SJSS SPANISH JOURNAL OF SOIL SCIENCE
SECS SOCIEDAD ESPAÑOLA DE LA CIENCIA DEL SUELO

ORIGINAL RESEARCH
published: 18 September 2025
doi: 10.3389/sjss.2025.15173

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From Soil Pits to Global Goals: Pedagogical Innovations for a Sustainability-Oriented Soil-Science Curriculum Aligned With the Sustainable Development Goals

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Soil science stands at a critical juncture, facing both mounting global environmental crises and transformative possibilities in education. This study advocates a bold re-envisioning of soil science pedagogy, aimed at cultivating the inter- and transdisciplinary competencies essential for achieving the 2030 Sustainable Development Goals (SDGs). Drawing on in-depth case studies from Sultan Qaboos University (Oman) and Moscow State University (Russia), along with global stakeholder insights and integrative frameworks, such as Soil Security, One Health, and the Pedometrics Challenge, we propose a future-facing curriculum focused on sustainability, systems thinking, and real-world engagement. This study showcases pedagogical innovations—including inquiry-based learning, SDG-aligned outcomes, debate-based reasoning, and community-engaged research—that foster core skills in transdisciplinary problem-solving. Supported by empirical findings and curriculum analysis, this study demonstrates that reframing soil-science education around ecosystem services and natural capital can empower students to become solution-oriented professionals. Ultimately, we call for a global curricular reform that positions soil education as a dynamic catalyst for sustainability transformation rather than as a technical subdiscipline.

Keywords: ecosystem services, inquiry-based learning, interdisciplinary competence, soil science education, sustainable development goals

Edited by:
Cristina Lull Noguera, Universitat Politècnica de València, Spain

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Received: *26 June 2025*
Accepted: *09 September 2025*
Published: *18 September 2025*

Citation:
Al-Ismaily S, Umarova A and Bouma J (2025) From Soil Pits to Global Goals: Pedagogical Innovations for a Sustainability-Oriented Soil-Science Curriculum Aligned With the Sustainable Development Goals. Span. J. Soil Sci. 15:15173. doi: 10.3389/sjss.2025.15173

INTRODUCTION

As global challenges intensify, ranging from climate change and biodiversity loss to land degradation and food and water insecurity, the urgency to cultivate a new generation of soil-literate professionals has increased. Soil science—an interdisciplinary field by nature—is fundamental to understanding and mitigating multifaceted environmental and societal threats. However, the prevailing paradigms of higher education remain inadequate to prepare students for the sustainability-driven futures that they are poised to inherit. Higher education institutions (HEIs) are uniquely positioned to produce graduates who can integrate scientific knowledge with practical, policy-relevant, and technological solutions (Kwok, 2018).

The United Nations' (UN) Sustainable Development Goals (SDGs) provide a timely and globally endorsed framework for soil-science education. Several SDGs, including SDGs 2 (Zero Hunger), 6 (Clean Water and Sanitation), 13 (Climate Action), and 15 (Life on Land), are directly dependent on the stewardship of soil resources.

The imperative to realign higher education with the SDGs necessitates a fundamental transformation in academic policy, curricula, and teaching methodologies. Accordingly, the UN and the United Nations Educational, Scientific and Cultural Organization (UNESCO) have positioned education at the heart of global sustainability efforts, emphasizing its pivotal role in fostering a more equitable and ecologically responsible world (Annan-Diab and Molinari, 2017; United Nations, 2015).

HEIs serve as catalysts in the transition toward sustainable societies by shaping individuals' capacity for critical reflection, ethical reasoning, and problem-solving (Sipos et al., 2008; Wiek et al., 2011). Specifically, SDG 4.7 calls for all learners to acquire the knowledge and skills needed to promote sustainable development by 2030 (United Nations, 2015), while UNESCO's (2020) Roadmap for Education for Sustainable Development *2030* provides strategic direction for integrating Education for Sustainable Development across higher education systems. Recent studies have confirmed this institutional responsibility. Avelar et al. (2023) highlighted that the strategic integration of SDGs within university curricula, research, and partnerships is critical to achieving sustainability outcomes. Similarly, Weiss et al. (2021) emphasized the structural and cultural patterns that influence curriculum reform processes, warning that superficial or fragmented integration risks undermine the transformative potential of sustainability education.

Soil is deeply interwoven with global sustainability imperatives, contributing directly to at least 14 of the 17 SDGs (Lal et al., 2021; Swan et al., 2024) by nutrient cycling, carbon storage, water purification, and biodiversity conservation.

Given the centrality of these ecosystem services—provisioning, regulating, supporting, and cultural—it is imperative that soil-science curricula be restructured to equip students with the interdisciplinary knowledge and practical skills needed to engage with these sustainability pillars holistically. Soil should not be taught merely as a physical medium or scientific construct but rather as a dynamic agent of sustainable transformation. This pedagogical shift requires framing soil as a form of natural capital—an asset that provides essential contributions to a continuous flow of ecosystem services essential for achieving the SDGs (Adhikari and Hartemink, 2016; Mikhailova et al., 2024). Soils contribute to ecosystem services in a multi- and transdisciplinary context; indeed, the definition of soil health by the European Union (2023) emphasizes "the continued capacity of soils to contribute to ecosystem services."

To facilitate meaningful integration, curriculum design should employ instructional models that explicitly connect soil properties and functions to sustainability outcomes. Matrix-based pedagogical frameworks have proven especially effective in this regard. These models enable educators to systematically map key soil attributes such as texture, cation exchange capacity, and saturated hydraulic conductivity that help define ecosystem services in line with specific SDGs. This approach not only enhances conceptual understanding, but also fosters students' ability to apply scientific principles in addressing real-world sustainability challenges (Mikhailova et al., 2024).

Furthermore, structuring curricula around soils' ecosystem services enables students to grasp the interdisciplinary significance of soil vis-à-vis both natural and socioeconomic systems. Thus, soil science education transcends disciplinary boundaries and empowers future professionals to engage in the SDG agenda as informed and responsible global citizens.

Bouma (2014) underscored the necessity of transitioning soil science from an inward-looking discipline to one that engages in transdisciplinary contexts. In doing so, soil science has become more relevant to key sustainability concerns, such as food, water, climate, and biodiversity. This approach supports the SDGs not as isolated targets, but as interconnected goals requiring integrated land management strategies. Bouma (2014) called for soil scientists to become "knowledge brokers" capable of linking scientific knowledge with local and policy-based action—an imperative that should be reflected in how we educate future soil professionals. An educational effort along these lines was a student challenge organized in 2021 at Wageningen University, the Netherlands, with the theme, "Make all soils healthy again." The challenge was conducted in the form of a game in which one team would win. After providing basic information, 18 teams worked for half a year on this theme and produced highly original and creative reports of high quality, indicating the intellectual potential of students that may not find a suitable outlet with classic topdown traditional lectures.[1] The Dutch Secretary of Agriculture addressed the students at the final session. The same element of competition is found in the soil judging contests in the USA, where teams from different states compete, which are now also introduced in Europe. Rather than producing soil profile descriptions, such efforts could also be focused on determining soil health and its functions within a particular landscape.

Similarly, Adhikari and Hartemink (2016) highlighted that soil scientists have been slow to adopt the language of ecosystem services, despite their work being inherently linked to it. Their global review illustrated that while provisioning and regulating services are commonly researched, cultural and supporting services remain underexplored. Moreover, the spatial dimensions of soil properties critical for services such as water purification and carbon sequestration are underutilized in teaching and policy engagement. Therefore, pedagogical models must emphasize ecosystem service thinking and its applicability across all dimensions of soil science practice. Recent reports by the European Union (2024) and European Commission (2025) on the future of agriculture support this approach (see also Bouma, 2025), emphasizing "the need for sustainable farm management and harmonization of methodologies for on-farm sustainability assessment," with

[1]https://shorturl.at/j1mke

"common metrics and indicators" aiming at the objective "to determine where each farm stands." In addition, there is a need to "provide quantifiable ecosystem services using robust indicators" in the context of "an agro-food system that is economically, socially and environmentally sustainable." This would involve "contributions to climate mitigation, providing clean water and air, soil health and biodiversity preservation."

Mikhailova et al. (2024) provided a compelling case for using matrix-based learning in soil-science education to directly link soil properties and ecosystem functions with the relevant SDGs. Their findings showed that students exposed to SDG-integrated soil curricula developed a heightened appreciation of soil's role in sustainability, particularly in regulating services such as climate control and water filtration. This supports the inclusion of practical problem-based learning, where students assess soil characteristics (e.g., texture and hydraulic conductivity) within the context of real-world environmental challenges. Such experiential learning allows students to internalize soil's role as natural capital, contributing directly to SDG outcomes.

Additionally, educational research by Zamora-Polo et al. (2019) and Serafini et al. (2022) confirmed that students' awareness of SDGs remains uneven, while their capacity to link disciplinary knowledge to global development frameworks is limited. This gap supports the embedding of SDG-specific competencies into soil-science pedagogy. Students must not only understand soil science but also develop the systems thinking, evaluative judgment, and ethical reasoning necessary to frame soil functions within broader socio-environmental goals. However, many academic programs continue to operate within disciplinary silos, lacking the integration of systems thinking, socio-environmental awareness, and cross-sectoral approaches (Heldal et al., 2024; Watkins et al., 2012).

There is a critical need to redesign the tertiary-level curricula to better reflect the complexity and interconnectedness of contemporary soil-related challenges. Embedding SDG-aligned learning outcomes such as socioecological systems analysis, participatory stakeholder engagement, sustainability impact assessment, and ethical reasoning can shift educational paradigms from traditional content-based instruction to transformative competence-oriented learning models (Mikhailova et al., 2024). Pedagogical experts call for embedding sustainability principles, critical thinking, and stakeholder communication within soil science curricula (Ross et al., 2012). These platforms not only validate empirical findings but also serve as crucibles for the development of pedagogical frameworks that emphasize integrative and applied learning.

Practical strategies for implementing these reforms include Living Lab environments, also advocated by European Union (2024); capstone projects centered on community-based sustainability challenges, and participatory research involving stakeholders such as farmers, environmental planners, and local communities. Brevik et al. (2022) advocated for student-centered innovations—flipped classrooms, problem-based learning, studio-integrated labs, and virtual soil explorations—that replicate real-world dynamics and foster collaborative problem solving. These experiential methods promote learner agency, critical reflection, and adaptive thinking (Brevik et al., 2022).

Structural curricular reform must also be underpinned by interdisciplinary collaboration. Integrating soil science with disciplines such as environmental science, agronomy, engineering, public health, and socioeconomics enhances transdisciplinary learning and mirrors sustainability challenges' systemic nature (Bouma, 2023; Lal et al., 2021). This integration will foster a holistic understanding of soil systems, ethical foresight, and innovation capacity among future professionals.

This call for transformation is supported by recent empirical data. A comprehensive stakeholder survey conducted by Veenstra et al. (2024) across 24 European countries (n = 669) revealed persistent gaps in soil-science education, particularly in systems thinking, stakeholder communication, and integrated understanding of soil within the One Health paradigm. Stakeholders ranked "a scientific basis of soil functioning" and "the ability to mobilize agronomic drivers to protect soils" as the most critical competencies. With 84% of the respondents working in soil-related fields and 67% self-identifying as experts, the data reflect a strong sectoral engagement and consensus on educational priorities.

Complementing this, Field et al. (2011) outlined 11 foundational soil science teaching principles developed through a stakeholder-driven multi-institutional process. These principles emphasized contextualized learning, cross-subdisciplinary integration, and the cultivation of metacognitive and communication skills. Grounded in constructivist and experiential learning theories, this pedagogical model provides a scaffold for reform that supports both dynamic environmental problem-solving and active professional engagement.

Despite the promise of integrating the SDGs into higher education, particularly in STEM fields such as soil science, numerous pedagogical and institutional challenges remain. One major obstacle is the SDGs' broad and often abstract nature, which can impede the design of specific actionable learning outcomes (Mikhailova et al., 2024). This lack of clarity often results in ambiguous instructional objectives and difficulty in understanding SDGs' relevance to the academic discipline. Such problems can be overcome by focusing on specifically defined ecosystem services that are in line with certain SDGs.

Furthermore, the subject-specific orientation of SDGs' content requires careful adaptation; however, most curricula are not structured to accommodate crosscutting themes. This lack of coherence can render SDG integration superficial or disconnected, particularly in isolated courses or modules (Mikhailova et al., 2024). Students' unfamiliarity with SDGs also presents a pedagogical barrier: nearly 80% of the students surveyed were unaware of basic SDG facts, while many continued to misunderstand key soil–SDG linkages, even after instruction.

Time constraints in academic scheduling further hinder deep engagement with the SDGs' content. As Cottafava et al. (2020) noted, short modules limit sustained exploration and shared language development across disciplines. Consequently, student learning may remain at the surface level, while innovative ideas seldom progress beyond conceptualization.

Moreover, student projects, while often imaginative, frequently lack feasibility due to gaps in managerial competencies, such as economic planning, feasibility analysis, and stakeholder involvement, resulting in what has been described as "SDG-washing" (Cottafava et al., 2020). It should also be noted that students often lack the necessary skills to present their projects in front of an audience that may include potential users of their work.

Institutionally, systemic inertia and resource limitations impede efforts toward mainstream SDG education. Without curricular integration, administrative support, or funding, such initiatives struggle for legitimacy and long-term impact. Further, traditional lecture-centric instruction constrains the adoption of transformative pedagogies, even though hands-on approaches, such as laboratory work and reflective writing, have been shown to deepen students' understanding of SDGs' relevance (Mikhailova et al., 2024). However, the lack of individualized assessments such as paired pre- and post-tests limits the evaluation of student progress.

Meanwhile, despite its central role in environmental sustainability, soil remains underrepresented in SDG documentation and discourse. This omission risks further marginalizing soil science in both the educational and policy arenas (Mikhailova et al., 2024). This underrepresentation can be overcome by demonstrating—through specific examples—the crucial role of soils in contributing to ecosystem services, in line with certain SDGs.

Nevertheless, soil science curricula are uniquely positioned to bridge the gap between scientific knowledge and sustainability strategies. As a STEM discipline that inherently intersects with planetary health, soil science provides a robust interdisciplinary platform for SDG-based education. Embedding soil ecosystem services into coursework, framed around provisioning, regulating, and cultural ecosystem service categories, facilitates conceptual linkages to the SDGs (Adhikari and Hartemink, 2016; Mikhailova et al., 2024).

Matrix-based instructional approaches, which align specific soil properties with individual SDGs, have shown promise in enhancing conceptual clarity and real-world applicability. For instance, linking soil texture with water filtration and nutrient retention fosters an understanding of its relevance to SDGs 6 (Clean Water and Sanitation) and 2 (Zero Hunger) (Mikhailova et al., 2024).

Meanwhile, transdisciplinary pedagogies focusing on systems thinking, open learning environments, and stakeholder collaboration are essential for cultivating the leadership skills required for sustainability transitions (Cottafava et al., 2020). The University of Torino exemplifies this approach by engaging students in applied problem-solving within local sustainability contexts.

Additionally, HEIs, with mandates for teaching, research, and outreach, are strategically positioned to lead this educational transformation. The institutional integration of SDGs—from curricula to management practices—could amplify their societal impact (Zamora-Polo et al., 2019). However, challenges persist in operationalizing these ambitions without clear, discipline-specific instructional frameworks (Mikhailova et al., 2024).

In summary, there is a compelling need to reimagine and revisit soil science programs to more deliberately align them with the SDGs (Noguera et al., 2021). As sustainability challenges become increasingly complex and interconnected, higher education must evolve to provide students with disciplinary expertise and the capacity for critical, systems-based thinking. According to the UN and UNESCO, transformative changes in educational policy, curricula, and pedagogy are indispensable for addressing sustainability across the social, environmental, and economic domains (Annan-Diab and Molinari, 2017; United Nations, 2015; UNESCO, 2020). As previously stated, soil science has a unique relevance across at least 14 of the 17 SDGs, given its foundational role in ecosystem services that support Earth-system sustainability (Bouma et al., 2019; Keesstra et al., 2016).

However, traditional approaches to soil education often remain narrowly focused on sub-disciplinary content and technical modeling—what some have termed a "soil pit" perspective (Bouma et al., 2019). This insularity inhibits engagement with broader transdisciplinary contexts, and reduces the visibility of soil science in addressing global sustainability objectives. To overcome this problem, soil-science curricula must be reframed through the lens of sustainability. This entails training students to see soils not just as physical and chemical entities but also as dynamic systems embedded within socio-ecological landscapes, thereby fostering the competencies necessary to engage with policy, community-based action, and interdisciplinary research (Sipos et al., 2008; Wiek et al., 2011).

Embedding SDG-relevant knowledge into soil-science education requires a strategic curriculum design. Avelar et al. (2023) emphasized that sustainability's integration into higher education should extend beyond isolated courses and instead permeate teaching, research, and institutional partnerships. Similarly, Weiss et al. (2021) highlighted that effective curriculum change demands coordinated institutional efforts rather than *ad hoc* or symbolic reforms. The SDGs—particularly SDG 4.7—call for educational systems to ensure that all learners acquire the knowledge and skills needed to promote sustainable development (United Nations, 2015). The *ESD Roadmap 2030* by UNESCO (2020) provides further guidance on how HEIs can operationalize these aims.

A transdisciplinary approach that links soil functions to ecosystem services and quantifies their contributions to specific SDG is essential (Keesstra et al., 2016). Such models not only reinforce the scientific relevance of soil processes but also contextualize them within human development frameworks, making the learning experience more meaningful and socially impactful. In doing so, soil-science education can cultivate a generation of professionals who are not only technically adept, but also ethically and systemically oriented toward sustainability transitions.

OBJECTIVES OF THIS STUDY

Building on the urgent call for pedagogical reform outlined in the introduction, this study seeks to contribute to the evolving discourse on integrating soil-science education with the SDGs. This is accomplished by aligning curriculum design, instructional

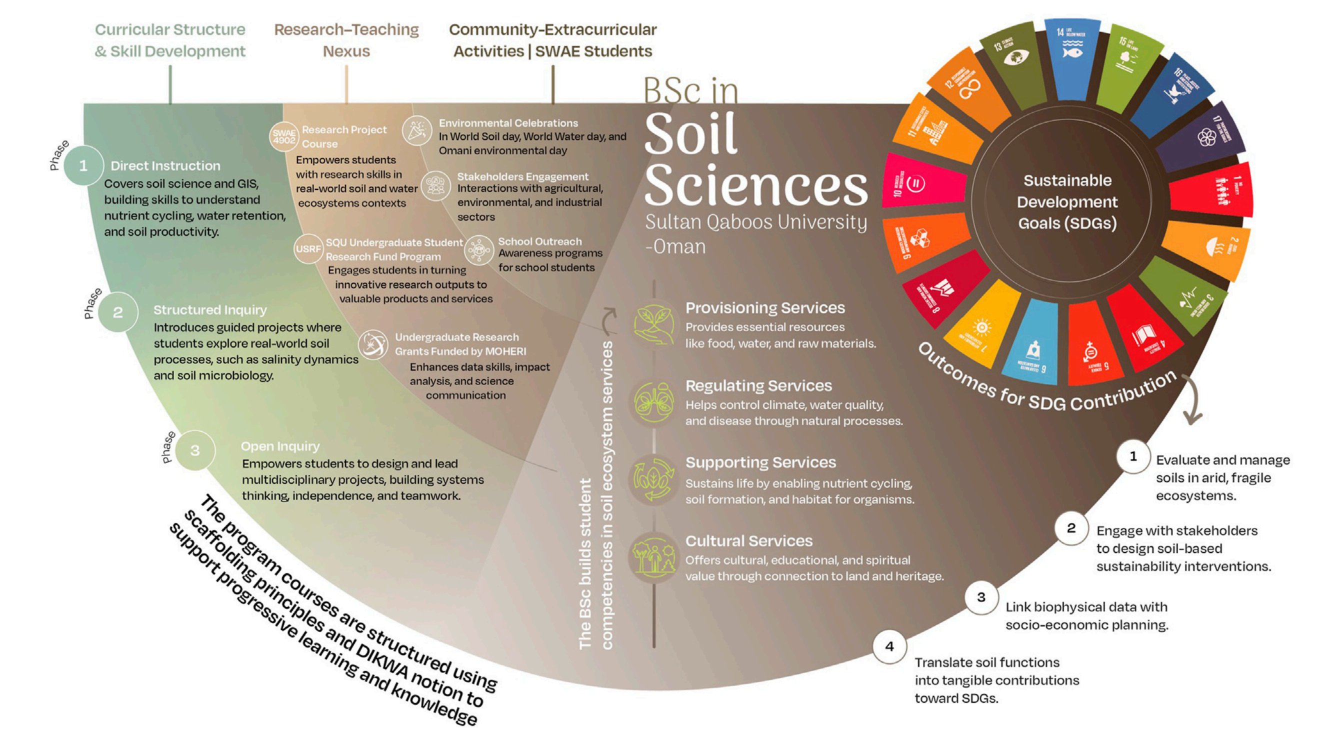

FIGURE 1 | Infographic visually encapsulating the comprehensive and sustainability-driven structure of the BSc in Soil Sciences program at Sultan Qaboos University (SQU), Oman.

strategies, and professional competencies with global sustainability challenges. The specific objectives of this study are as follows:

a) To document and analyze the curriculum tuning of undergraduate soil-science programs at Sultan Qaboos University (SQU; in Oman) and Moscow State University (MSU; in Russia), focusing on enhancing student competencies related to soil ecosystem services, interdisciplinary knowledge, and SDG-relevant outcomes.
b) To present selected case studies and experiential learning practices implemented within these programs, aiming to illustrate how specific pedagogical approaches such as project-based learning, community engagement, and ecosystem services mapping can equip students with practical skills aligned with the SDG targets.

TRANSFORMING SOIL-SCIENCE EDUCATION AT SQU

The Bachelor of Science (BSc) in Soil Sciences at SQU is the only undergraduate degree dedicated to agriculture and soil science in Oman (**Figure 1**). Offered by the Department of Soils, Water, and Agricultural Engineering (SWAE) at the College of Agricultural and Marine Sciences, this four-year program (126 credits) blends foundational sciences with applied instruction in soil and water systems. Delivered in English and aligned with national accreditation standards, the curriculum emphasizes Oman's unique arid and saline landscapes, such as mountain terraces and traditional *aflaj* irrigation systems, providing students with regionally tailored and globally relevant education (Al-Ismaily et al., 2018).

The program was scaffolded across three progressive phases of inquiry, reflecting the complexity of soil ecosystem services and promoting sustainability-oriented education. Phase I, Direct Instruction, lays the scientific groundwork, focusing on core topics, such as Introduction to Soil and Water, Environmental Soil Chemistry, Environmental Soil Physics, Hydrology, and Geographic Information Systems (GIS). Students develop the foundational knowledge necessary to understand nutrient cycling, soil-water retention, and biological productivity, which are crucial to providing and supporting ecosystem services. These competencies contribute directly to SDGs 2 and 6. In Phase II, Structured Inquiry, students engage in guided projects that examine real-world soil processes such as salinity dynamics and soil microbiology. This phase strengthens their ability to interpret data and address regulatory services such as pollution mitigation and climate control, aligned with SDG 13 (Climate Action). Finally, Phase III, Open Inquiry, empowers students to lead multidisciplinary projects, such as urban soil health assessments, holistic hydropedological understanding and modeling of soilscapes, land-use planning, enhancing water conservation, and resilience to water scarcity in challenging soil environments. This encourages systems thinking and collaborative problem solving essential for landscape-scale decision-making and contributes to SDG 15 (Life on Land).

The central pillar of the BSc in Soil Sciences at SQU is its robust research-teaching nexus, which actively integrates student learning with applied scientific inquiry. This integration is most evident in the three key platforms that scaffold undergraduate research. The Research Project Course (Research Projects in Soil, Water, and Agricultural Engineering–SWAE4902) offers structured opportunities for students to apply classroom theories to field-based investigations of soil and water systems. Through this course, students develop critical competencies in experimental design, environmental data analysis, and scientific reporting. Second, the SQU's Undergraduate Student Research Fund Program offers competitive grants and structured mentorship, empowering students to undertake both independent and team-based research projects that align with national development goals, particularly in the areas of arid-land sustainability and soil-salinity management. An important dimension of this initiative is its emphasis on generating innovative research outputs with the potential to be transformed into value-added products, sustainable processes, and practical services, thereby bridging academic inquiry with real-world applications and socioeconomic impacts (For the Undergraduate Student Research Fund Program at SQU, see [2]). Third, the program connects students with nationally competitive Undergraduate Research Grants funded by the Ministry of Higher Education, Research, and Innovation, which expand research capacity through support for fieldwork, laboratory experimentation, and stakeholder engagement.

Together, these platforms operationalize the research–teaching nexus by enabling students to obtain real-world insights and contribute meaningfully to soil and environmental science. They cultivate high-level competencies in data interpretation, impact assessment, and science communication and advance broader educational and societal goals, particularly SDGs 4 and 17. This integrative model transforms the undergraduate experience into a trajectory of innovation, civic responsibility, and professional readiness within the context of Oman's fragile but vital soil ecosystems.

The program's aim is to build graduates' capacity to evaluate and manage soils in arid, fragile ecosystems, as well as foster transdisciplinary approaches for sustainable soil-based solutions. Students learn to engage with diverse stakeholders, link biophysical data to socioeconomic contexts, and translate soil functions into actionable strategies that support the SDGs. By connecting theory, inquiry-based pedagogy, and practical applications, the BSc in Soil Sciences at SQU is a model of higher education aligned with global sustainability imperatives and tailored to local ecological realities.

In the classroom, students in the SWAE program at SQU engage in diverse community and extracurricular activities that strengthen their environmental leadership and reinforce the social dimension of soil science. These activities are integral to the program's applied learning philosophy and contribute to the development of cultural and educational ecosystem services. A highlight is the organization and participation in World Soil Day events, where students lead public awareness campaigns, exhibitions, and scientific demonstrations aimed at increasing soil literacy across Omani society. Additionally, students regularly conduct outreach workshops at local schools and engage young learners in interactive lessons on soil health, irrigation, and sustainable land use. These events foster early environmental awareness and position the SWAE students as ambassadors of sustainability education.

By extending their community footprint, students are also involved in student-led field courses that simulate professional environments by combining technical skills with stakeholder interactions. These experiences are often framed within student clubs and environmental societies that support collaborative initiatives such as tree planting, urban garden assessments, and field-based conservation practices. Through these initiatives, the students gain practical experience in teamwork, public engagement, and environmental stewardship. These activities not only complement academic learning but also help build soft skills, such as communication, leadership, and civic responsibility, thereby aligning with the broader mission of SDGs 4 (Quality Education) and 13 (Climate Action). By embedding community engagement in the academic journey, the SWAE program cultivates well-rounded graduates equipped to act as agents of positive change in both local and global environmental contexts.

The BSc in Soil Sciences curriculum at SQU is fully in line with the rapid advancement of modern instrumental methods in soil research, which has transformed soil science into a data-driven, digital discipline (Brevik et al., 2022). This evolution requires proficiency in diverse technological domains, including big data analytics, mathematical modeling using HYDRUS-1D, Internet of Things for irrigation, remote sensing, GIS, among others. These competencies are becoming increasingly critical for effective soil monitoring, environmental planning, and sustainable land management (Lomonosov, 1763; Mikhailova et al., 2018).

SOIL-SCIENCE EDUCATION AT MSU

The educational approach of the Soil Science Faculty at MSU is characterized by a systematic framework that integrates soil science with broader biosphere and societal functions. Key elements include (1) a systemic perspective on soil as a dynamic component of natural and anthropogenic processes, (2) interdisciplinary instruction spanning the natural and social sciences, and (3) the incorporation of modern research methodologies, including experimental analysis, statistical evaluation, and mathematical modeling.

This model reflects both the historical roots of soil education at MSU and the guiding principles of the Russian higher education system, which emphasizes foundational knowledge and its practical applications. The curriculum is also shaped by the mandatory inclusion of humanities and physical development courses to ensure a holistic education.

MSU's soil science tradition dates back over two centuries, preceding the formalization of the discipline by Dokuchaev. M.V.

[2]https://l1nq.com/z28M9

TABLE 1 | Undergraduate curriculum in soil science at MSU.

Disciplinary area	Course	Academic units	Contact hours	Faculty
General (Social Sciences)	Economics	4	72	Faculty of Economics
	Sociology	2	54	Faculty of Sociology
	Law	2	36	Faculty of Law
	Philosophy			Faculty of Philosophy
	Fundamentals of Land Law	2	36	Faculty of Law
	Land Use and Management	2	36	Soil Science Faculty
	Food Security	3	36	Soil Science Faculty
	Sustainable Development	3	36	Soil Science Faculty
	Life Safety	2	24	Soil Science Faculty
	Russian Language and Speech Culture	4	60	Faculty of Teacher Education
Mathematics	Introduction to Calculus	8	156	Faculty of Mechanics and Mathematics
	Informatics	4	90	Faculty of Mechanics and Mathematics
	Mathematical Statistics	4	120	Soil Science Faculty
	GIS	2	48	Soil Science Faculty
Chemistry	General Chemistry	3	90	Faculty of Chemistry
	Physical Chemistry	2	72	Faculty of Chemistry
	Colloidal Chemistry	2	54	Faculty of Chemistry
	Organic Chemistry	3	72	Faculty of Chemistry
	Soil Chemistry	2	48	Soil Science Faculty
	Agrochemistry	5	144	Soil Science Faculty
Physics	Physics	5	120	Faculty of Physics
	Soil Physics	4	132	Soil Science Faculty
	Erosion and Soil Protection	2	60	Soil Science Faculty
Geography	Geology	2	60	Faculty of Geology
	Cartography & Topography	3	36	Faculty of Geography
	Geomorphology	3	36	Soil Science Faculty
	Soil Cartography	2	48	Soil Science Faculty
	Soil Geography	3	72	Soil Science Faculty
	Mineralogy	4	36	Faculty of Geology
Agronomy and Soil Science	Agriculture	3	72	Soil Science Faculty
	Fundamentals of Soil Science	5	72	Soil Science Faculty
	Soil Reclamation	3	90	Soil Science Faculty
	Soil Science	2	60	Soil Science Faculty
	Crop Production	2	60	Soil Science Faculty
	Soil Properties and Processes	2	54	Soil Science Faculty
	Paleosoil Science & Evolution	3	30	Soil Science Faculty
	Land Resource Assessment	3	36	Soil Science Faculty

Lomonosov's (1763) publication "On the Layers of the Earth" laid the groundwork by conceptualizing soil as a product of geological and biological interactions. In the early 19th century, pioneering faculties such as P.I. Strakhov conducted empirical soil research, while A.A. Prokopovich-Antonsky established the Moscow Society of Agriculture. By 1823, soil and agricultural education had been formally recognized as a scientific discipline through Pavlov's work. The Department of Agronomic Chemistry (now the Department of Agrochemistry and Plant Biochemistry) was founded in 1863, and Dokuchaev advocated for soil science departments in universities by 1895. In 1906, soil science was officially introduced as a natural science course at the MSU.

Throughout the 20th century, structural reforms, including temporary shifts away from faculty-based systems, eventually led to the consolidation of soil science as an academic focus. In 1973, the Faculty of Biology and Soil was split, leading to the creation of the independent Faculty of Soil Science. Today, the Faculty employs 344 staff members, including 75 faculty members and 83 researchers, and boasts of a legacy that spans collaborations with multiple faculties, such as those of Physics, Geography, Biology, and Geology.

The Faculty's educational philosophy is rooted in rigor and clarity, a perspective articulated by Professor Vladychensky (Shein and Umarova, 2008), who emphasized the delivery of essential scientific knowledge, the development of analytical thinking, and the importance of self-directed learning. The curriculum aims to foster fundamental competencies across disciplines including mathematics, physics, chemistry, biology, geography, and soil science. Students are expected to develop general and specialized professional skills that allow them to conduct research, engage in applied science, and meaningfully contribute to land management, agriculture, environmental protection, and education.

The MSU operates on a credit-hour system, according to which one credit equals 36 academic hours (45 min each). **Table 1** shows the main courses of the Bachelor's degree program in soil science at MSU. The bachelor's program spans 4 years of full-time study, totaling 240 credits divided into a basic core module (137 credits), a variable module (27 credits), practical and research training (39 credits), and a final certification (9 credits). Courses are delivered by faculty holding professorial ranks across multiple departments to ensure interdisciplinary exposure.

The undergraduate program in soil science at MSU was founded on a comprehensive and interdisciplinary educational framework. It integrates a well-balanced mix of the general sciences, natural sciences, technical disciplines, and applied soil studies. The curriculum is organized into five core disciplinary domains: general (social sciences), mathematics, chemistry, physics and geography, and agronomy and soil science, each contributing critical knowledge and skills that support both theoretical foundations and practical applications in soil science.

This interdisciplinary design ensures scientific depth and promotes an integrated understanding of soil ecosystem services, including nutrient cycling, water retention, carbon storage, and biodiversity support. By embedding sustainability concepts throughout the coursework, the program effectively prepares students to contribute to global priorities, particularly those outlined in SDGs 2 (Zero Hunger), 6 (Clean Water and Sanitation), 13 (Climate Action), and 15 (Life on Land).

Students follow a uniform curriculum for the first two years before choosing a specialization in the third year. The faculty houses 10 departments, including agrochemistry, soil biology, soil geography, soil chemistry, physics and recreation, and radioecology, each offering tailored courses. Specializations include agroecology, soil biology, land resources and functioning, soil physics and erosion, and soil chemistry. Students are assigned supervisors for their research activities starting in their third year.

The program is designed not only to prepare soil science experts, but also future researchers, educators, and policymakers. Approximately 70% of graduates pursue master's degrees, while 40% continue to pursue PhDs. Alumni work in agriculture, environmental agencies, governmental bodies, universities, and international institutions such as Michigan State University (USA), the University of Alberta (Canada), and the National Autonomous University of Mexico (Mexico).

Practical training is integral and includes nearly 4 months of summer fieldwork. Courses in geology, botany, topography, and soil science are supplemented with training in soil cartography, erosion control, and zonal soil surveys. The communication, teamwork, and research designs are developed through conferences and group projects. Students also participate in outreach events such as "Science Days," "Soil Science Day," and summer schools that engage local communities.

MSU's emphasis on applied learning is supported by a pedagogical approach that encourages problem-solving, ethical collaboration, and scientific communication. Despite criticism of the rigidity of the Russian education system, MSU's soil science program fostered the development of soft skills through laboratory work, team-based field assignments, and participation in public science events.

Group projects, field training, and oral presentations reinforce soft skills. Students develop competencies in scientific reasoning, experimental design, data analysis, and ethical execution of collaborative work. These experiences position graduates in roles that demand interdisciplinary insight and evidence-based decision-making.

Students specializing in physics, land recreation, and soil erosion have gained expertise in physical soil processes, degradation assessment, and remediation. They studied both core and elective subjects tailored to their focus areas, gaining hands-on experience with laboratory instrumentation and field-survey equipment.

INTEGRATING SOIL-SCIENCE EDUCATION WITH SUSTAINABLE DEVELOPMENT: COURSE-LEVEL PERSPECTIVES FROM SQU AND MSU

The following section presents a pedagogical analysis of selected courses and instructional practices from the BSc in Soil Sciences at SQU and MSU. These examples were chosen to illustrate how the program translates its broader educational strategies into specific learning experiences that equip students to understand and support soil ecosystem services within the framework of the SDGs. The selected courses (i, ii, iii, and iv from SQU and v from MSU) included the following:

(i) A theoretical course for junior-level students—Soil and Water Conservation (SWAE3304).
(ii) A field-intensive experiential course, Soil and Water Winter Tour (SWAE4110).
(iii) An advanced capstone-level course integrating lectures and hands-on applications—Hydropedology for Soil–Water–Landscape Interactions (SWAE4111).
(iv) Final year research project: Research Project in Soils, Water, and Agriculture. Engineering (SWAE4902).
(v) Advanced theory–practice integrated course: Soil physics.

Next each course will be examined through the lens of its pedagogical design, learning outcomes, and the specific competencies it fosters, particularly those related to ecosystem service thinking, interdisciplinary integration, and sustainability problem-solving.

Soil and Water Conservation (SWAE3304): Building Foundational Competence in Sustainable Soil Stewardship

The Soil and Water Conservation (SWAE3304) course provides junior-level students in the BSc in Soil Sciences at SQU with essential theoretical grounding and an applied understanding of soil and water as finite and life-sustaining natural resources. Through a combination of lectures, interactive debates, and continuous assessment, the course is structured to bridge the disciplinary foundations in soil physics, hydrology, and environmental science with real-world conservation strategies.

Pedagogical Design

The course leverages a multi-modal teaching approach encompassing (**Figure 2**):

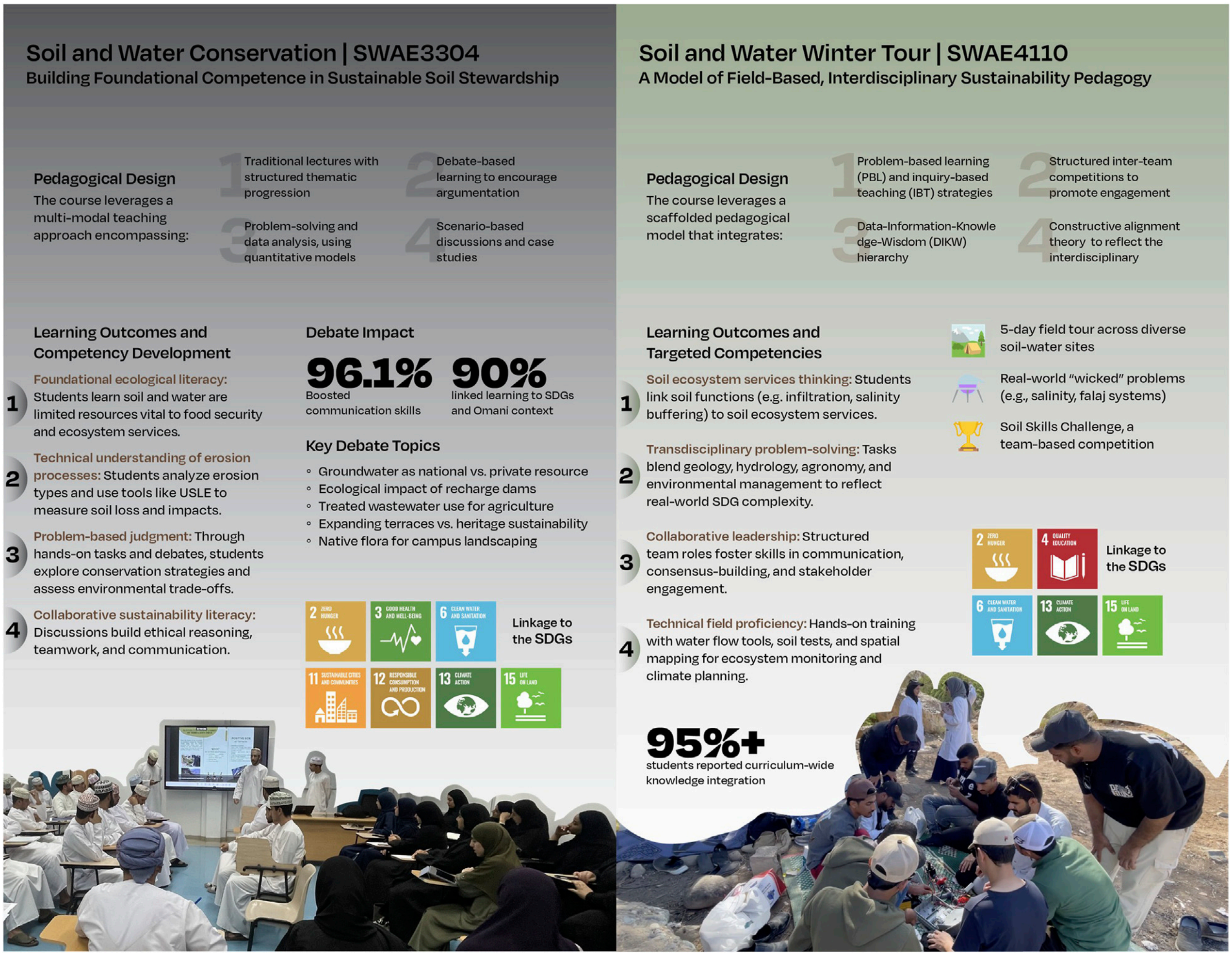

FIGURE 2 | Infographic highlighting two integrated courses: SWAE3304 uses lectures, debates, and modeling to build foundational skills in soil and water conservation, while SWAE4110 offers field-based, interdisciplinary learning focused on ecosystem services, technical fieldwork, and SDG-linked problem-solving.

- Traditional lectures with structured thematic progression.
- Debate-based learning, which encourages argumentation, evaluation, and synthesis of knowledge regarding controversial soil- and water-management issues.
- Problem-solving and data analysis using quantitative models such as the Universal Soil Loss Equation.
- Scenario-based discussions and case studies that contextualize soil degradation and conservation within Oman's unique arid ecosystem.

This scaffolded design supports active engagement while fostering systems thinking and the ability to diagnose and intervene in soil-degradation scenarios.

Learning Outcomes and Competency Development

The course systematically nurtures the following skill sets:

- Foundational ecological literacy: Students comprehend soil and water as non-renewable environmental assets whose degradation threatens food security, water availability, and long-term land productivity, contributing to a foundational understanding of the support and regulation of soil ecosystem services.
- Technical understanding of erosion processes: Students analyze geological, water, and wind erosion dynamics and learn to apply predictive tools (e.g., the universal soil loss equation) to quantify soil loss, linking physical processes to environmental degradation and restoration potential.
- Problem-based judgment: Through practical exercises and group debates, learners explore diverse conservation practices, compare remediation strategies, and critically engage with topics such as salinization, irrigation inefficiencies, and chemical pollution, which are essential for evaluating the tradeoffs among environmental solutions.
- Collaborative sustainability literacy: Debates and peer discussions promote ethical reasoning, communication skills, and teamwork, thus enabling students to

TABLE 2 | Debate topics: Soil ecosystem services and SDG relevance.

Debate topic	Key controversy	Relevance to soil ecosystem services	Relevant SDGs
Should groundwater in Oman remain private property or become a national resource?	A clash between traditional rights and public sustainability	Affects soil-water interactions, recharge zones, and access equity—impacts provisioning and regulating services	SDG 6, SDG 15, SDG 12
More recharge dams in Oman: A smart investment or an ecological misstep?	Balancing water security with environmental concerns	Alters hydrological cycles, infiltration, and sedimentation—directly affects regulating and supporting soil services	SDG 6, SDG 13, SDG 15
Is Oman ready to embrace treated wastewater as a source of drinking water?	Necessity vs. public perception and health	Impacts soil health and microbial balance if reused in agriculture—ties to pollution control and soil filtering services	SDG 6, SDG 3, SDG 12
Expanding mountain terraces in Oman: reviving heritage or misusing resources?	Heritage conservation versus cost and climate adaptation	Reduces erosion, improves soil stability and water retention—supports regulating and supporting services	SDG 2, SDG 15, SDG 11
Is replacing exotic flora with native species a viable water conservation strategy for SQU?	Aesthetic landscape vs. ecological responsibility	Enhances water-use efficiency, supports native soil biodiversity and nutrient cycles—boosts supporting and habitat services	SDG 6, SDG 15, SDG 13

participate effectively in multi-stakeholder conservation efforts.

The student debate initiative is structured around a robust framework of guidelines, procedures, and timing protocols that ensure academic rigor, fairness, and effective skill development. Central to this framework is the formal nomination and assignment of Student Debate Coordinators entrusted with the end-to-end logistical and procedural management of the debate process. Their responsibilities include scheduling with instructors, assigning teams, facilitating topic selection through class voting, ensuring timely communication of rules and deadlines, managing presentation materials, and moderating debate sessions to uphold procedural compliance.

The debate format is designed to foster analytical thinking and communication skills by engaging two teams—Proposition and Opposition—to present and defend contrasting viewpoints. Each team comprises 5–6 members, and debates topics that must be both controversial and intellectually stimulating. To ensure contextual relevance, selected topics should align directly with course themes (e.g., soil, water, and conservation) and be linked to broader objectives such as the SDGs. **Table 2** depicts examples of debate topics for the 2025 fall semester, outlining key environmental issues in Oman, each framed by a central controversy. These topics are directly linked to soil ecosystem services (e.g., water regulation, erosion control, and biodiversity) and align with the relevant SDGs. Whenever possible, emphasis is placed on regional relevance, especially concerning Oman and other arid or semi-arid regions, thereby enhancing the applicability and depth of student engagement.

The procedural timeline is structured meticulously to promote equity and clarity. A total of 25 min is allocated to each debate session. This includes 10 min for initial problem statements (5 min per team), followed by a 12-min rebuttal phase spanning three rounds (2 min per team, per round). Each team then delivers a 1-min closing statement, and an additional minute is reserved for transitions and setup. This tightly managed schedule reinforces time discipline, while providing ample opportunity for critical argumentation and structured dialogue.

To uphold academic integrity and constructive engagement, the debating process is governed by a set of formal rules. The participants must demonstrate mutual respect, avoid interruptions, and adhere strictly to the allotted time. The arguments should be logical, clearly articulated, and supported by credible data, sources, and case studies. Teams are also expected to listen and respond directly to opposing arguments, fostering a dynamic and evidence-based dialogue. Citing sources when referencing studies or data is not only encouraged but required, thereby reinforcing critical scholarship and accountability.

Figure 3 shows a stacked bar chart illustrating how a cohort of 51 students evaluated their level of agreement with 17 reflective statements following their participation in a classroom debate. The responses are categorized on a five-point Likert scale, ranging from "strongly disagree" (indicated in red) to "strongly agree" (indicated in blue). This visual representation offers a concise overview of student perceptions of the various cognitive, communicative, and collaborative outcomes associated with debate activities. Overall, the responses demonstrate a high degree of positive engagement, with most students selecting either "agree" or "strongly agree" for most statements. This pattern reflects a broadly favorable reception and confirms the effectiveness of the debate format in promoting active learning and reflection.

Among the highest-rated outcomes were "improved teamwork and communication" with 96.1% of students expressing agreement, and "more engaging than lectures," with 58.8% of students selecting "strongly agree." Furthermore, statements related to debate topics' relevance to the SDGs and Oman-specific issues also received strong endorsement, with over 90% agreement, thus highlighting the success of the activity in fostering contextual awareness and real-world applications.

The students also reported notable developments in key academic skills. These included enhanced public speaking confidence, improved research and evidence-based reasoning, and a deeper appreciation of interdisciplinary connections and outcomes that aligned well with the course's intended learning objectives.

However, only a few areas presented opportunities for enhancement. Statements such as "linked to sustainability" and "understanding Oman's conservation issues" elicited relatively lower levels of strong agreement and included a higher proportion of "neutral" or "disagree" responses. This indicates

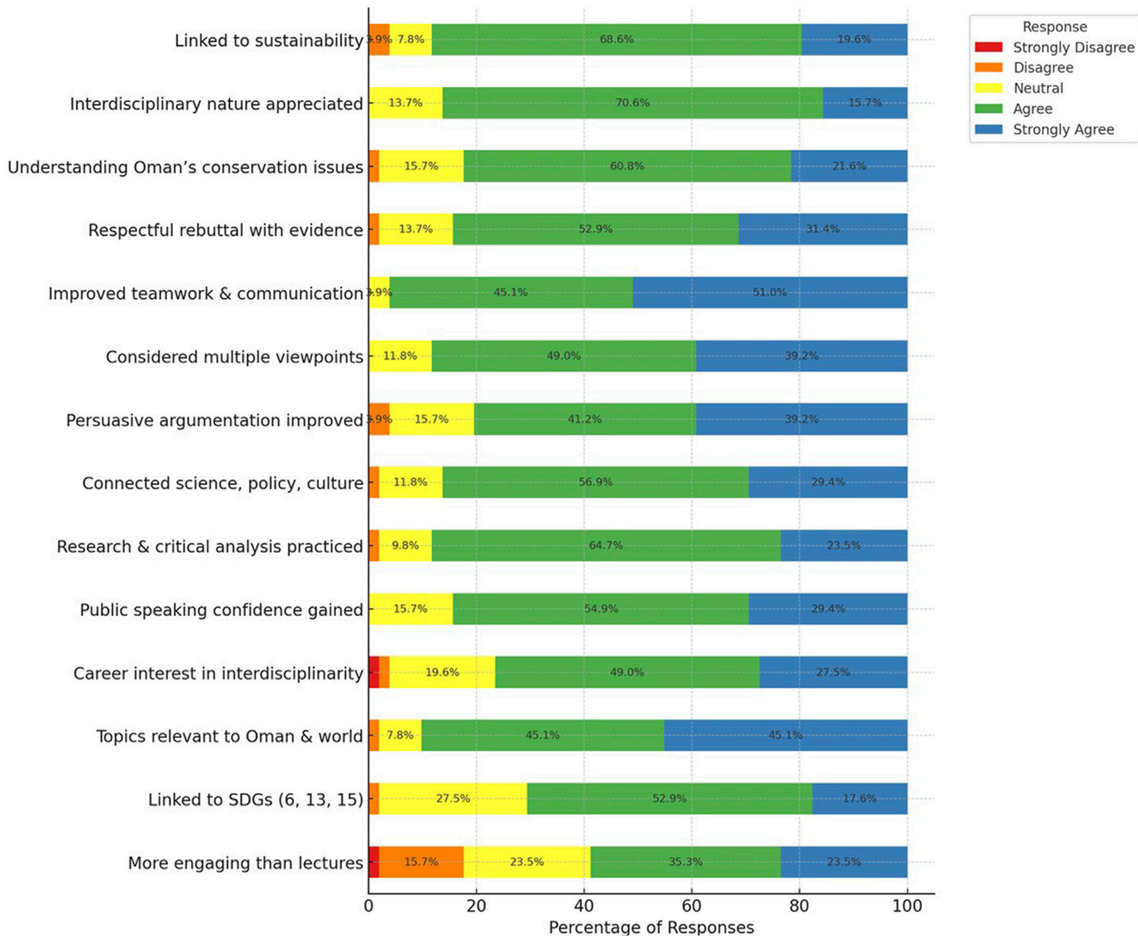

FIGURE 3 | Student reflections on debate-based learning outcomes.

that these themes may benefit from a greater instructional emphasis or clearer integration within the debate structure.

When students were asked to reflect on their debate experiences, their responses revealed a strong appreciation for both the academic and personal benefits of the activity. Many identified the most valuable aspect as the opportunity to enhance their argumentation and rebuttal skills, especially through the use of evidence and real-time reasoning. Students also noted gains in confidence, public-speaking skill, and the ability to communicate ideas clearly. Working in teams fostered collaboration, while engaging in complex sustainability topics helped them explore diverse perspectives and apply critical thinking.

Regarding improvements, the students overwhelmingly requested more time for preparation, delivery, and rebuttals. Several studies have suggested reducing or removing the presentation segment to allow for a deeper discussion. Others have recommended structured feedback, rubrics, and smaller teams to ensure equal participation. Suggestions for improvement also include using interactive formats (e.g., fact-checking and audience Q&As), advanced topic briefs, and better timing within the academic calendar to reduce pressure.

In their final comments, students expressed gratitude, calling the debate enriching, enjoyable, and unique, compared with traditional class activities. Many wished that it would continue in future courses, while a few proposed a more professional setup with clear rules, competitive rounds, and expert involvement. Overall, the responses reflected a deep appreciation of the activity's value in building essential skills, and a strong desire to see it grow and improve.

Soil and Water Winter Tour (SWAE4110): A Model of Field-Based, Interdisciplinary Sustainability Pedagogy

The Soil and Water Winter Tour (SWAE4110) represents a flagship experiential course within the BSc in Soil Sciences at SQU, designed to embody the pedagogical values of active learning, interdisciplinary integration, and ecosystem service-based education (Al-Ismaily et al., 2021; Al-Ismaily et al., 2023). The course is delivered as a five-day immersive field experience and culminates in the Soil Skills Challenge, a structured team-based competition that blends technical soil

FIGURE 4 | Infographic illustrating two complementary upper-level courses: SWAE4111 emphasizes system modelling and experimental hydropedology through integrated lab–field modules, while SWAE4902 engages students in interdisciplinary, research-driven projects tackling real environmental challenges with clear SDG alignment.

science tasks with real-world environmental problem solving (**Figure 4**).

Pedagogical Design

The course architecture leverages a scaffolded pedagogical model that integrates:

- Problem-based learning and inquiry-based teaching strategies.
- Structured inter-team competitions to promote engagement and critical reasoning.
- The data-information-knowledge-wisdom hierarchy (Ackoff, 1989) guides students from data collection to decision making.
- The constructive alignment theory ensures that assessments reflect a course's interdisciplinary and skill-based objectives.

Field scenarios are deliberately complex and often "wicked" in nature—for instance, they involve addressing secondary salinization in arid home gardens or installing precision irrigation systems—requiring students to synthesize competencies from hydrology, soil chemistry, landscape interpretation, and agroecology.

Learning Outcomes and Targeted Competencies

The course delivered various targeted learning outcomes that served both soil-science education and the broader goal of environmental sustainability. These include:

- Soil ecosystem services thinking: Students analyze and interpret the relationships among soil functions (e.g., infiltration and salinity buffering) and their role in delivering regulating, provisioning, and cultural services.
- Transdisciplinary problem-solving: Tasks require the integration of knowledge from geology, hydrology, agronomy, and environmental management, mirroring the multifactorial nature of SDG challenges.

- Collaborative leadership and communication: Through structured team roles and leadership rotations, students build real-world competencies in consensus-building, scientific dialogue, and stakeholder reporting.
- Technical field proficiency: Training includes direct experience with tools for water flow measurements, soil property testing, and spatial mapping, which are vital for ecosystem monitoring and climate-resilient land planning.

Linkage to Ecosystem Services and the SDGs

Through this pedagogy, students not only master disciplinary content, but are also equipped to actively contribute to SDG-relevant areas:

- SDGs 2 (Zero Hunger) and 15 (Life on Land): Investigating soil fertility, salinity control, and sustainable irrigation.
- SDG 6 (Clean Water and Sanitation): Water quality testing and flow analysis in the *falaj* and *wadi* systems.
- SDG 13 (Climate Action): Insights into carbon cycling, soil water retention, and climate adaptation strategies.
- SDG 4 (Quality Education): Embodying experiential, equity-centered pedagogy that emphasizes lifelong, practical learning.

In post-course evaluations, students reported enhanced capacities for problem analysis, communication, and sustainability planning. Over 95% confirmed that the Soil Skills Challenge helped integrate knowledge across the curriculum and connect theory to practice in impactful ways.

Hydropedology for Soil–Water–Landscape Interactions (SWAE4111): Advanced Integration of Soil Physics, Landscape Hydrology, and Sustainability Modeling

The course Hydropedology for Soil–Water–Landscape Interactions (SWAE4111) is a senior-level research-based course within the BSc in Soil Sciences at SQU. Designed as both a theoretical and practical learning experience, the course demonstrates how advanced soil-science pedagogy can align academic instruction with the competencies required to manage soil ecosystem services and respond to the sustainability imperatives articulated in the SDGs.

Pedagogical Design

This course is built in a multi-module format that blends lectures, laboratory experimentation, and field-based modelling (**Figure 4**). It integrates:

- Project-based learning anchored in real-world hydrological modeling scenarios.
- Active application of numerical modeling tools (HYDRUS-1D) for simulating vadose zone processes.
- Hands-on soil column experimentation for analyzing stratified water flow.
- Critical systems thinking links hydrological fluxes to soil formation, water quality, and land use.

The course follows a systems-based framework that emphasizes feedback between pedological properties and hydrological behavior, equipping students to bridge technical insight with environmental design and land management.

Learning Outcomes and Targeted Competencies

The course cultivates several advanced competencies relevant to sustainability-oriented soil science:

- Predictive modeling: Students gain the ability to simulate one-dimensional water and solute dynamics using HYDRUS-1D, a tool widely employed in environmental impact assessments and irrigation planning.
- Interdisciplinary soil-water analysis: Through case-based learning, students explore flow pathways (overland, lateral, and groundwater) and their influence on pedogenic features (e.g., salinity and redox indicators), thereby enhancing their understanding of regulating and supporting ecosystem services.
- Research design and problem solving: Students design and interpret column experiments and, in teams, tackle landscape-scale soil–water challenges (e.g., contaminant transport, irrigation efficiency), integrating experimental hydrology, quantitative analysis, hypothesis-driven inquiry, and collaborative solution-building aligned with community and ecological needs.

Linkage to Ecosystem Services and the SDGs

SWAE4111 plays a critical role in training students to apply soil-science knowledge to real-world challenges in which soil–water interactions drive ecosystem functioning. Its specific contributions to the SDGs include the following:

- SDG 6 (Clean Water and Sanitation): Modeling and mitigation of water contamination and inefficient irrigation through vadose zone simulations.
- SDG 13 (Climate Action): Understanding soil-water dynamics for climate resilience through water retention, infiltration, and root-zone modelling under harsh arid conditions.
- SDG 15 (Life on Land): Assessment of soil landscape heterogeneity and its role in biodiversity, vegetation dynamics, and catchment management.
- SDG 2 (Zero Hunger): Enhanced understanding of moisture redistribution and plant–water interactions across diverse geomorphological landscape features to optimize agricultural productivity in arid environments.
- The course enables students to treat soil not merely as a substrate but as a dynamic interface of biophysical, hydrological, and socio-ecological processes. Graduates are equipped to become integrative professionals capable of applying scientific tools to multiscale sustainability issues.

Research Project in SWAE

Pedagogical Design

SWAE4902 is designed as a capstone research experience that synthesizes theoretical, analytical, and field-based competencies acquired through SWAE programs. The course leverages a flexible yet rigorous independent study format in which students conduct original research under faculty mentorship (**Figure 4**). It integrates:

- Research-based learning grounded in real-world soil, water, and agricultural challenges, allowing students to address environmental and engineering questions.
- Iterative engagement with scientific methods, from hypothesis formulation to data analysis and critical evaluation.
- Hands-on experimentation and/or fieldwork depending on the project scope, with a focus on data generation, interpretation, and technical reporting.
- Cross-disciplinary research framing, blending technical engineering knowledge with socio-environmental insights, and stakeholder relevance.

This project-based framework emphasizes independent inquiry, scientific integrity, and methodological rigor, enabling students to transform abstract classroom concepts into actionable solutions that are aligned with sustainable land, soil, and water management goals.

Learning Outcomes and Targeted Competencies

SWAE4902 develops advanced competencies essential for professional and academic pathways in environmental sciences, engineering, and sustainability. By the end of the course, students are expected to:

- Apply research methods to study environmental systems and integrate interdisciplinary knowledge to solve SWAE problems—from problem definition and hypothesis formation to protocol design and analysis of complex data—with ecological, climatic, and socioeconomic dimensions.
- Develop academic and professional communication skills. Students produce high-quality research output, including technical reports and formal presentations suitable for diverse stakeholders.
- Demonstrate autonomy and scientific integrity. Students manage time-bound projects independently, reflect on research ethics, engage in peer and expert reviews, and enhance their lifelong learning capacity.
- Collaborate across disciplines and cultures. Through opportunities for group or interdepartmental projects, students refine their teamwork, leadership, and intercultural communication skills while tackling real-world sustainability issues.

Linkage to Ecosystem Services and the SDGs

The SWAE4902 equips students with the skills and knowledge to engage in complex sustainability problems in which soil, water, and agriculture intersect with human and ecological systems. This directly contributes to the following SDGs:

- SDG 6 (Clean Water and Sanitation): Students develop research projects addressing water quality, irrigation efficiency, or groundwater management using data-driven approaches.
- SDG 13 (Climate Action): Projects focus on climate-smart soil and water practices to assess the vulnerability and resilience of agriecosystems under variable climate regimes.
- SDG 15 (Life on Land): The program emphasizes land degradation, soil health, and land-use dynamics, thus contributing to preserving terrestrial ecosystems and promoting sustainable agriculture.
- SDG 4 (Quality Education): This course fosters inquiry-based learning and knowledge co-creation, helping develop critical scientific thinking and research skills.
- SDG 9 (Industry, Innovation and Infrastructure): Students explore innovation in agricultural engineering, including precision irrigation, sensor-based monitoring, and sustainable water infrastructure design.

Through SWAE4902, students are not only trained in technical research skills, but also encouraged to become thoughtful practitioners capable of translating academic knowledge into innovative solutions for sustainable development in soil and water resource management.

Table 3 showcases five student investigations illustrating our emphasis on interdisciplinary methods and applied learning, each contributing uniquely to soil ecosystem processes and SDGs. The projects range from the development of biodegradable hydrogels for improved soil moisture retention in arid regions to the AI-powered classification of traditional adobe architecture for cultural preservation (**Table 3**). Other students explore optimal hydrogel application strategies through experimental columns and HYDRUS-1D modeling, evaluate the effects of gravel content on infiltration and drainage in sandy soils, and examine the influence of soil texture on the distribution of native Omani tree species such as Sidr and Ghaf. These projects employ diverse methodologies, including laboratory analyses, numerical simulations, remote sensing, and fieldwork, and cultivate essential skills in data analytics, soil physics, modeling, and scientific communication. Moreover, the research outcomes extend beyond academic knowledge by reinforcing critical ecosystem services, such as water regulation, soil structural integrity, and vegetation support.

Figure 5 shows a vibrant snapshot of student engagement at SQU, where learning extends beyond the classroom. Students are actively involved in a dynamic blend of field experimentation (e.g., soil sampling and infiltration tests), along with sensor-based environmental monitoring and classroom-based hydrological modelling. Practical sessions also included the operation of technical equipment (e.g., drilling rigs and data loggers) to foster familiarity with the professional tools used in environmental research. This immersive, interdisciplinary learning environment bridges theoretical knowledge with real-world applications, thereby cultivating essential competencies in soil physics, hydrology, and environmental engineering.

TABLE 3 | SWAE4902: Selected student research projects summary during the Spring 2025 semester.

Title	Objectives	Activities involved	Skills gained	Link to soil ecosystem services	Linked SDGs
Natural hydrogel for water retention	Enhance soil water retention and antimicrobial activity using a natural hydrogel (sodium alginate + frankincense)	Hydrogel formulation, lab testing (FTIR, TGA), field validation with soil sensors	Polymer chemistry, soil physics, microbial analysis, lab instrumentation	Improves water holding, supports microbial balance, enhances plant water uptake	SDG 6, SDG 13, SDG 15
AI analysis of adobe architecture	Use AI to classify structural features and materials of heritage adobe walls in Nizwa and Izki	Image collection, model training with TensorFlow, classification, real-time Q&A interface	Machine learning, computer vision, cultural heritage analytics, Python programming	Preserves earthen architecture that depends on traditional soil compositions	SDG 11, SDG 9, SDG 15
Hydrogel application methods in sandy soil	Compare effectiveness of different hydrogel application techniques on water dynamics using HYDRUS-1D	Column experiments, modeling (HYDRUS-1D), RETC fitting, water retention and evaporation measurement	Soil-water simulation, lab experimentation, numerical modeling, irrigation management	Reduces water loss, enhances root-zone moisture, supports drought resilience	SDG 2, SDG 6, SDG 13
Role of gravel in water retention and drainage	Quantify how gravel percentages affect infiltration, retention, and hydraulic conductivity	Soil column tests, infiltration and drainage measurement, Ksat analysis	Soil physical analysis, experimental setup, data logging, water budgeting	Optimizes soil structure for irrigation, reduces erosion and nutrient leaching	SDG 2, SDG 6, SDG 15
Soil properties influencing native tree distribution under arid soil ecosystem	Assess how soil texture influences the growth of native trees like Sidr (Ziziphus spina-christi) and Ghaf (Prosopis cineraria)	Soil profile excavation, lab analysis (texture, EC, XRF), field surveys	Field soil analysis, GIS mapping, plant-soil relationship assessment	Supports afforestation, enhances biodiversity, improves root–soil synergy	SDG 15, SDG 13, SDG 2

FIGURE 5 | Students at SQU combining fieldwork, sensor use, modelling, and technical training to link theory with real-world soil and water management.

Soil Physics (Mandatory Course, 4th Semester): Advanced Study of Soil's Physical Behavior and Multiphase Interactions

The soil physics course, a core component of the BSc in Soil Sciences at MSU, is delivered in the fourth semester, following foundational instruction in mathematics, physics, chemistry, and introductory soil science. This course represents a pedagogically integrated approach to teaching that combines theoretical foundations with intensive hands-on experimentation and field-based learning (**Figure 6**). It is designed to teach students to analyze and quantify soil physical properties and regimes, which are fundamental to ecosystem functioning and environmental sustainability.

Integrated Instructional Design

The course architecture strategically combines lectures, seminars, laboratory practicums, and field training to foster a

FIGURE 6 | A comprehensive set of field and laboratory activities during soil science training in Chashnikovo and MSU: From left to right: (1) an experiment using Brilliant Blue dye to trace preferential water flow paths in soil profiles; (2) pressure filtration rate measurements across soil horizons; (3) evaluation of soil gas emissions; (4) morphological description of soil profile; (5) a student-led conference presenting results from hands-on soil physics practice; (6) flooded soil profile inspection after rainfall; and (7) filtration experiments.

comprehensive understanding of soil physical systems. Instruction emphasizes the dual development of foundational theory and applied skillsets, thereby enabling students to diagnose and interpret physical soil characteristics in diverse environmental contexts.

Lecture Delivery and Engagement

A total of 48 classroom hours—comprising 24 lectures—cover essential domains such as solid-phase physics, unsaturated flow and soil water retention, gas and thermal regimes, mass and heat transfer, soil deformation, and introductory mathematical modeling of mass transport. Lectures are designed for interactive learning, involving blackboard-based notetaking, open discussions, and active questioning. Theoretical exposition is augmented by visual media (e.g., slides, photographs, and graphs) to reinforce conceptual understanding and contextual relevance.

Seminar-Based Deepening of Knowledge

Seminars are delivered in small groups (8–12 students), providing a platform for personalized academic engagement. The sessions include problem-solving exercises, theoretical dialogues, and student-led presentations. Advanced topics, such as laser diffractometry and sedimentation analysis, are explored through infographics and technical summaries, thus enhancing both subject mastery and communication skills.

Laboratory Practicum and Experimental Training

Students engage in weekly laboratory sessions (five academic hours), each working with a unique soil sample, to assess its physical properties such as bulk density, porosity, water content, infiltration rate, and compaction behavior. This practicum emphasizes procedural design, methodological selection, and data interpretation, supported by detailed manuals and individualized data cards. Since soil samples for each group are collected from different layers of the same soil profile, students have the opportunity to collectively discuss and evaluate the soil properties and functions in relation to SDGs toward the end of the course. The immersive laboratory experience fosters autonomy, precision, and scientific reasoning.

Assessment and Evaluation Framework

Students' academic progress is regularly monitored during the semester. This includes checking the results of an experimental analysis of soil properties conducted by a student in a laboratory setting. To do this, each student completes an individual workbook that records their findings. Theoretical knowledge is assessed through tests. High-performing students may qualify for exemption from the final examination based on sustained excellence throughout the semester. This incentive motivates students to study consistently throughout the course.

Field Practice and Research Integration

A two-week summer field training session at the Chashnikovo Soil Ecology Center immerses students in real-world terrain featuring diverse soil types and vegetative covers. Students analyze soil profiles and measured physical parameters, including hydrological flow, thermal gradients, gas exchange, and pressure conditions. The instruments are calibrated on-site, and a comparative analysis of the measurement methods is encouraged. Each student group designs and conducts a small research project—ranging from waterlogging impacts to compaction studies—promoting experiential inquiry-based learning.

Capstone Outputs and Communication

Field experiments culminate in detailed student-authored reports, followed by group presentations at student-led conferences. These activities emphasize the synthesis and articulation of findings. Select projects are also presented at the prestigious annual MSU "Lomonosov" student conference and other academic forums, highlighting the course's integration into the university's broader research culture.

Competency Development and Relevance to Ecosystem Services

This course cultivates essential competencies in experimental soil physics, environmental monitoring, analytical reasoning, scientific documentation, and collaborative inquiries. It equips students to interpret physical soil data in the context of land use and ecological stability. It focuses on applying this knowledge to sustain critical ecosystem services, including the following:

- Water infiltration and retention processes.
- Soil structural resilience under mechanical stress.
- Regulation of gas and heat exchange.
- Enhancement of land productivity through informed soil management.
- Selection and maintenance of *suitable foliage* based on the soil moisture regime, compaction level, and aeration capacity.

By training students to assess how soil physical behavior influences vegetation compatibility, the course strengthens their understanding of plant–soil interactions and supports integrated decisions in agroecosystem planning and ecological restoration. The resulting knowledge base enables graduates to contribute meaningfully to sustainable land management, conservation practices, and adaptive responses to environmental changes.

LIMITATIONS AND PRACTICAL CHALLENGES

Despite encouraging outcomes from the pedagogical strategies we have presented, implementation revealed several hurdles. Group-based activities sometimes led to uneven participation and varied individual learning gains—a pattern widely reported in inquiry-based learning contexts (e.g., Beers, 2005; Hupy, 2011). Two factors were most salient: insufficient ongoing evaluation during the project and, in some cases, interpersonal frictions or limited interest among certain students. Although these behaviors can hamper project activities, they are often masked by aggregate group performance. Such challenges are well documented in inquiry-based teaching group work (Beers, 2005). Mitigation approaches include structured peer assessment within teams and an overarching appraisal of each member's contribution by the designated group leader via a direct report to the instructor. Assessing multi-component tasks that span fieldwork, laboratory analysis, modeling, and presentation remained complex. Riga et al. (2017) highlighted similar issues for instructors in evaluating the performance of inquiry-based teaching for multi-component student activities. Field-intensive, research-based courses impose substantial time and logistical demands on both students and staff (Brew and Mantai, 2017). As a result, commitment can wane over time (Spronken-Smith et al., 2011). To alleviate instructor fatigue, in programs, measures could be taken to establish rotation systems for new faculty; recruit graduate teaching assistants; and enlist former students as short-term evaluators and assistants, particularly during field activities. Gaps in scaffolding between phases and courses, as in the Omani case, were evident, with downstream effects on open-inquiry tasks. Student feedback also indicated that links to sustainability and Oman-specific conservation priorities were not always explicit. Analogously, Lazonder and Harmsen (2016) highlighted persistent challenges in linking the three tiers of inquiry-based teaching scaffolding. As preparation for Phase III projects (**Figure 1**), students benefit from a concise refresher of relevant fundamentals from earlier courses. We also recommend circulating recent, topic-aligned research articles prior to fieldwork. Instructors should continually develop novel Phase III project themes to engage new cohorts and avoid repetition across years. As Brew and Mantai (2017) argue, effective inquiry instructors are active researchers who design assignments that are "wicked" authentic and complex yet still comprehensible and manageable within the constraints of time, logistics, and resources. Competition- or research-oriented pedagogies are prone to productivity losses when teams are oversized and tasks lack sufficient granularity—conditions that elevate the risk of "social loafing" (Aggarwal and O'Brien, 2008). In our context, groups of 5–10 students proved sub-optimal: workload distribution became uneven, role ambiguity increased, and attendant frustration emerged, with measurable declines in both group and individual efficiency (see Wheelan, 2009). Optimal team size is contingent on the number of discrete roles and the complexity of assigned tasks; when these are mismatched, idle time is difficult to avoid. Finally, ambiguity regarding authorship and credit occasionally arose in research–teaching outputs (e.g., the Research Projects in Soil, Water, and Agricultural Engineering—SWAE4902). To ensure transparency and academic integrity, sponsoring agencies should adopt clear, public guidelines for publication and award attribution, and universities should promulgate explicit policies defining undergraduate contributors' roles, including criteria for co-authorship on scientific papers and conference presentations (see Rasmussen et al., 2020).

DISCUSSION AND CONCLUSION

Soil science is at a crossroads. As one of the most vital yet underrepresented disciplines in the global sustainability agenda, its educational paradigms must evolve to meet the complexity of 21st-century challenges. Although soils are central to food security, water quality, climate regulation, and biodiversity—the core pillars of the SDGs—soil science education remains largely siloed, technically focused, and insufficiently aligned with sustainability frameworks. This manuscript presents two case studies that illustrate fundamental transformations with regard to how we teach, learn, and apply soil science. The approach presented can help overcome problems identified by a recent European stakeholder survey of 24 countries (Veenstra et al., 2024), showing gaps in soil science education in terms of systems thinking, stakeholder communication, and an integrated understanding of soil science functioning in an inter- and transdisciplinary context. A focus on ecosystem services provides a structural link with the UN SDGs. At SQU (Oman), the BSc in Soil Sciences program was deliberately structured as a whole-of-program reform anchored in graduate attributes, with explicit alignment of learning outcomes and assessments to SDGs articulated through the contributions of soil to ecosystem services in arid Omani contexts. To our knowledge, few (if any) undergraduate soil programs have involved a comparable degree-level redesign rather than piecemeal course revisions, underscoring the distinctiveness of the SQU model. This approach aligns with Spronken-Smith et al.'s (2011) perspectives, who note that "the focus on graduate attributes, together with the holistic consideration of the degree program rather than on a piecemeal course-by-course basis, allowed the development of a coherent program, progressively building skills and knowledge through to graduation." Revitalizing soil-science education is not a supplementary curricular innovation but a strategic imperative. Embedding ecosystem service thinking, systems-based pedagogy, and SDG-linked outcomes into curricula is essential for repositioning soil education as a cornerstone of sustainability science. Training students to assess, manage, and communicate the multifunctionality of soil through interdisciplinary, inquiry-driven, and stakeholder-informed models will cultivate professionals equipped with technical expertise, ethical foresight, a transdisciplinary vision, and action-oriented thinking.

Case studies from SQU (Oman) and MSU (Russia) demonstrate how transformative pedagogy (through debate-based learning, research–teaching integration, hydropedological modelling, and field-based collaboration) can produce graduates capable of translating soil knowledge into policy impacts, community engagement, and resilience-building strategies. These programs show that when soil is framed not merely as a scientific subject, but as natural capital fundamental to planetary health, students emerge as sustainability stewards prepared to drive change across sectors.

To unlock soil science's full potential in service of the SDGs, HEIs must embed soil literacy at the heart of sustainable development education. Doing so will not only elevate the visibility and relevance of soil-science globally but also empower a new generation of professionals capable of safeguarding the Earth's most life-sustaining resource.

To realize soil-science education's transformative potential, various strategic actions are recommended. First, the curricular integration of the SDGs must be prioritized. Programs should explicitly embed SDG 4.7 and related targets into course outcomes, design, and assessment frameworks. Creating course matrices that link soil properties to ecosystem services and specific SDG indicators will enhance the conceptual clarity and applied relevance. Importantly, these transformations must be implemented at the program level (rather than limited to individual courses) to ensure coherence, scalability, and sustained institutional impact.

Second, there is a pressing need to promote interdisciplinary pedagogy. Soil-science curricula should be broadened to include linkages with environmental engineering, public health, economics, and policy studies to reflect sustainability challenges' systemic nature. Simultaneously, stakeholder-informed curriculum development should be actively pursued. Collaboration with farmers, policymakers, urban planners, and non-governmental organizations can ensure that educational content remains locally grounded while addressing complex real-world issues.

Another critical recommendation involves strengthening the research–teaching nexus. Embedding student-led research projects, living laboratories, and community-engaged science in undergraduate programs fosters experiential learning and cultivates scientific agencies. In support of this, institutions should focus on the modernization of tools and technologies by equipping students with skills in HYDRUS modeling, GIS, remote sensing, data analytics, and tools essential for modern environmental decision-making.

Further, students should be prepared to function as policy advocates and knowledge brokers with dedicated training in science communication, sustainability discourse, and participation in policy platforms such as intergovernmental committees. Global collaboration and mobility have a significant potential. Joint degree programs, field exchanges, and cross-institutional teaching partnerships can expose students to diverse soil systems and sustainability strategies.

Faculty development and institutional incentives are essential for sustaining such innovations. Training educators in sustainability pedagogy, transdisciplinary approaches, and co-creation techniques will build instructional capacity, and the recognition of teaching excellence should be institutionalized. Additionally, establishing longitudinal impact assessment frameworks could help monitor the effectiveness of SDG-integrated curricula on graduate skills, civic engagement, and professional success.

Finally, we call for greater visibility of soil in SDG policies and discourse. Advocating the explicit recognition of soil systems in UN documents, national education strategies, and sustainability science literature is vital for positioning soil science as a key discipline for achieving global development goals.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

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

SA-I and AU made substantial contributions to the study concept/design and drafting of the manuscript. JB revised the manuscript critically for important intellectual content. All authors contributed to the article and approved the submitted version.

FUNDING

The author(s) declare that financial support was received for the research and/or publication of this article. This work was funded by Sultan Qaboos University, projects no. RC/AGR/SWAE/17/01 and IG/AGR/SWAE/24/01.

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.

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ACKNOWLEDGMENTS

Special thanks to Sajia Said Al-Ismaily for her work on the infographics, and to Prof. Anvar Kacimov for his valuable support. Helpful comments and critiques by referees are appreciated.

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