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Advancing higher education on sustainable land use: designing socioscientific inquiry-based learning units on oil palm cultivation

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Land-use change driven by the global oil palm boom has widespread environmental and socioeconomic consequences. Recent scientific research offers strategies to mitigate negative effects of oil palm cultivation. This Curriculum, Instruction, and Pedagogy article presents a design-based research (DBR) approach to increase students' knowledge and interest in interdisciplinary scientific research for sustainable oil palm cultivation. The land-use research addressed in this DBR is based on the international Collaborative Research Centre 990 "Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems" (EFForTS). It focused on sustainable land-use change in Indonesia. Through a collaborative design process, researchers and educators from Indonesian and German universities designed two educational units on oil palm cultivation as a socioscientific issue for Indonesian higher education, specifically for science teacher education and forestry study programs. We systematically analyzed curricular needs, objects of recent scientific research, teaching and learning frameworks, and evaluation approaches to determine design principles. A pre-post-follow-up evaluation (N = 943) showed that the units, when integrated into curricular courses, increased and sustained students' self-reported knowledge and interest, with improvements from pilot to implementation cycles. The formative and summative evaluations indicated positive ratings for instructional design quality, while also identifying areas for future improvement. Our DBR focused on Indonesian higher education, but the evaluation and reflection findings suggest that our approach can be adapted to a wide range of educational contexts and environmental socioscientific issues, also beyond Indonesia. Our DBR serves as a transferable approach for making scientific research topics, methods, and findings accessible and interesting to students, thereby contributing to the preparation of future change agents for sustainable land use at both local and global scales.

KEYWORDS

design-based research, sustainable development, land use, socioscientific issue, higher education, teacher education, inquiry-based learning

1 Introduction

Land-use change in tropical regions involves complex sustainability challenges, such as the conversion of rainforests to oil palm plantations on Sumatra, Indonesia (EFForTS, 2024). While expanding oil palm cultivation brings socioeconomic benefits, it also exacerbates social inequalities and causes severe environmental damage, e.g., due to deforestation (Zemp et al., 2023). Addressing sustainability issues requires holistic strategies that engage multiple stakeholders and draw on interdisciplinary knowledge for achieving the Sustainable Development Goals (SDGs) (United Nations, 2015; Mohd Hanafiah et al., 2022).

Numerous interdisciplinary projects generate science-based knowledge on sustainable land-use change, particularly on sustainable oil palm cultivation. One example is the Collaborative Research Centre "Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems" (EFForTS), which involved over 160 international scientists studying land-use change on Sumatra from 2012 to 2023. Researchers from fields such as agronomy, climatology, ecology, and human geography examined the socioeconomic and environmental impacts of oil palm cultivation, revealing complex trade-offs (EFForTS, 2024). Their findings highlighted strategies for sustainable cultivation, showing that reducing chemical inputs and adopting agroforestry systems can benefit the environment without compromising profitability (Iddris et al., 2023; Zemp et al., 2023).

Science education can facilitate the implementation of these science-based strategies into practice by integrating recent research insights into study programs of higher education. University courses play a crucial role in preparing future professionals—including science educators, teachers, as well as forestry educators and consultants—to disseminate and apply knowledge for sustainable development (Winter et al., 2022; Yli-Panula et al., 2023). Integrating interdisciplinary insights from natural and socioeconomic sciences into university courses can enhance students' competencies to address land-use issues more holistically. In particular, this can foster students' competencies to deal with complexity, engage in perspective-taking, utilize socioscientific reasoning as well as communicate and collaborate effectively with diverse stakeholders (Amos and Levinson, 2019). It is essential that students are both cognitively and motivational-affectively equipped to act as future change agents (Winter et al., 2022).

One key factor in fostering motivation is interest (Renninger and Hidi, 2016). High individual interest promotes sustained engagement with topics and activities, making interest development a core goal of science education (Knekta et al., 2020). Developing interesting, high-quality educational units requires a systematic, theory-driven, and evidence-based design process with a suitable evaluation approach (McKenney and Reeves, 2019). Evaluating instructional quality such as the comprehensibility of instructions, the quality of content and media representation, as well as the suitability of learning objectives, can provide such evidence (Branch, 2009).

In collaboration with EFForTS researchers and educators with expertise in both (inter)disciplinary content and pedagogical content knowledge from four Indonesian and one German university, we developed a design approach for integrating science-based knowledge on sustainable land use into Indonesian science teacher education and forestry programs. The goal was to create competence-oriented educational units that enhance students' knowledge and interest in cutting-edge scientific research for sustainable oil palm cultivation aligned with the SDGs, preparing students for becoming competent and motivated change agents.

This article addresses the following guiding question: How can a researcher–educator team effectively design curricular-valid educational units that promote students' knowledge and interest in scientific research for sustainable oil palm cultivation?

2 Design-based research of education on scientific research for sustainable land use

To develop and assess high-quality educational units for curricular implementation, we adopted a design-based research (DBR) approach (McKenney and Reeves, 2019). DBR aims to advance educational practice through a theory-driven and iterative design process. It also investigates the design process, the impact of design principles, and the designed units to advance educational research. We followed the four DBR phases outlined by McKenney and Reeves (2019); Figure 1:

1. Analysis and Exploration (section 3): understanding and framing the prerequisites for addressing the guiding question through analyzing relevant focal points such as literature reviews, expert consultations, and networking.
2. Design and Construction (section 4): developing educational units through systematic, theory-based design and empirical testing.
3. Evaluation and Reflection (section 5): assessing the units using a suitable evaluation approach and reflecting on the process and outcomes.
4. Spread and Implementation (section 6): implementing, transferring, and disseminating the units and publishing evaluation findings.

2.1 Scope and objectives

In preparation for our DBR, workshops with institutional representatives helped to clarify expectations and define the project scope within the EFForTS research. The focus was on developing comprehensive land-use education on oil palm cultivation as a relevant and authentic issue. This comprehensive emphasis highlights the multidimensional and interdisciplinary nature of scientific research on sustainable oil palm cultivation, in alignment with the SDGs (e.g., SDGs 1, 2, 3, 6, 7, 8, 10, 12, 13, and 15; Mohd Hanafiah et al., 2022).

The primary target group was identified as university students, specifically those in science teacher education and forestry programs, given their potential to integrate science-based knowledge on sustainable oil palm cultivation into their future professional practices (e.g., Nida et al., 2021). The content was structured in self-contained modules, allowing flexible adaptation and integration into various

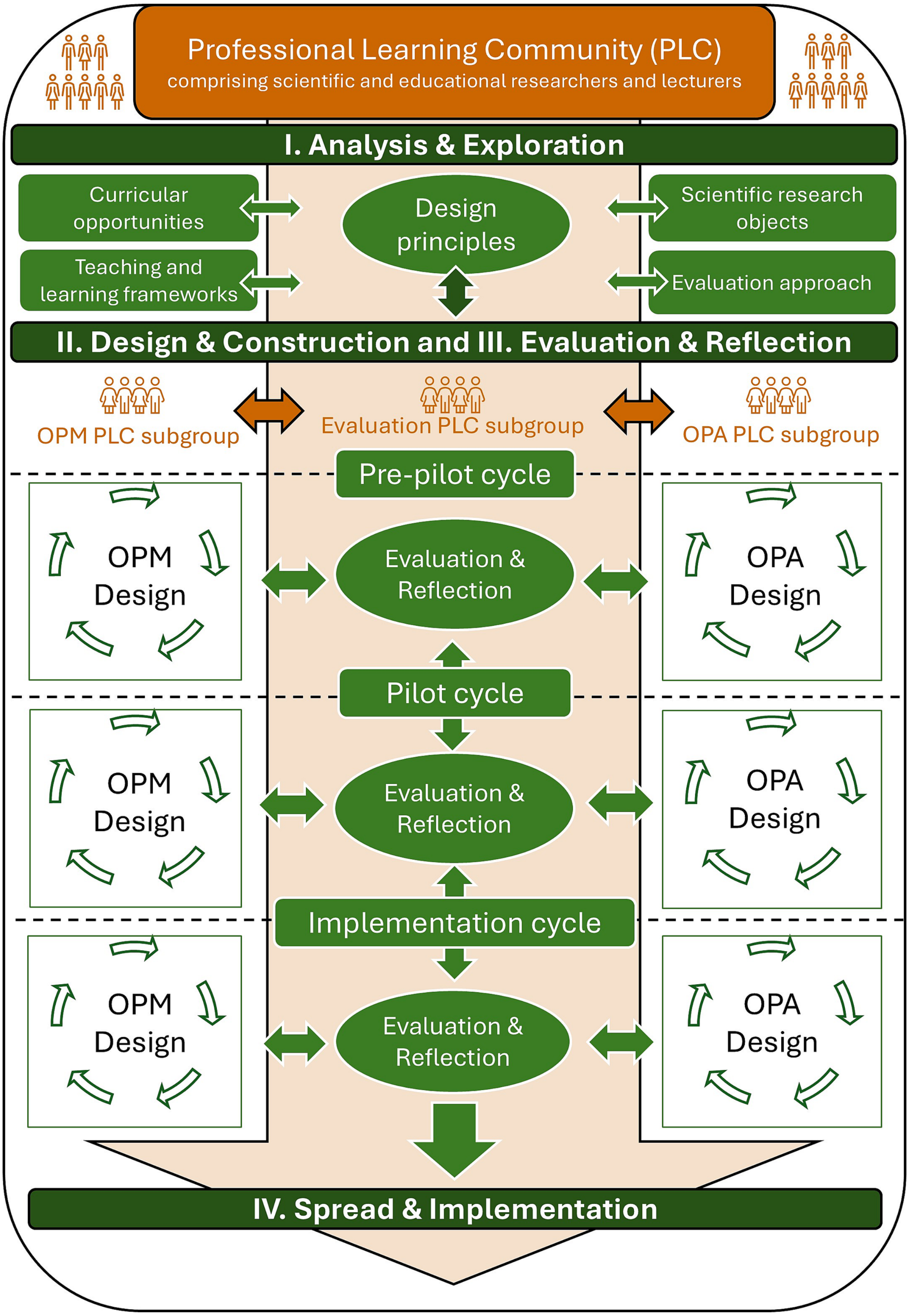

FIGURE 1
Design-based research approach comprising four phases (I. Analysis and Exploration, II. Design and Construction, III. Evaluation and Reflection, IV. Spread and Implementation), and three design cycles (pre-pilot, pilot, and implementation) for the Oil Palm Management (OPM) unit for science teacher education programs and the Oil Palm Agroforestry (OPA) unit for forestry programs.

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land use-related courses and subject-specific curricula. To ensure both national and international accessibility, the educational units were designed to be bilingual, available in English and Indonesian. Additionally, the units were accessible both online and offline to support diverse educational settings and ensure usability under challenging conditions, such as internet disruptions, or home quarantine during pandemics.

2.2 Professional learning community as teamwork format

Establishing a structured teamwork format is crucial for efficient DBR (McKenney and Reeves, 2019). To foster mutual learning, trust, and collaboration, we organized the the international, intercultural, and interdisciplinary team as a professional learning community (PLC). The PLC included 32 members from 2020 to 2023: deans, professors, researchers, lecturers, master's students, and assistants from Sumatra, Java, Bali in Indonesia and from Germany, with expertise in land-use research as well as in science teacher and forestry education and research.

The joint design process aimed to ensure that educational units were shaped by both land-use and educational research expertise as well as practical teaching experience at national and international levels. To further structure the collaboration, PLC subgroups addressed specific needs: one focused on science teacher education, one on forestry education, and a third on refining the evaluation approach. In the first two subgroups focusing on the instructional design of the units, land-use researchers recommended the choice of content and scientific resources. Moreover, they ensured that content was accurately presented in the educational units. Lecturers contributed insights into land-use concepts (e.g., nutrient cycling, agroforestry systems), competencies and skills (e.g., research competencies, media production skills), instructional approaches and classroom activities (e.g., case study analysis, project-based learning), and task formats (e.g., quizzes, open-ended tasks) with which students were either familiar or needed additional support. Additionally, deans and lecturers ensured that the units aligned with the respective curricula, also considering synergies with other courses and curricular activities, such as outreach activities (e.g., stakeholder engagement in villages and student creativity competitions). Educational researchers focused on evidence-based and theory-driven instructional design, ensuring alignment with theoretical pedagogical content knowledge. In the evaluation subgroup, lecturers and educational researchers developed and adapted literature-based evaluation instruments, ensuring that questionnaires were validated, reliable, contextually appropriate, and familiar to students.

Throughout the subgroup discussions, different cultural backgrounds and perspectives were systematically incorporated. Indonesian team members provided insights into students' typical perceptions as well as perspectives of various stakeholders from different regions on oil palm cultivation as a controversial issue. The Indonesian members also ensured that the texts and task instructions were culturally and linguistically appropriate. German members contributed an external perspective, fostering cross-cultural insights to enhance the adaptability of the units, supporting their potential for worldwide dissemination. Regular PLC meetings of all members facilitated collaboration and decision-making. Subgroups provided updates, obtained feedback, and discussed further procedures, ensuring a cohesive and efficient DBR process.

3 Analysis and Exploration

In the first phase of our DBR, the goal was to lay the foundation for the design process. This phase was divided into five focal points that informed each other and led to the derivation of key design principles (Figure 1). Below, we briefly describe the focal points and how they informed the process.

1. Curricular opportunities: We analyzed Indonesian university curricula, including course syllabi, and consulted with institutional representatives to identify opportunities for aligning our educational units with study programs.
2. Teaching and learning frameworks: A review of Indonesian and international science education literature helped us identify suitable frameworks for our units, which were validated in PLC meetings with educational stakeholders.
3. Educational potential of scientific research: We reviewed EFForTS research and related literature to identify topics, concepts, methods, and findings (=EFForTS objects) with the highest educational potential. Discussions with EFForTS researchers during PLC meetings were crucial to determine which objects should be integrated into the units.
4. Evaluation approach: We reviewed the literature for instruments that could assess both the instructional design quality and the impact on students' knowledge and interest, adapting them to the Indonesian context.
5. Deriving design principles: By reconciling insights from the four focal points above, we developed design principles to systematically guide the design process and evaluation, ensuring coherence, transferability, and generalizability (McKenney and Reeves, 2019).

3.1 Requirements, needs, and opportunities in Indonesian curricula

Recent societal challenges, including the COVID-19 pandemic, have underscored the need for Indonesian curricula to address interdisciplinary issues and promote higher-order thinking skills aligned with the SDGs (Faisal and Martin, 2022; Nizam, 2023). The analysis of curricular documents from science teacher and forestry programs revealed strong potential for integrating EFForTS research into higher education. Project- and problem-based learning approaches have become more prevalent in these programs (Çalik and Wiyarsi, 2024). Many courses within these programs had a parallel structure across universities, facilitating the design of educational units for multiple universities (Nizam, 2023). Moreover, the 'Independent Campus' ('Kampus Merdeka') program, established in 2020 by the Indonesian Ministry of Education, Culture, Research, and Technology, allows students to allocate 'free' credits for course choices and actively supports innovative, curricular courses for interdisciplinary and cross-institutional teaching and learning

(Nizam, 2023). This flexibility of 'Independent Campus' gave us the freedom to choose suitable EFForTS objects and appropriate teaching and learning frameworks.

3.2 Socioscientific issue teaching and learning as promising framework

Socioscientific issue teaching and learning (SSI-TL) offers a promising framework for addressing real-world issues like oil palm cultivation. By engaging students with authentic and controversial scientific-societal issues, SSI-TL promotes key competencies, such as dealing with complexity, scientific inquiry, perspective-taking, reasoning, and decision-making (Sadler et al., 2017; Çalik and Wiyarsi, 2024). In Indonesia, the framework is increasingly recognized as an effective approach for fostering responsible citizenship and scientific literacy (Nida et al., 2021; Faisal and Martin, 2022; Çalik and Wiyarsi, 2024).

A case study by Nida et al. (2021) demonstrated that integrating SSI-TL about palm oil-based biodiesel into chemistry teacher education can promote teacher students' positive perceptions of SSI-TL and their motivation to engage with related chemical concepts and societal issues. However, due to the complexity of sustainability-related SSI-TL topics such as oil palm cultivation, teacher students found biodiesel SSI-TL more suitable for higher than for school education. This aligns with findings by Faisal and Martin (2022). They reported that while both teachers and teacher students expressed positive attitudes toward SSI-TL, they also raised concerns about their pedagogical content knowledge (PCK) and competencies. This particularly accounts for teacher students' ability to facilitate socioscientific discussions (Faisal and Martin, 2022). Currently, Indonesian school curricula for natural science subjects and national exams predominantly focus on science content, with limited integration of social and societal aspects (Faisal and Martin, 2022). Nida et al. (2021) emphasized the need for innovative SSI-TL concepts that can be implemented and evaluated in both higher and school education, with the goal of curricular integration of SSI-TL. Faisal and Martin (2022) further highlight the importance of increased funding support for the promising development and advancement of SSI-TL in Indonesian science teacher education. Given that forestry students may also act as educators in various contexts, these considerations extend to their education as well.

To facilitate the practical implementation and prepare (future) professionals for engagement with socioscientific issues (SSI), the SSI-TL model (Sadler et al., 2017) and Amos and Levinson (2019) socioscientific inquiry-based learning approach provide structured sequences for integrating scientific research into science learning:

- Sadler et al. (2017) SSI-TL model, derived from several DBR projects, suggests a three-part sequence involving the scientific and socioscientific encounter and engagement with SSI to synthesize key findings of the learning process into a culminating activity, e.g., a policy letter. Learning objectives include issue awareness, epistemology of science, media literacy, and identity development to become reflective contributors in dealing with complex SSI.
- Amos and Levinson (2019) approach suggests a three-part sequence of 'Ask' (research-based questions), 'Find out' (conducting research), and 'Act' (communicating solutions). This approach emphasizes scientific research, active citizenship, and solution approaches towards the SDGs.

In PLC meetings, we selected SSI-TL and the combination of both SSI-TL frameworks for their synergistic suitability in integrating scientific research on sustainable oil palm cultivation with a societal focus. For effective SSI-TL, Amos and Levinson suggest (co-)designing SSI-TL units in teams comprising different expertise. SSI-TL is compatible with other educational approaches, such as education for sustainable development (Nida et al., 2021). Moreover, our PLC included experts in SSI-TL research and practice, making it an ideal fit for our objectives.

3.3 Suitable scientific research objects as educational content

In selecting suitable EFForTS research objects for the educational units, we aimed to capture EFForTS interdisciplinary approach to environmental processes, ecosystem services, and the human dimensions of land-use change. Two long-term experiments, the Oil Palm Management Experiment and the Biodiversity Enrichment Experiment, served as platforms integrating numerous research disciplines of EFForTS (EFForTS, 2024). The Oil Palm Management Experiment, started in 2016, has evaluated fertilizing and weeding strategies concerning ecological and socioeconomic functions in oil palm plantations. The Biodiversity Enrichment Experiment, established in 2013, has investigated the effectiveness of multipurpose tree islands in oil palm plantations. Both experiments were chosen as the core of the educational units due to their relevance to sustainable oil palm cultivation and their contributions to multiple SDGs (Mohd Hanafiah et al., 2022; EFForTS, 2024).

3.4 Evaluation approach

Our evaluation approach aimed to assess both the instructional design quality and the cognitive and motivational-affective effects of the SSI-TL units on students over time, while avoiding 'evaluation overload' (Songer and Ibarrola Recalde, 2021). Combining formative and summative evaluation provided valuable insights for DBR (McKenney and Reeves, 2019). Thus, we selected and developed instruments, which focus on providing ongoing feedback to improve the unit design and assess the overall impact of the units.

Criteria for evaluating the instructional design quality can vary depending on the objectives, target groups, and format of educational units (Branch, 2009). Given the limited availability of validated instruments for assessing instructional design in science education—particularly for SSI-TL on land-use issues in higher education—we developed a customized instrument. The instrument integrates both theory-driven cross-context as well as context-specific instructional design criteria (see 5.2.1 and Supplementary Table S1). Still, the context-specific criteria remain interchangeable, ensuring flexibility across different SSI and educational settings, e.g., item 6 (Supplementary Table S1): "The unit encourages me to address the topic of oil palm cultivation and land-use change issues in my own (prospective) profession."

For evaluating cognitive and motivational-affective outcomes, we adapted existing instruments with permission (see 5.2). We adapted self-reported knowledge scales from Richter-Beuschel and Bögeholz (2020). We surveyed students on their perceived understanding of oil palm-related topics (e.g., ecosystem functions of oil palm) and sustainable development concerning oil palm cultivation (e.g., knowledge on oil palm cultivation-related sustainability issues and SDGs). Moreover, we surveyed students on their knowledge on processes of scientific research, e.g., generating research questions and interpreting results. This evaluation provides initial insights into the potential effectiveness of the units in equipping future change agents with science-based knowledge for sustainable oil palm cultivation and sustainable development.

Evaluating students' interest in the topics of the units is a crucial indicator for the effectiveness of the units and the likelihood of sustained learning and motivation (Renninger and Hidi, 2016). We adapted the Knekta et al. (2020) instrument on interest in biology to focus on sustainable development and scientific research. Based on the Renninger and Hidi (2016) conceptualization of individual interest, this instrument assesses changes in interest through three dimensions: positive feelings, perceived value, and reengagement. In the design process of the units, we targeted these dimensions and integrated corresponding interest-promoting elements (e.g., Renninger and Hidi, 2016).

3.5 Design principles

Based on the insights gained from the 'Analysis and Exploration' phase, five key design principles were developed to guide the design process.

1. Ensure accessibility and adaptability: The educational units were designed to be modular, allowing for easy adaptation across different curricula. They were intended to be accessible to students from diverse educational backgrounds and with varying levels of prior knowledge. Additionally, the design prioritized ease of implementation and dissemination across multiple universities, both nationally and internationally.
2. Address scientific research through authentic, relevant, and controversial SSI: By integrating scientific research into an inquiry-based SSI-TL sequence, the units aimed to systematically engage students with complex, real-world issues. This approach was intended to foster project-based learning experiences and competencies that aligned with the SDGs.
3. Make scientific research meaningful and tangible: Research objects were chosen to present scientific research in a meaningful and tangible way, reflecting the multidimensional nature of land-use SSI and ensuring they were comprehensible and engaging for students.
4. Unlock the potential of the PLC: The PLC was employed to integrate the interdisciplinary expertise of educators and researchers. The design process emphasized open dialogue and mutual learning in a collaborative environment, facilitating the sharing of diverse perspectives and knowledge.
5. Create comprehensive but minimally invasive evaluation approach: A comprehensive evaluation approach was developed. It combines both formative and summative assessments. This approach was designed to assess the instructional design quality as well as cognitive and motivational-affective outcomes while minimizing the evaluation burden on students. It also provided ongoing feedback for refining the educational units and for evaluating their overall impact.

4 Design and Construction

The 'Design and Construction' phase followed a systematic, iterative process through three design cycles (McKenney and Reeves, 2019; Figure 1), each informed by the 'Analysis and Exploration' and 'Evaluation and Reflection' phases.

In the pre-pilot cycle, we developed two initial prototypes: the Oil Palm Management (OPM) unit, designed for science teacher education programs, and the Oil Palm Agroforestry (OPA) unit, aimed at forestry programs. The OPM unit, titled "Research-based oil palm management strategies: how can weeding and fertilizing contribute to sustainable oil palm cultivation?" was based on the Oil Palm Management Experiment. The OPA unit, titled "Research-based oil palm agroforestry: how can tree enrichment contribute to sustainable oil palm cultivation?" was built on the Biodiversity Enrichment Experiment. These prototypes were tested, refined in the pilot cycle, and further developed in the implementation cycle.

To develop both units, we adapted the SSI-TL frameworks by Sadler et al. (2017) and Amos and Levinson (2019). The units comprise the three self-contained modules for self-learning: 'Ask' authentic questions about oil palm cultivation as SSI, 'Find out' by conducting scientific inquiries across disciplines of land-use research, and 'Act' by communicating findings with respect to several SDGs (Amos and Levinson, 2019). A fourth module, 'Reflect', was added to enhance reflective opportunities within SSI-TL (Sadler et al., 2017).

To account for varying levels of pre-knowledge, key concepts and scientific terms were briefly introduced within the module texts, supplemented with links to literature and explanations in the glossary. Each module included self-learning tasks, followed by virtual meetings for plenary and group discussion, reflection, and troubleshooting. In particular, socioscientific discussions were structured through carefully designed tasks, instructions, and scaffolding. The aim was to ensure that students actively engaged with one another while lecturers hold a facilitator role. After completing a module, students accessed an expectation horizon for the tasks, promoting self-assessment. The self-contained modules in combination with the group activities and discussions in virtual meetings adhered to the inverted classroom principle (Nizam, 2023).

Both units were structured into seven key steps (Figure 2):

1. Pre-session: Students were introduced to the DBR, the units, and the evaluation process. Those who consented to participate in the evaluation completed a pre-test survey.
2. Module I—'Ask': Students explored oil palm cultivation as a complex and controversial SSI based on research findings and media. Thereby, they examined the environmental, socioeconomic, and political dimensions of the SSI. They developed research-oriented questions: In the OPM unit, teacher students focused on fertilizing and weeding, and in the OPA unit, forestry students addressed ecosystem functions of oil palm plantations and agroforestry. In the subsequent virtual meeting, students discussed the controversies surrounding oil palm

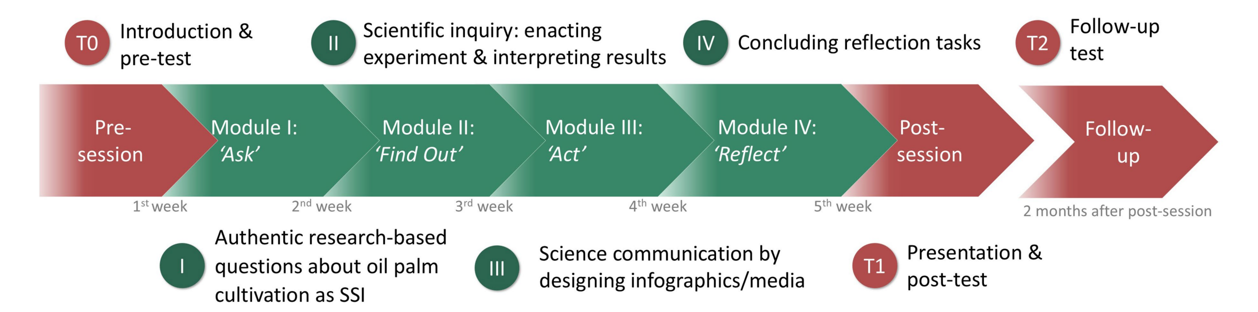

FIGURE 2
Sequence of the five-week socioscientific issue (SSI) teaching and learning units comprising four modules (I–IV) (depicted in green), and a pre-post-follow-up evaluation procedure (depicted in red) of the pilot and implementation cycles.

cultivation at both national and global levels. Their discussions also explored how the social, economic, and environmental dimensions of oil palm cultivation as an SSI are interconnected and influence the SDGs.

3. Module II—'Find out': Students engaged with cutting-edge EFForTS research on land-use change. In the OPM unit, students analyzed environmental effects of fertilizers and herbicides, while in the OPA unit, students reviewed tree enrichment research to design agroforestry concepts. In the subsequent virtual meeting in both units, they applied their knowledge to other crops, such as discussing cabbage management practices in Germany.
4. Module III—'Act': Students synthesized their knowledge to create science communication media (e.g., infographics, videos) on sustainable oil palm cultivation, critically engaging with oil palm cultivation as a controversial SSI.
5. Module IV—'Reflect': Students completed individual writing tasks related to the content reflections of the units or relevance reflection of learning about oil palm cultivation for their personal, professional, and societal lives (see Matthiesen et al., 2025).
6. Post-session: Students presented their science communication media, which was credited as part of their course performance, and obtained feedback from peers and lecturers. After, they completed a post-test survey.
7. Follow-up: Two months later, students were asked to complete a follow-up survey.

In consultation with deans and lecturers, the five-week SSI-TL units were integrated at appropriate points within curricular science content courses with three or four credits (see 5.1).

5 Evaluation and reflection

In this phase, we evaluated and reflected on the instructional design quality and the cognitive and motivational-affective effects of the SSI-TL units on the students.

5.1 Participants

A total of 943 undergraduate students participated in the pilot and implementation cycles, using pre-test, post-test, and follow-up surveys to evaluate the educational units. The participants (65% female) were second- and third-year teacher and forestry students, usually between 19 and 21 years old, from universities in Sumatra, western and eastern Java, and Bali.

- OPM unit: 355 science teacher students (116 in the pilot and 239 in the implementation cycle) participated in courses such as ecology, plant physiology, horticulture, and organic chemistry.
- OPA unit: 588 forestry students (255 in the pilot and 333 in the implementation cycle) participated in agroforestry, community, and social forestry courses.

5.2 Measurements and statistical analyses

With respect to the formative evaluation, students had the opportunity to provide formative open-ended written and oral feedback (Songer and Ibarrola Recalde, 2021). However, this Curriculum, Instruction, and Pedagogy article focuses on the quantitative, self-reported measures of instructional design, knowledge, and interest, which are presented as preliminary results of the summative evaluation (see 5.4). The instructional design quality was surveyed as post-test, while self-reported knowledge and interest were surveyed in a pre-post-follow-up design (Figure 2). For more details on instruments see Supplementary Tables S1–S3.

5.2.1 Instructional design quality

We developed a theory-driven instrument for instructional design quality through factor analysis in a pre-pilot study. The final instrument comprised 28 items divided into six criteria to survey learners' perceptions (Cronbach's alpha: 0.87—0.94):

1. Learning potential of the units on scientific research
2. Relevance of learning objectives
3. Quality of content representation
4. Instructional quality regarding the unit, modules, and tasks
5. Quality of media representation
6. Design quality (e.g., design features, usability)

The Likert scale used was as follows: (0) disagree, (1) slightly agree, (2) mostly agree, (3) agree, (4) strongly agree. An additional item asked for an overall rating of the units: (0) poor, (1) fair, (2) good, (3) very good, (4) excellent.

5.2.2 Knowledge measurement

Self-reported knowledge was measured using 28 items divided into three scales (Cronbach's alpha: 0.93—0.97): oil palm-related topics (6 items), sustainable development (12 items), and scientific research (10 items). The Likert scale used was as follows: (0) insufficient, (1) sufficient, (2) satisfactory, (3) good, (4) very good.

5.2.3 Interest measurement

We used 40 items in total divided into three scales (Cronbach's alpha: 0.89—0.95) for measuring students' interest in scientific research and sustainable development (Knekta et al., 2020): Feeling-related (2 × 6 items), Value-related (2 × 5 items), Reengagement (2 × 9 items). The Likert scale used was as follows: (0) strongly disagree, (1) disagree, (2) slightly agree, (3) mostly agree, (4) agree, (5) strongly agree.

5.2.4 Statistical data analysis

We used linear mixed-effects models to analyze the multilevel data, including repeated measures for knowledge and interest (Meteyard and Davies, 2020). More details on the analysis and its robustness and limitations are provided in the Supplementary material (preliminary remarks and Supplementary Tables S4–S6). We report the results with estimated marginal means and confidence intervals (CI).

5.3 Findings from formative evaluation: key areas for improvement from pilot to implementation cycle

Based on feedback from students and lecturers in the pilot cycle, we identified several key areas for improving the units in the PLC:

- Enhancing goal orientation: strengthen project-based learning by expanding science communication activities and anchoring the SDGs more firmly.
- Simplifying content: emphasize practical knowledge and reduce complex theoretical content, e.g., decreasing the number of English language scientific articles and complex calculations for experimental designs.
- Incorporating more socioeconomic content: include more recent socioeconomic EFForTS objects and showcase existing science communication approaches developed by EFForTS researchers.
- Increasing interactive activities: replace some tasks with discussions and provide better scaffolding, e.g., enhance guidance on how to read scientific research articles efficiently.
- Improving clarity: enhance the language quality of the Indonesian and English versions of the self-learning modules and clarify instructions.

These key areas were addressed in the PLC subgroup work. The resulting improvements were integrated into the units for the implementation cycle.

5.4 Summative evaluation: quantitative results

5.4.1 Instructional design quality

Overall, the students rated the units positively: 0.5% poor, 5.1% fair, 26.8% good, 43.5% very good, and 6.7% excellent, while 17.4% did not respond.

Agreement with the instructional design quality criteria was rated higher in the implementation compared to the pilot cycle (Table S4, main effect: 2.82, 95% CI [2.72, 2.92] vs. 2.71, [2.57, 2.85]). Agreement with the learning objective criterion increased in both units, with no criteria showing a decline from the pilot to the implementation cycle (Figure 3). For the OPA unit specifically, there were improvements with respect to the criteria: learning potential, content representation, instructional quality, and design quality.

5.4.2 Knowledge and interest gains

Despite variations in self-reported pre-knowledge among students of different units and cycles, both units, the OPM and the OPA unit, showed an increase in self-reported knowledge from pre-test to post-test/follow-up in the pilot and implementation cycle (Figure 4 and Supplementary Table S5). Students' interest in scientific research for sustainable oil palm cultivation increased in the implementation cycle for both units, but not in the pilot cycle (Figure 5 and Supplementary Table S6). For both units, the increase in self-reported knowledge (Figure 4) and individual interest (Figure 5) from pre-test to post-test was greater in the implementation cycle compared to the pilot cycle. There was no decline in self-reported knowledge or interest from post-test to follow-up.

5.4.3 Summary of the summative findings

The improvements made between the pilot and implementation cycles positively affected students' knowledge and interest gains as well as the instructional design quality of both the OPM unit and OPA unit. The units of the implementation cycle increased and sustained students' self-reported knowledge on scientific research on sustainable oil palm cultivation and sustained their interest in scientific research and sustainable development.

5.5 Discussion of summative findings

This discussion of the summative findings focuses on the impact of modifications made for the implementation cycle. These modifications included enhancing goal orientation, simplifying content, incorporating more socioeconomic perspectives, increasing interactivity, and improving clarity (see 5.3). The discussion is structured in four paragraphs: (i) students' perceptions of instructional design quality and interest development, (ii) knowledge gains, (iii) retrospective reflections of lecturers, and (iv) potential external factors influencing the results, along with the need for further research.

Students' higher ratings for instructional design quality in the implementation cycle—particularly in learning potential, learning objectives, content representation, and instruction—suggest the effectiveness of modifications aimed at improving goal orientation, clarity, and interactivity. Strengthening project-based learning through expanded science communication activities and a stronger connection to socioeconomic content and the SDGs likely enhanced students'

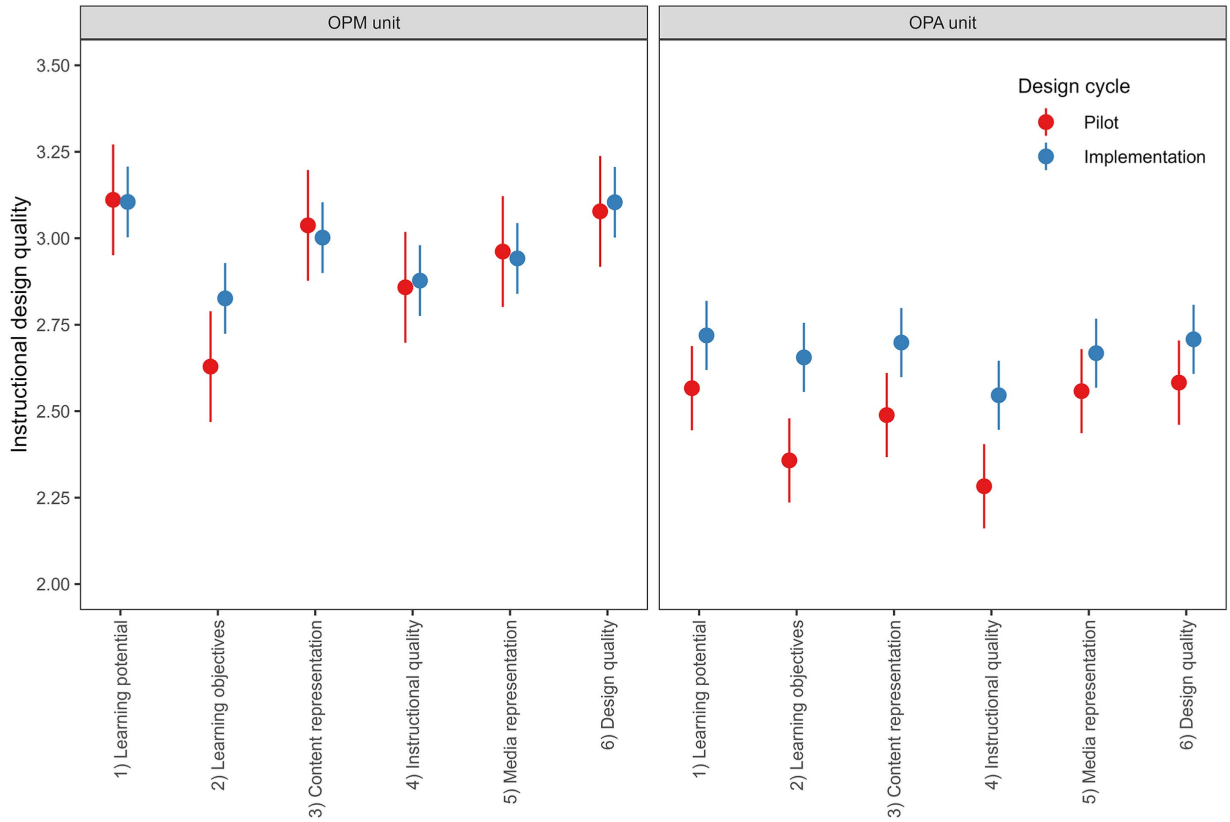

FIGURE 3
Instructional design quality for six criteria compared between the pilot and implementation cycles, and between the Oil Palm Management (OPM) educational unit for science teacher students (n_{OPM_pilot} = 116, $n_{OPM\_implementation}$ = 239) and the Oil Palm Agroforestry (OPA) educational unit for forestry students (n_{OPA_pilot} = 255, $n_{OPA\_implementation}$ = 333). Likert scale: (0) disagree, (1) slightly agree, (2) mostly agree, (3) agree, (4) strongly agree. Error bars indicate 95% CI.

perceived real-world relevance of learning about oil palm cultivation as SSI (Matthiesen et al., 2025). The increase in students' interest in scientific research for sustainable oil palm cultivation in the implementation cycle, compared to the pilot cycle, further suggests that these modifications contributed to more engaging and meaningful learning experiences (Renninger and Hidi, 2016; Knekta et al., 2020). Additionally, simplifying complex theoretical content—such as reducing the number of English-language scientific articles and complex calculations—likely lowered cognitive barriers, improving accessibility and clarity of the units.

The results regarding students' self-reported knowledge indicate that the instructional design and content of the units effectively supported students with diverse prior knowledge across study programs and academic years. The sustained knowledge gains from post-test to follow-up suggest that the educational units had a lasting impact. Notably, knowledge gains were particularly pronounced in the implementation cycle, likely due to modifications informed by formative evaluation.

In retrospective reflections within the PLC, lecturers from both study programs perceived the modifications made from the pilot to the implementation cycle also as successful. Particularly, they highlighted improvements in student engagement, comprehension, and participation in discussions. Across both cycles, the involved lecturers and deans viewed the integration of inquiry-based SSI-TL units positively. They emphasized the units' value for higher education, particularly in providing students with real insights into cutting-edge scientific research on a controversial SSI. Additionally, they recognized the socioscientific discussions and students' design of science communication media as an enriching format for project-based learning. Thereby, the students have the opportunity to gain competencies in synthesizing and communicating complex SSI. Furthermore, the international focus of the units was seen as beneficial for broadening students' perspectives and fostering greater engagement with sustainability challenges and the SDGs.

While modifications based on the formative evaluation likely enhanced students' cognitive and motivational-affective outcomes, it is important to acknowledge other contributing factors. These include student's course, study sequence, personal experiences, origin, and the broader learning environment of study programs and universities. To prevent overgeneralization, further differentiated studies are needed to deepen understanding of these relationships within the educational units. Future research should employ more rigorous experimental designs to establish stronger causal links between instructional design refinements and observed effects. Additional limitations are discussed in section 5.6.2.

5.6 Areas for improvement, constraints, and strengths

Based on the evaluation and reflections in PLC meetings after the implementation of the units, we outline further key areas for improvement, limitations, and strong points of our DBR.

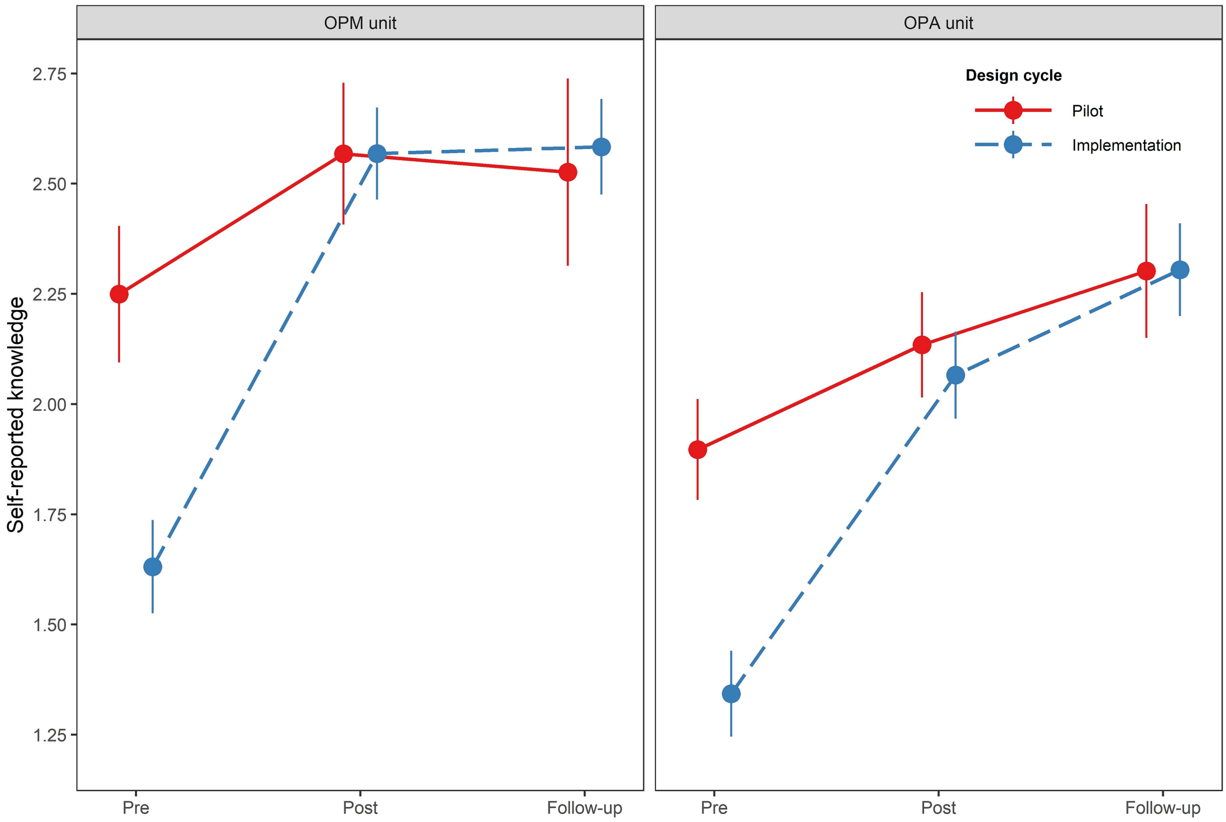

FIGURE 4
Differences in self-reported knowledge between the pilot and implementation cycles, and between the Oil Palm Management (OPM) educational unit for science teacher students (n_{OPM_pilot} = 116, $n_{OPM\_implementation}$ = 239) and the Oil Palm Agroforestry (OPA) educational unit for forestry students (n_{OPA_pilot} = 255, $n_{OPA\_implementation}$ = 333) over time (pre-test, post-test five weeks later, and follow-up two months after the post-test). Likert scale: (0) insufficient, (1) sufficient, (2) satisfactory, (3) good, (4) very good. Error bars indicate 95% confidence intervals.

5.6.1 Areas for further improvement

The first area of improvement concerns enhancing motivation-promoting design elements. While we incorporated interest-promoting elements, there remains a need to increase opportunities for student autonomy still (Godin et al., 2015; Renninger and Hidi, 2016). The complexity of the scientific research involved led to more guidance than potentially necessary, perhaps hindering student autonomy. Future design cycles could explore ways to increase autonomy and active learning while maintaining sufficient guidance, e.g., students' choice of own research foci and activities.

The second area focuses strengthening transdisciplinary approaches and indigenous knowledge. A key feature of this DBR was making interdisciplinary scientific research on sustainable oil palm cultivation accessible through socioscientific inquiry-based learning units aligned with the SDGs. There is potential to further complement the units by incorporating indigenous perspectives and reconciling them with science-based knowledge (Zidny and Eilks, 2022).

The third area focuses extending researcher involvement for better access to scientific research. Some tasks related to specific scientific research were perceived by students as too complex. Greater involvement from researchers in these fields could have improved these tasks and scaffolding. However, time constraints were a challenge in securing researcher input at key stages. Addressing this may require other resource allocation and credit for science communication in joint projects, as well as emphasizing the mutual benefits of collaboration.

5.6.2 Acknowledgements of constraints

There are several limitations of the present DBR. First, the quantitative responses rely only on self-reported measures, which may introduce potential bias through underestimation or overestimation. A more in-depth qualitative analysis of open-ended student responses and learning artefacts is still pending, which can provide additional insights. The qualitative analysis is expected to yield a deeper understanding of the students' learning processes, challenges faced during the units, and the impact on student engagement, ultimately contributing to a more comprehensive evaluation of the units' effectiveness.

While the PLC included members from four different Indonesian universities across three islands, oil palm is a predominant crop only in the region surrounding the Sumatran University. To ensure a more comprehensive and globally representative understanding of oil palm cultivation as SSI, future efforts could incorporate perspectives from other major oil palm-producing regions, such as Kalimantan and Sulawesi in Indonesia, as well as from other countries and continents (e.g., Africa and South America). Additionally, more differentiated surveys on students' backgrounds, perceptions, prior experiences, and prior knowledge regarding the SSI—while further integrating diverse cultural perspectives on land-use issues—would enhance both the current units and future developments of similar DBR projects.

Conducting DBR as part of a large international and interdisciplinary research collaboration on land-use change was a unique opportunity within a specific context. Nevertheless, our DBR

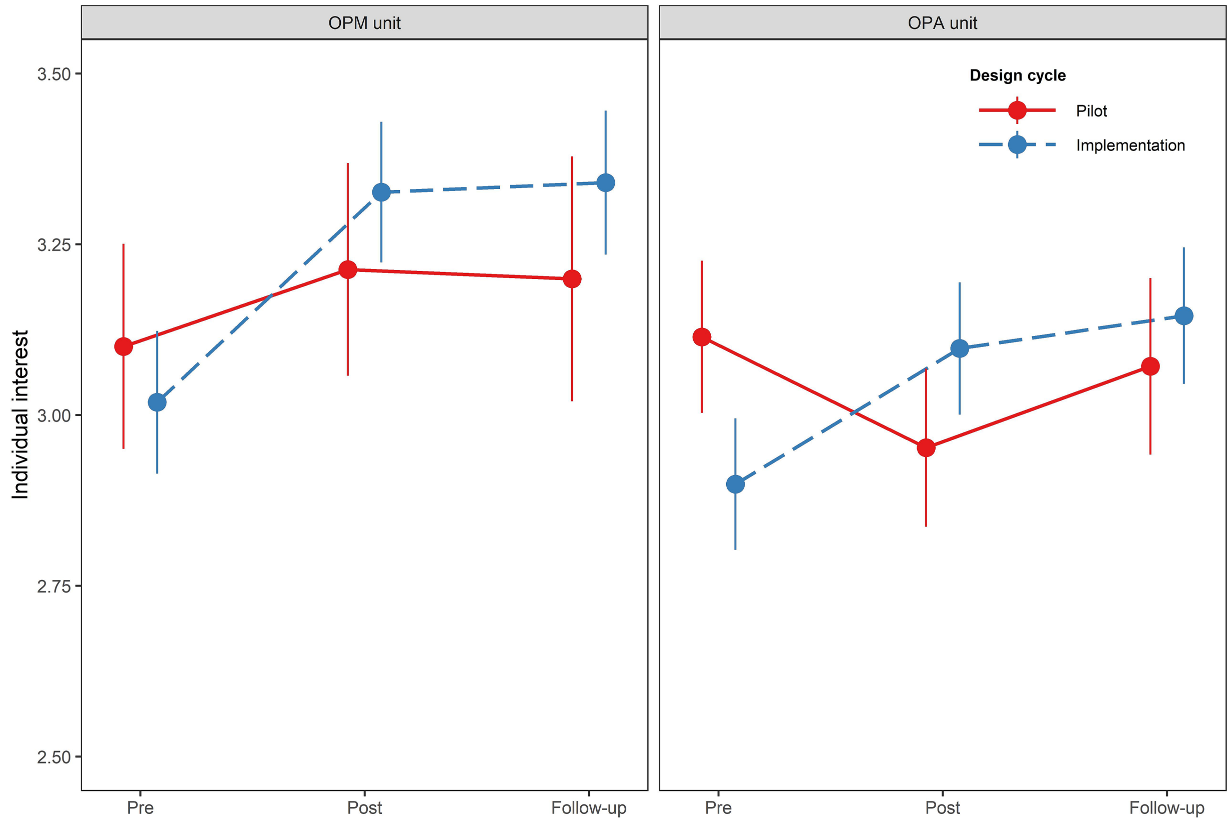

FIGURE 5
Differences in individual interest between the pilot and implementation cycles, and between the Oil Palm Management (OPM) educational unit for science teacher students (n_{OPM_pilot} = 116, $n_{OPM\_implementation}$ = 239) and the Oil Palm Agroforestry (OPA) educational unit for forestry students (n_{OPA_pilot} = 255, $n_{OPA\_implementation}$ = 333) over time (pre-test, post-test five weeks later, and follow-up two months after the post-test). Likert scale: (0) strongly disagree, (1) disagree, (2) slightly agree, (3) mostly agree, (4) agree, (5) strongly agree. Error bars indicate 95% confidence intervals.

follows a generalizable format with an innovative approach (see 5.6.3). Our findings suggest that our approach is transferable to other land-use and educational contexts. This potential is demonstrated by the conceptual approach, unit design, and evaluation framework presented in this article. We used the same design principles and evaluation approach for two educational units (OPM and OPA) designed for different target groups—science teacher students and forestry students—at four universities across three Indonesian islands.

5.6.3 Strengths

In the following three paragraphs, we elaborate on three main strengths of our outlined DBR approach, i.e., (i) innovative and effective approach, (ii) high transferability and adaptability, and (iii) SSI-TL as a suitable framework for integrating interdisciplinary scientific research into higher education towards the SDGs.

The systematic DBR process and a well-composed and goal-oriented PLC enabled the design of innovative educational units that had positive cognitive and motivational-affective effects on students over time. This is crucial for supporting the development of change agents for sustainable oil palm cultivation (Winter et al., 2022).

The DBR procedure, based on McKenney and Reeves (2019), along with the derived design principles (see 3.5) and evaluation approach (see 3.4 and 5), holds high potential for transferability and adaptability to other land-use and real-world issues addressed by interdisciplinary research. Its modular and international nature enables customization across different study programs and institutional settings, making it applicable beyond its original scope.

The use of SSI-TL to combine curricular, scientific, and learning objectives was a key decision (Amos and Levinson, 2019; Sadler et al., 2017). Selecting interdisciplinary EFForTS experiments focused on the SDGs, along with incorporating science communication media design, proved fruitful and underscored the value of socioscientific inquiry-based learning (Amos and Levinson, 2019). The successful integration of SSI-TL units into curricular courses further contributed to students' engagement with socioscientific and sustainability dimensions beyond traditional instructional design, aligning with evolving curriculum trends in Indonesian higher education (Nida et al., 2021; Faisal and Martin, 2022).

6 Spread and Implementation

In total, the OPM and OPA units have already been implemented twelve times in curricular courses and are published as open book (Matthiesen and Bögeholz, 2024). These units have also been adapted for use at participating universities, focusing on crops other than oil palm while still utilizing the foundational concepts of fertilization, weeding, and agroforestry. For instance, a partner university applied this DBR model to address citrus greening disease, using our approach as a template (Priyanka et al., 2023). Beyond the immediate implementation, our approach and findings have been disseminated to national and international networks in science education, science communication, education for sustainable development, and agroforestry. This broad dissemination has enhanced the adaptability and impact of the units, ensuring their relevance across diverse educational contexts.

Further, elements of our DBR, such as the PLC approach, have been adapted for another science communication project on learning dispositions for nonhuman primate research within an interdisciplinary Collaborative Research Centre (CRC 1528) (Bögeholz and Matthiesen, under review).

In conclusion, our DBR project has demonstrated the potential of socioscientific inquiry-based learning to advance higher STEM education on sustainable land use. By making cutting-edge scientific research accessible and engaging for students, we have supported the preparation of future professionals to become science-informed change agents for promoting sustainable practices in land use and contributing to the achievement of the SDGs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving humans were approved by the Indonesian National Research and Innovation Agency (BRIN). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

FM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JD: Conceptualization, Investigation, Methodology, Writing – review & editing. RM: Conceptualization, Investigation, Methodology, Writing – review & editing. FS: Conceptualization, Investigation, Methodology, Writing – review & editing. INS: Conceptualization, Project administration, Writing – review & editing. SB: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Gen AI was used in the creation of this manuscript. We utilized AI tools provided by the University of Göttingen to enhance language and readability.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1502070/full#supplementary-material

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