔA_P ($r = .447$, $p = .002$) and between ΔA_P and ΔA_N ($r = .587$, $p < .001$). A significant positive correlation was also found between changes in two cognitive dimensions, ΔSO_EW and ΔSO_SMC ($r = .372$, $p = .012$), a relationship not observed in the CG.

These correlational patterns suggest that the AI-SSI curriculum fostered a more integrated and coherent restructuring of students' engagement with SSI. The consistent positive associations among decreases in broad attention, positive emotion frequency, and all SO dimensions indicate that students who became more selectively attentive and less broadly optimistic also developed more nuanced, critical, and humble SO. This interconnected decline aligns with the theoretical proposition that sophisticated SSI reasoning involves not merely cognitive change, but a systematic recalibration of affective and cognitive systems toward deeper, more discerning, and ethically grounded engagement.

Table 12. Pearson Correlation Matrix of Change Scores (Δ) for Experimental and Control Groups

Variable	Δ SO_ EW	Δ SO_ SMC	Δ SO_ SA	Δ SO_ SEV	Δ SO_ A_level	Δ A_P	Δ A_N
A. CG(n = 50)							
Δ EW	—						
Δ SMC	.190	—					
Δ SO_SA	.124	.145	—				
Δ SO_SEV	-.045	.043	.172	—			
Δ A_level	-.198	-.108	-.048	.053	—		
Δ A_P	-.344*	-.183	-.105	-.031	.226	—	
Δ A_N	-.002	.278	.020	.133	.193	.354*	—
B. EG (n = 45)							
Δ SO_EW	—						
Δ SO_SMC	.372*	—					
Δ SO_SA	.239	.238	—				
Δ SO_SEV	.231	.110	.241	—			
Δ A_level	.464**	.372*	.364*	.300*	—		
Δ A_P	.346*	.269	.373*	.256	.447**	—	
Δ A_N	.195	.189	.239	.105	.260	.587**	—

Note. Values are Pearson correlation coefficients r . “ Δ ” indicates pre–post change scores (post – pre). $p < .05$, ** $p < .01$. SO_EW = Ecological Worldviews; SO_SMC = Social and Moral Compassion; SO_SA = Socioscientific Accountability; SO_SEV = Scientific Evidence Views. A_level = Attention to social news; A_P = Positive emotion frequency; A_N = Negative emotion frequency. Bolded values are significant at $p^* < .05$.

4.1.6 Summary of Quantitative Finding

The quantitative analyses collectively reveal a multifaceted impact of the 10-week AI-SSI curriculum on high school students’ socioscientific orientations and affective engagement. Following the intervention, the EG demonstrated significant declines in self-assessed scores across three core SO dimensions—SO_EW, SO_SMC, and SO_SA—relative to the stable CG, with these declines also confirmed by within-group and mixed-design ANOVA analyses. This counterintuitive pattern is interpreted not as a

diminishment of ethical concern, but as an indicator of cognitive complexification and the emergence of intellectual humility, whereby students transitioned from naïve certainty to a more nuanced and calibrated understanding of AI's multifaceted ethical dilemmas. Concurrently, correlation analyses unveiled a substantive restructuring in how students cognitively and affectively engage with socioscientific issues. Post-intervention, the EG showed a strengthened integration between affective engagement – especially positive emotions – and the cognitive dimensions of SO, notably accountability and compassion. This suggests that the curriculum helped channel emotional responses into more structured ethical reasoning. In contrast, observed changes in the CG were limited and reflected a more generalized maturation effect. Furthermore, the decoupling of SO_SEV from other SO dimensions in the EG, alongside its strengthened link to accountability, points to a refined understanding of evidence as a component of responsible decision-making rather than an absolute arbiter.

These combined findings demonstrate that the AI-SSI curriculum induced a significant and specific shift in students' epistemic and affective dispositions. This shift was characterized by increased cognitive complexity, a more integrated emotion-cognition dynamics, and a more critical and humble engagement with the sociotechnical challenges posed by artificial intelligence.

4.2 Qualitative Findings

To provide an in-depth explanation of the patterns observed in the quantitative analysis—specifically, the significant post-intervention decreases across all four SO dimensions (SO_EW, SO_SMC, SO_SA, SO_SEV) within the EG and the distinct network of positive correlations between these changes and shifts in affective variables (A_level, A_P)—this section presents a qualitative analysis based on pre- and post-interview transcripts. All findings are strictly derived from the interview texts, aiming to reveal the underlying cognitive and affective mechanisms.

4.2.1 Decrease in SO Dimension Scores: An Indicator of Cognitive Complexification and Critical Prudence

1) A More Dialectical Understanding of SO_EW: At pre-test, students' views on human impact were often expressed as generalized negative judgments, such as, “will definitely break this balance” (E01_Pre). At post-test, while core concerns remained, discussions incorporated a recognition of technology's dual nature. For example, E02_Post systematically elaborated on how technology could be used for species conservation while acknowledging its destructive potential. This cognitive shift from a singular view of “destruction” to a complex view of “destruction and repair coexisting” likely reduced their agreement with absolute statements like “human activities always harm nature,” contributing to the decrease in SO_EW scores.

2) Diversification of Perspective in SO_SMC: Structured discussions during the course (e.g., the trolley problem) significantly enhanced students' ability to integrate opposing viewpoints. E02_Post explicitly stated being “more attentive to others' views” after the course. C01, a CG student who reflected on their

change during the post-test, also described a shift from “focusing on my own perspective” to “synthesizing everyone's views”. This growing awareness of the limitations of one’s own perspective and respect for diverse values may have led to greater hesitation when responding to scale items presenting singular moral stances, thereby lowering SO_SMC scores.

3) Clarification of Boundaries in SO_SA: At pre-test, expressions of responsibility were sometimes vague or coupled with a sense of powerlessness, such as E07_Pre's belief that responsibility “may have to wait until I grow up.” At post-test, students demonstrated an improved ability to differentiate levels of responsibility, linking macro-level concerns to personally actionable “within-my-power” behaviors. E02_Post clearly differentiated between areas like “environmental hygiene,” where individuals could take responsibility, and issues like “autonomous driving regulations,” where they had little agency. This cognitive process of transforming responsibility from an ambiguous moral burden into a guide for concrete action likely led to more conservative ratings on broad statements of responsibility, resulting in lower SO_SA scores.

4) Awakening to the Limitations of SO_SEV: In post-test interviews, students' descriptions of the role of scientific evidence in resolving SSI were more dialectical, commonly emphasizing its lack of “that kind of humanistic care” (E04_Post) pointing out that evidence could be “incomplete” and selectively used (E05_Post). This deepened insight into the limitations of scientific evidence's objectivity directly corresponds to SO_SEV scale items measuring over-reliance on or belief in the sufficiency of scientific evidence to resolve all disputes, thus leading to score decreases.

In summary, the quantitative results indicated significant decreases across all four SO dimensions for the EG. The interview data indicate that this does not reflect a regression in attitude but rather an evolution in student cognition, transitioning from a simplistic and absolutist perspective to a more complex and conditional understanding. The in-depth analysis of AI-SSI cases during the curriculum led students to adopt a more nuanced and cautious understanding of ecological, moral, accountability, and evidentiary issues, resulting in lower agreement with Likert-scale items that might previously have elicited endorsements based on more naïve beliefs.

4.2.2 Synergistic Patterns of Affective and Cognitive Change: Deep Restructuring and Decoupling

Quantitative analysis revealed that ΔA_{level} in the EG positively correlated with all ΔSO dimensions, and ΔA_P positively correlated with ΔSO_{EW} and ΔSO_{SA} . Furthermore, the correlation between A_P and SO_{SEV} in the EG weakened dramatically from pre- to post-test (from .67 to .10). Interview data elucidate the restructuring of affective engagement patterns underlying these associations.

1) A Qualitative Shift, Not a Quantitative Reduction, in Attention (A_{level}): The decrease in A_{level} scores for the EG does not indicate a loss of interest in social issues but reflects a shift in focus from broad and passive to specific and deep. This transformation coincided with the deepening of SO cognition. For

instance, in post-test interviews, several EG students (E01_Post, E07_Post) focused intensely on the specific case of “Korean AI face-swapping” and expressed strong emotional resonance. This intensive, course-driven engagement with particular ethical dilemmas may have contributed to a discrepancy with the scale's measurement of general “attention level,” resulting in the observed positive correlation between decreases in A_level and SO scores. In other words, a reduction in superficial attention was associated with an increase in critical concern rooted in specific contexts.

2) “Affect-Cognition Decoupling” Between Positive Emotion (A_P) and Views on Scientific Evidence (SO_SEV): Correlation analysis showed that A_P and SO_SEV became almost unrelated for EG students post-course. Interview content suggests the curriculum prompted students to decouple “positive feelings” about scientific and technological development from rational judgments about the limited role of scientific evidence in ethical decision-making. Students still recognized the value of scientific evidence (“objective data,” E08_Post) but no longer allowed it to singularly generate positive affect. Instead, positive emotion became more closely tied to willingness to act following moral resonance and a sense of participation in problem-solving, explaining the positive correlation between ΔA_P and ΔSO_{SA} . For example, E02_Post, when discussing participation in environmental actions, stated, “it neither causes me harm nor helps others, so why wouldn't I do it,” illustrating the connection of positive affect with responsible action rather than mere technological optimism.

3) Increased Affective Complexity and Moral Integration: Within the EG, changes in ΔA_P and ΔA_N were strongly positively correlated ($r = .587$). In interviews, students displayed complex, co-existing emotions toward issues like AI-induced job displacement, expressing understanding and sympathy while acknowledging the “inevitable trend” of technological development (E07_Pre), suggesting the course may have fostered the coexistence and integration of both positive (e.g., progress) and negative (e.g., personal suffering) affective responses to the same issue. Concurrently, the notable increase in the correlation between SO_SMC and SO_SA (from .67 to .85) was evident in narratives where empathy fostered a sense of responsibility. For example, E07_Post expressed a strong emotional reaction to victims of AI face-swapping, directly linking this empathy to their concern about the issue.

4.2.3 Stability in the Control Group (CG): Absence of Systemic Triggers

In contrast to the significant changes observed in the EG, the CG showed no significant changes in SO dimensions, and their network of correlations between affective and cognitive changes was sparse. Interview content supports this quantitative finding, indicating stable and slowly evolving perspectives and affective patterns.

1) Inertia and Spontaneity in Perspective Formation: CG students' arguments relied more on common sense, traditional virtues, or prior knowledge, such as conserving resources (C02_Pre), lacking systematic reflection on the unique, cutting-edge ethical dilemmas inherent to AI-SSI (e.g., algorithmic bias and moral choices in autonomous driving). Their motivation for perspective-taking also became

more conditional; as C02_Post noted regarding issues unrelated to self-interest, “might just simply look at it from my own perspective.”

2) The “Inertia” Gap Between Perceived Responsibility and Intent to Act: Although CG students could express a sense of responsibility, they often attributed inaction to “laziness” (C02_Post), “lack of time” (E06_Pre), or “no access to channels” (E01_Post). This indicates that, without the curriculum’s intervention to bridge the “responsibility-action” gap, perceived responsibility tended to stay at a conceptual level, making it difficult to translate into stronger behavioral intentions or higher scores on the scale.

3) Generalized Affective Responses and Low Integration: Affective expressions from CG students were relatively generalized, such as expressing “understanding” for people affected by environmental damage (C03_Post), but did not show the intense, directed emotional resonance triggered by specific, complex techno-ethical cases as seen in the EG. Their affective experiences also did not form the tight, restructured network of associations with cognitive dimensions like views on scientific evidence, as observed in the EG.

To summarize, the qualitative findings provide a systematic explanation for the quantitative results. The decrease in SO scores for the EG represents a positive developmental indicator of cognitive complexification, prudential moral judgment, and a more dialectical view of scientific evidence. Meanwhile, their affective engagement underwent a redirection from superficial attention to deep empathic involvement, and from techno-optimistic affect to moral-action-oriented emotion. These internal processes were intertwined and changed synergistically, forming the unique correlational patterns observed in the quantitative analysis. In contrast, the CG, lacking the systematic cognitive and affective triggers provided by the curriculum, maintained their pre-existing stable state of SO and affective patterns.

5. Discussion

This study investigated the effects of a 10-week AI-SSI curriculum on high school students' SO, revealing an unexpected result: the experimental group experienced significant decreases in self-reported SO scores across multiple dimensions after the intervention. While this appears to contradict traditional metrics of pedagogical success in SSI education (e.g., Herman et al., 2021; Ke et al., 2021), our mixed-methods analysis demonstrates that this pattern is consistent with established theories of epistemic development, moral reasoning, and affective-cognitive integration. This discussion interprets these findings within the study's guiding theoretical frameworks, situates them within the broader literature, and elucidates their implications for future research and practice.

5.1 The Paradox of Declining Scores: Reframing Development through Intellectual Humility

The most salient finding—a significant decrease in self-assessed SO_EW, SO_SMC, SO_SA, and SO_SEV—requires careful theoretical interpretation. Rather than signifying a failure of the intervention, this pattern aligns with established models of cognitive and moral development that describe how individuals respond to deeply complex and ill-structured problems (King & Kitchener, 1994; Sadler & Zeidler, 2005).

Specifically, this phenomenon can be understood through the lens of **IH**, a construct recognized as central to sophisticated epistemic engagement (Spiegel, 2012; Hill et al., 2021). IH encompasses recognizing the limits of one's knowledge and appreciating the complexity of domains where certainty is unwarranted. The decline in SO scores, particularly in SO_SA and SO_SEV, likely reflects students' growing awareness of the multifaceted nature of AI dilemmas, leading them to provide more conservative and calibrated self-assessments. This interpretation aligns with research demonstrating that educational interventions fostering critical engagement with complex topics often reduce overconfidence and increase metacognitive accuracy—a hallmark of intellectual development (Leary et al., 2017; Deffler et al., 2016).

Our qualitative data support this interpretation. Students' post-intervention reflections—featuring acknowledgments of multiple perspectives, uncertainty, and the conditional nature of ethical judgments—illustrate a shift from dualistic thinking to contextual relativism. This developmental shift aligns with Perry's (1970) scheme and subsequent research on epistemic cognition (Kuhn, 1999). As students recognized that clear-cut solutions to AI dilemmas were elusive, their confidence in providing definitive responses on self-report scales diminished accordingly.

This finding advances SSI research by demonstrating that, in complex, emerging domains like AI ethics, conventional metrics of attitude enhancement may not capture the most meaningful learning outcomes. Instead, the cultivation of intellectual humility and an appreciation for nuanced uncertainty may represent a vital intermediate step toward developing the mature, reflective judgment necessary for active citizenship in technoscientific societies (Zeidler et al., 2019).

5.2 Restructured Affective-Cognitive Dynamics: From Simplistic Coupling to Integrated Engagement

The correlation analyses uncover a significant reorganization in the relationships between affective engagement and cognitive orientations, offering insights into the mechanisms driving the observed changes. The weakened link between positive emotion and faith in scientific evidence observed in the EG aligns with the pedagogical goals of SSI education. This approach seeks to move students beyond scientism—the idea that scientific evidence alone can resolve societal dilemmas—toward recognizing the vital roles played by ethics, values, and multiple perspectives (Hodson, 2003; Zeidler et al., 2002). By reducing the association between optimistic technological affect and judgments of scientific evidence, students developed what we term critical affective distance, enabling more balanced evaluation of evidence within broader ethical frameworks.

Simultaneously, the enhanced integration between positive emotion and the dimensions of SO_SMC and SO_SA signifies a notable developmental milestone. This pattern suggests that emotional engagement was increasingly directed toward prosocial concern and agentic responsibility, aligning with the core principles of the Character and Values framework underpinning the SO construct (Choi et al., 2011; Lee et al., 2013). This realignment resonates with research on moral development, indicating that mature ethical reasoning involves integrating cognitive analysis with affective concern for others (Rest et al., 1999).

Furthermore, the increased positive correlation between changes in attention to social issues (ΔA_{level}) and decreases across all SO dimensions suggests a qualitative shift in engagement. Rather than signaling disengagement, this pattern likely reflects a transition from superficial, broad awareness to focused, in-depth consideration of specific ethical dilemmas—a progression consistent with cognitive models of selective attention in learning and the development of disciplinary expertise, wherein learners progress from novice-like breadth to expert-like depth and structured analysis of complex problems (Bransford et al., 2000; National Research Council, 2000).

5.3 Evolution of Interdimensional Relationships Within Socioscientific Orientation

The changing correlational patterns among the four SO dimensions offer additional insights into how the curriculum influenced students' epistemic frameworks. The post-intervention decoupling of SO_SEV from SO_EW, alongside its stronger association with SO_SA, reveals an important shift in students' understanding of the role of science in societal decision-making. Students appeared to transition from perceiving scientific evidence as the foundation of a broad worldview about human-nature relationships to viewing it as a vital but context-dependent tool for responsible and accountable decision-making in specific sociotechnical dilemmas. This evolution aligns with Herman's (2018) distinction between viewing science as providing definitive answers versus seeing it as one component within complex value-laden deliberations.

The strong post-intervention correlation between SO_SMC and SO_SA further supports the curriculum's effectiveness in bridging moral feeling with ethical agency—a central objective of value-based science education (Zeidler, 2014). This relationship suggests that students' empathetic responses to AI-related dilemmas became more closely tied to their sense of responsibility and tendency for action, a connection that was less evident in the CG's stable correlation patterns.

Before concluding, it is important to contextualize these findings by noting that this study evaluates the “enacted curriculum”—the curriculum as implemented through specific pedagogical practices—rather than the curriculum materials in isolation. The observed shifts in students' SO likely emerged from the dynamic interaction between the designed learning activities, the teachers' facilitation strategies—guided by the ENACT model and SSI-TL principles—and the quality of classroom discourse. While these outcomes are primarily attributed to the AI-SSI curriculum framework, we acknowledge that teacher implementation and student interactions were integral mediators in shaping the overall impact.

5.4 Implications for Theory and Practice

5.4.1 Theoretical Implications

This study contributes to SSI theory by demonstrating that cognitive complexification and the cultivation of intellectual humility are valid and meaningful outcomes of SSI instruction, particularly in emerging, high-complexity domains like AI ethics. These outcomes may initially appear as declines in traditional self-report measures, but should be interpreted as signs of epistemic growth rather than pedagogical shortcomings. This insight broadens our understanding of developmental trajectories in SSI education, moving beyond simplistic linear progression models to acknowledge the nuanced, non-linear nature of students' epistemic development.

Furthermore, the observed reconfiguration of affective-cognitive linkages provides empirical support for theoretical models positing that sophisticated socioscientific reasoning involves both the decoupling of emotion from evidence evaluation and the integration of emotion with moral concern and responsibility—a dual process that has been hypothesized but less commonly demonstrated in empirical studies (Khishfe, 2012; Sadler, 2004a).

5.4.2 Practical Implications

For educational practice, these findings highlight the need for assessment approaches that capture cognitive complexity and intellectual humility. Traditional Likert-scale measures that implicitly value higher scores may misrepresent meaningful developmental progress. Instead, assessment should incorporate qualitative methods, performance-based tasks, and measures specifically designed to evaluate nuanced understanding and calibrated self-assessment (Porter et al., 2022).

Pedagogically, educators should be prepared to support students through the potentially unsettling process of moving from certainty to nuanced uncertainty. This can be achieved by implementing instructional strategies that explicitly frame intellectual humility as a strength in complex domains, thereby normalizing it as a valuable epistemic disposition. Concurrently, scaffolding should be provided to help students navigate uncertainty constructively, preventing disengagement. Furthermore, learning experiences should be designed to foster affective-cognitive integration, creating opportunities for emotional engagement with ethical dilemmas while simultaneously developing critical analytical skills. Finally, educators must consciously bridge the responsibility-action gap by linking students' moral concern to tangible, age-appropriate forms of agency, translating ethical reflection into a sense of empowered possibility.

5.5 Limitations and Future Research Directions

Methodological Limitations

Several limitations warrant consideration. First, the use of adapted but primarily quantitative measures may not have fully captured the nuances of students' reasoning. Future research should employ more

comprehensive assessment approaches, including performance-based assessments and longitudinal interviews. Second, the quasi-experimental design, while practical in authentic educational settings, limits strong causal inference. Third, the single cultural context necessitates caution regarding generalizability.

Implementation and Contextual Factors

Beyond methodological considerations, the interpretation of our findings must also account for implementation factors. The observed outcomes reflect the impact of the curriculum as enacted within the specific conditions of this study. First, the effects stem from the intertwining of curricular content and pedagogical enactment, shaped by the participating teachers' facilitation approaches and classroom dynamics. Second, and crucially, the intervention's design was adapted to real-world constraints. The ENACT model, which culminates in students taking action on SSI, could not be fully realized within the limited 10-week in-class timeframe and was further constrained by the substantial academic pressures faced by Chinese high school students. The 'take action' phase was necessarily limited to simulated proposals and discussions rather than extended project-based action in the community. This partial implementation may have influenced the results, particularly the observed decline in dimensions like SA, by limiting opportunities for students to translate ethical reasoning into concrete agency. Consequently, the study evaluates a contextually adapted version of the AI-realted SSI curriculum. Future research could employ design-based research to iteratively test implementation strategies under different constraints, or incorporate extended project phases to examine how completing the full action cycle affects SO development.

Future Research

Building upon the present findings and considering its methodological and contextual boundaries, future research should pursue several refined avenues. First, longitudinal research is necessary to determine whether the initial decline in self-assessed SO represents a transitional phase within a longer developmental trajectory toward more integrated and responsible engagement. Second, research could investigate **implementation-specific factors** more directly; for instance, studies might compare the effects of the AI-SSI curriculum when the ENACT model is fully realized—including substantial 'take action' phases—versus its more constrained implementation as reported here. This would help disentangle the contributions of curricular design, pedagogical enactment, and contextual constraints. Third, methodological advances are warranted, including the development and validation of more refined measures that can accurately capture emerging constructs such as intellectual humility and cognitive complexification—distinguishing them from indicators of disengagement or attitudinal regression. Finally, cross-cultural comparative research remains crucial for understanding how educational systems, cultural values, and varying levels of academic pressure shape the development of socioscientific orientations toward AI and other emerging technologies.

6 Conclusion

This study demonstrates that a carefully crafted AI-SSI curriculum can produce meaningful shifts in high school students' socioscientific orientations, though these shifts may not always be reflected as straightforward positive improvements on traditional self-report measures. The observed decline in SO scores, when interpreted through integrated theoretical frameworks of epistemic development and affective-cognitive integration, emerges as evidence of meaningful cognitive complexification and the development of intellectual humility. Coupled with the restructuring of emotion-cognition linkages toward more mature and integrated engagement, these findings suggest that the curriculum fostered the development of more nuanced, critical, and ethically grounded approaches to AI dilemmas—dispositions essential for responsible citizenship in an increasingly AI-saturated world. This research underscores the importance of theoretical sophistication and methodological pluralism in evaluating the complex outcomes of SSI education, particularly when addressing emergent, high-stakes technologies.

Abbreviations

I. Theoretical Constructs & Frameworks

AI: Artificial Intelligence

SSI: Socioscientific Issues

SO: Socioscientific Orientation

EW: Ecological Worldview

SMC: Social and Moral Compassion

SA: Socioscientific Accountability

SEV: Scientific Evidence Views

SEL: Social-Emotional Learning

IH: Intellectual Humility

II. Research Design & Variables

CG: Control Group

EG: Experimental Group

PSTs: Pre-service Teachers

A_level: Attention to social issues

A_P: Frequency of positive emotional responses to social news

A_N: Frequency of negative emotional responses to social news

Δ : Change score (Post-test minus Pre-test)

III. Curriculum & Instructional Models

ENACT: A model for cultivating social responsibility in STEM contexts

PBL: Problem-Based Learning

GenAI: Generative Artificial Intelligence

AIEd: Artificial Intelligence in Education

AISE: Artificial Intelligence in Science Education

IV. Statistical & Methodological Terms

ANOVA: Analysis of Variance

ANCOVA: Analysis of Covariance

KMO: Kaiser-Meyer-Olkin measure

α : Cronbach's alpha

Declarations

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Author Contribution

Yujing Chen conceptualized the study, designed the curriculum, collected and analyzed the data, and drafted the manuscript. Jessica supervised the research, provided critical theoretical and methodological guidance, and revised the manuscript substantively. All authors read and approved the final manuscript.

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Data Availability

The data supporting the findings of this study were collected through surveys and interviews conducted as part of a doctoral research project at The University of Hong Kong (HKU). In accordance with the

ethical guidelines and confidentiality provisions stipulated in the approved research protocol, the data are not publicly accessible. However, they may be made available upon reasonable request and subject to approval by the Human Research Ethics Committee (HREC) of HKU and the corresponding author, provided such requests comply with applicable data protection and privacy regulations.

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Table

Table 6 is available in the Supplementary Files section.

Figures

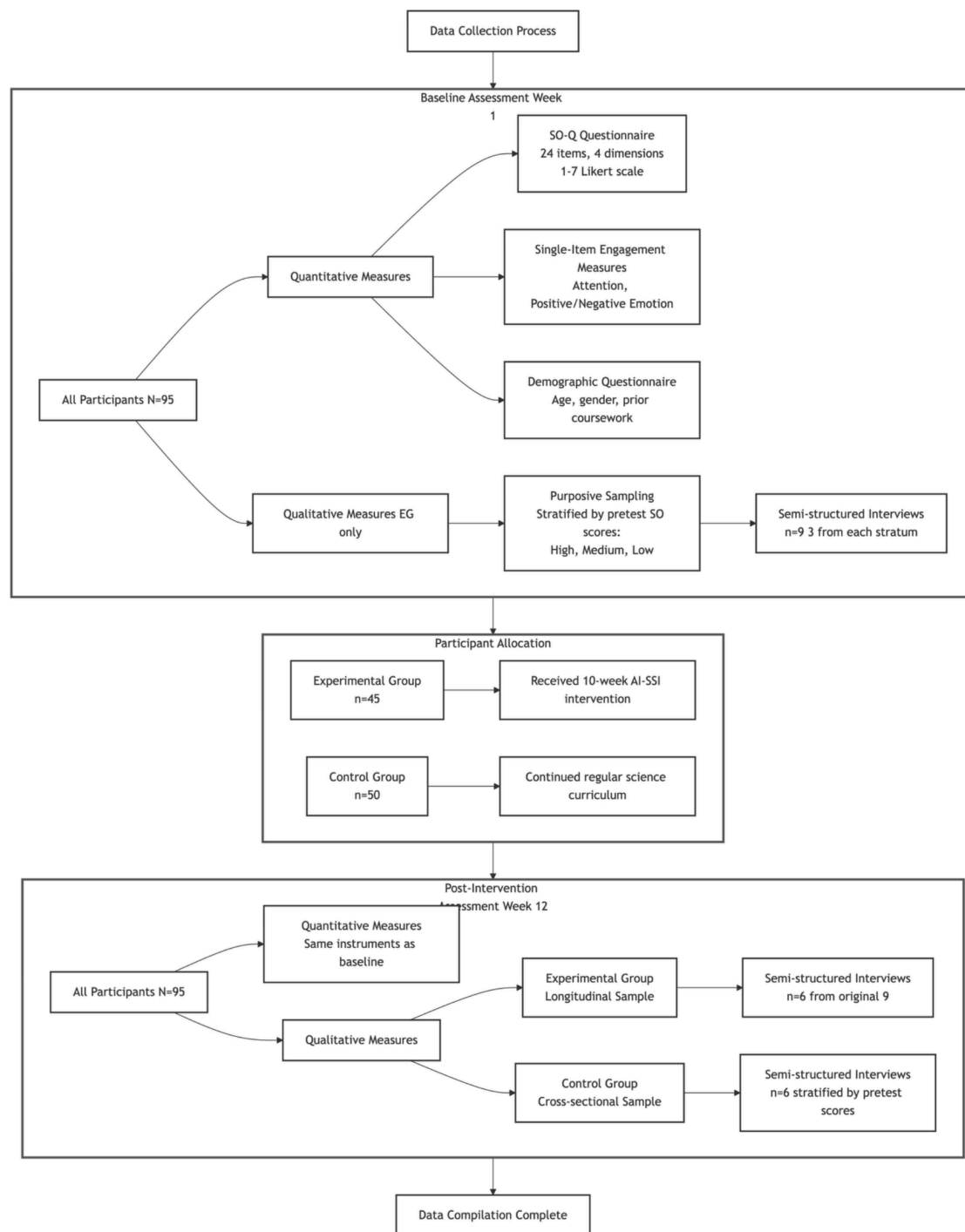


Figure 1

Flow chart of Data collection process

Supplementary Files

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- [Table6.PrePostComparisonsWithintheControlGroupCGandExperimentalGroupEG.docx](#)