Transdisciplinary education for reducing environmental impact of AEC industry

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Abstract: *The Architecture, Engineering, and Construction (AEC) industry plays a crucial role in shaping the built environment but contributes significantly to environmental impact, accounting for nearly 40% of global energy-related carbon dioxide emissions. An interdisciplinary systematic literature review (SLR) explores how transdisciplinary education (TDE) can be integrated into AEC curricula to address environmental sustainability challenges. TDE facilitates students' understanding of the environmental impact (EI) of their design projects and equips them with the knowledge and skills to develop sustainable solutions. This review examines various pedagogical models, including problem-based learning, to evaluate their effectiveness in fostering TDE for reducing EI in the AEC sector. Findings from the literature are synthesized to present a framework aligned with sustainable development goals (SDGs) that promotes sustainability in AEC education. The review aims to inform future research and curriculum development, advancing the role of education in equipping future professionals to mitigate environmental impacts in the AEC industry.*

Keywords: Transdisciplinary education, environmental impact, AEC curriculum, sustainable building design

1 Introduction

The AEC industry comprises architecture, engineering, and construction, and has a crucial role in the design, construction, and management of the built environment. Simultaneously, the AEC industry has a significant environmental impact (EI) due to high greenhouse gas emission levels. According to the United Nations Environmental Programme (UNEP), the construction sector contributes nearly 40% of global energy-related carbon dioxide emissions (Ahmetoğlu & Tanık, 2020). Various studies (Hyun, 2012; Almusaed et al., 2023; Dou et al., 2024) highlight the critical need for the industry to adopt sustainable practices to reduce its impact. Recent advancements in

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sustainable building design (SBD) have focussed on the development and use of green building materials (Patel & Patel, 2021; Sharma & Sharma, 2022), energy-efficient building systems (Pacheco et al., 2012), and sustainable construction practices (Pitt et al., 2009).

Most current universities and educational systems are based on a single-disciplinary style, although various attempts have been made for education to shift to interdisciplinary or transdisciplinary approaches to meet real-world expectations (Max-Neef, 2005; Després et al., 2010; del Cerro Santamaría, 2019, 2020). Transdisciplinary education (TDE) requires opening the boundaries of disciplines to integrate to see a variety of situations and investigate problems through interdisciplinary thinking to enable resolving and identifying solutions (Lawrence, 2010; Nicolescu, 2012; Gibbs, 2016; Daneshpour & Kwegyir-Afful, 2022).

TDE has the potential to integrate environmental sustainability (Clark & Button, 2011; del Cerro Santamaría, 2019; Lawrence, 2022) into the curriculum of AEC disciplines (Ibrahim et al., 2007; Oliveira et al., 2022; Tadesse & Cavka, 2023; Lawrence, 2024). TDE in the AEC industry can facilitate students with a comprehensive understanding of the EI (Walter et al., 2007; Ertas, 2010; Tasdemir & Gazo, 2020) of their design projects and provide them with the knowledge, skills, and experience to develop and test innovation solutions that reduce EI (Steiner & Posch, 2006; McEwen, 2013).

This interdisciplinary systematic literature review (SLR) (Burgers et al., 2019) aims to investigate various pedagogical models (Lehmann et al., 2008; Belluigi & Cundill, 2017) including problem-based learning for enabling TDR to reduce EI in the AEC industry. The main goal of this systematic literature review is to identify and evaluate existing research, which shows evidence or has the applicability to be integrated for the TDE into AEC curricula. The review aims to synthesize findings on how TDE can enhance students' understanding of environmental impacts to equip them with the necessary skills to create sustainable and innovative solutions in the AEC industry. Section 2 explains the undertaken methodology for the review article in detail approaches to theory development, development of search protocol, identification of search strings, and databases, and data analysis techniques. Section 3 presents the interdisciplinary systematic literature review, and thematic analysis introducing themes and subthemes supported by evidence from included studies. Section 4 presents the TDE framework aligned with sustainable development goals (SDGs) to instil reduction of EI by increasing notions of sustainability in AEC curricula. Section 5 presents the discussion identifying key research findings; comparison with other frameworks; and potential methodological constraints. Section 6 outlines the conclusions of the research; implications for academia, industry, and wider public; and future research directions to address unanswered questions, and gaps in the literature.

2 Methodology

The research relies on inductive approaches for analysing studies to form a theory that could explain the patterns in research related to TDE, reducing EI, and enhancing AEC curricula. For the search protocol to be robust, reliable, and interdisciplinary, the research relied on the design of a systematic literature review (SLR). The SLR (Kitchenham, 2004; Kitchenham et al., 2011) was conducted to identify studies related to TDE for reducing EI of the AEC industry, the overarching research aim.

Search strings ("problem-based learning" for "transdisciplinary education"; transdisciplinary education for reducing environmental impact of AEC industry; transdisciplinary collaboration for reduced carbon emissions by AEC industry; "problem-based learning" for AEC students; problem-based learning and transdisciplinarity for improving sustainability curriculum; and transdisciplinary collaboration for reducing environmental of AEC industry) were used to accumulate studies indexed on ScienceDirect, JSTOR, and MDPI to identify 317 studies. The next step entailed the deletion of duplicates, followed by a screening of keywords. A total of 126 studies were scanned by their titles and abstracts, leaving 110 studies. An inclusion and exclusion criteria were established. The inclusion criteria comprised online accessibility of research published in English and related to TDE, EI reduction, and AEC industry. Exclusion criteria entailed research published as opinion papers, short communication, case reports, or pilot studies. 94 studies were included in the interdisciplinary systematic literature review. The identified studies were used to develop themes to propose a TDE framework aligned with sustainable development goals (SDGs) to instil reduction of EI by increasing notions of sustainability in AEC curricula.

3 Interdisciplinary systematic literature review

The review results identified three main themes, which included advances in core theoretical ideas aiding TDE; best practices from built environment and AEC disciplines; and interdisciplinary collaboration (IDC)/transdisciplinary collaboration (TDC) concepts from other disciplines.

3.1 Advances in core theoretical ideas aiding TDE

Advances in core theoretical ideas supporting TDE are associated with crucial research findings linked to interdisciplinary bridges for problem- and solution-oriented research; novel advancements to educational structures to promote TDE; and systemic advancements for achieving TDE.

3.1.1 Interdisciplinary bridges for problem- and solution-oriented research

The development of problem- and solution-oriented research relies on the formation and development of transdisciplinary thinking (Klein, 2004). Additionally, transdisciplinary thinking stems from the need for a transdisciplinary attitude aided by transdisciplinary capacity linked to interdisciplinary education and IDC (Figure 1). Transdisciplinary attitude and transdisciplinary capacity are not just relevant for problem- and solution-oriented research, but also enable the creation of interdisciplinary bridges to promote cooperative societal culture across various disciplines for conceptualising, designing, and developing sustainable solutions (Klein, 2004).

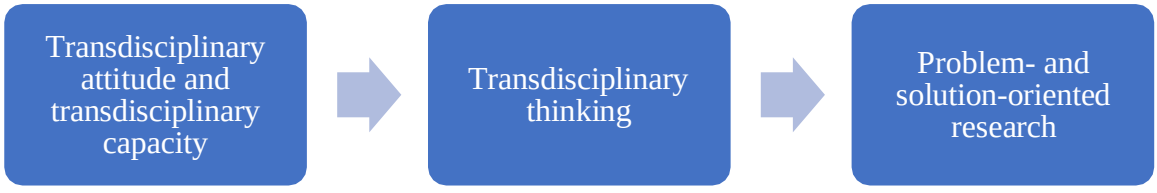

Figure 1: Progressing towards problem- and solution-oriented research.

Robinson (2008) specified that interdisciplinary bridges for resolving complex societal problems require characteristics related to issue-driven interdisciplinarity, such as integration, interactivity and emergence, reflexivity, and partnership. While institutions and universities continue to work in silos, issue-driven interdisciplinarity supported by participatory approaches can be institutionalised in the prevailing disciplinary culture of various universities (Pasquier & Nicolescu, 2019). An example is the study conducted by Tötzer et al. (2011) in which the industrial city of Steyr, Austria was explored. The region competes with other regional industrial centres in the automotive sector. Transdisciplinary approaches such as interviews, photo elicitation, workshops and scenario building are used to identify local strategies to cope with the global competition (Tötzer et al., 2011). Transdisciplinary approaches led by interdisciplinary bridges supported by participatory approaches seemed to be more advantageous than expert solutions in regions with a long industrial history and tradition as they have more in-depth stakeholder engagement to develop bespoke strategies and initiate joint learning and long-term change processes (Tötzer et al., 2011).

A few principles are directly applicable to AEC curricula and the implementation of TDE, such as problem-solving through holistic thinking and collaboration through the integration of transdisciplinary approaches by problem-based learning (PBL) to enhance the effectiveness of educational strategies and prepare future professionals to tackle environmental issues within industry (Patricia, 2012). Imperatively, these principles align with the ethical imperative of promoting sustainability and environmental responsibility in the AEC field. Similarly, Clark and Wallace (2015) focussed on designing a policy sciences framework as a practical interdisciplinary meta-framework reliant on problem orientation, social process, decision process, multiple methods, standpoint and common interests to guide education and encourage problem- and solution-oriented research. From a broader perspective, a pragmatic and reflexive approach to transdisciplinarity in sustainability research can uncover assumptions and underlying research practices to enhance social learning and experiments pivotal for sustainability transitions (Popa et al., 2015).

Four aspects of reflexivity (normative and epistemic orientation of research; socially relevant framing of research problems; generative reflexivity on values and problem-solving and social experimentation processes; and generative reflexivity on normative commitments and ideological orientation in social transformative processes) have been classified that can cultivate competencies for sustainability (Popa et al., 2015) and equip AEC professionals to engage in mutual learning and address ill-defined problems to resolve gaps in industry and research (Figure 2).

Embedding TDE to reduce EI of the AEC industry and promote education for sustainable development (ESD) can be onerous, as Zguir et al. (2022) explored that the integration of sustainability values should not contradict with local values moving beyond subjects' compartmentalisation.

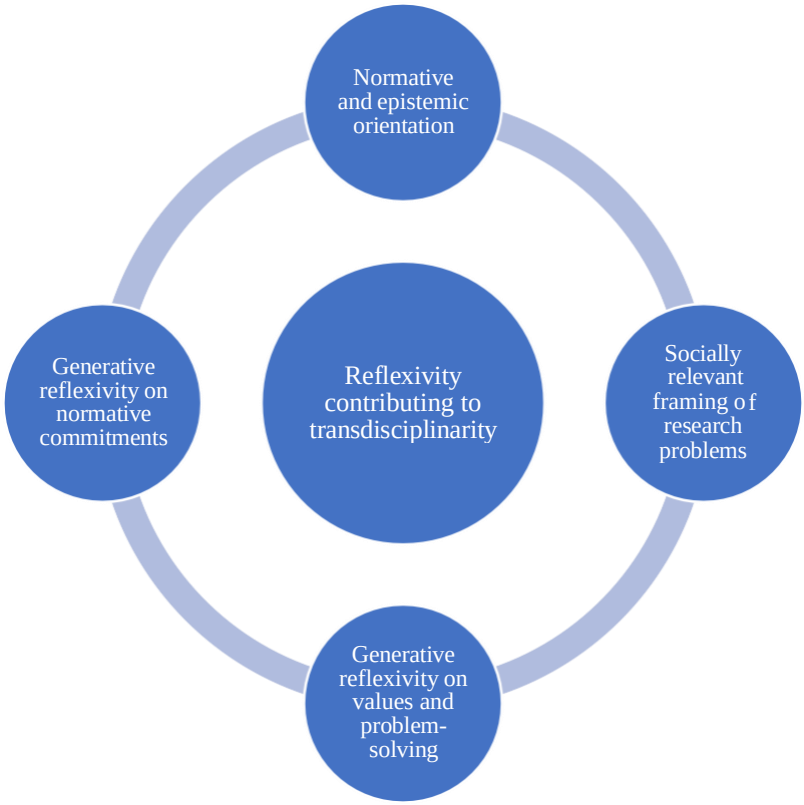

Figure 2: Reflexivity contributing to transdisciplinarity.

3.1.2 Novel advancements to educational structures to promote TDE

Innovation in educational structures tends to promote TDE, e.g., through the pursuit of double degree programmes, even if not focussed on sustainability may reveal nuances supporting interdisciplinary thinking (Russell, Dolnicar, et al., 2008). The sustenance of double degrees requires robust support structures and clear communication for mitigating interfaculty/interdepartmental challenges to maximise the potential of interdisciplinary education (Russell, Dolnicar, et al., 2008), and to design effective TDE programmes for a more sustainable built environment.

Another example relates to the heuristic reflective tool for TDR developed by Gaziulusoy and Boyle (2013) to integrate disciplinary knowledge and stakeholder perspectives. This four-stage tool focuses on reflective questions and narrows down from paradigm filters to problem/solution filters to context/scope filters to knowledge/skills filters and can be crucial for developing comprehensive educational frameworks (Gaziulusoy & Boyle, 2013). TDE can also be implemented to transdisciplinary doctoral programmes in sustainability having significant relevance to the AEC sector's education paradigm (Muhar et al., 2013; Ertas, 2016).

However, these programmes need structure to introduce core transdisciplinary concepts (sustainability challenges; complex systems and complexity theory; research paradigms, methodologies, and methods; and transdisciplinarity and transdisciplinary research) to prepare doctoral students for empirical practice and engage in regular interdisciplinary dialogue and team-building processes (Muhar et al., 2013). Application of novel advancements to educational structures includes the use of systems thinking and problem-based learning for TDE in built environment disciplines (Gray et al., 2014). Best practices in transdisciplinary projects are summarised in Figure 3.

A literature review exploring critical attributes of sustainability in higher education (Viegas et al., 2016), specified that interdisciplinary collaboration led by experiential learning and community engagement enhances critical thinking and problem-solving abilities. Their findings encompassed (i) epistemologies of sustainability in higher education develop in a learning context; (ii) creativity links to foundational and personal assets; (iii) transdisciplinarity is an epistemic transgression; (iv) resilience of active learners emerges in knowledge and personal assets relationship; (v) unlearning and knowledge deconstruction forms active learning; and (vi) personal assets need to fit complex dynamics of reality. While Russell, Dolnicar, et al. (2008) focused on double-degrees; Tang and Werner (2017) explored the impact of a two-week intensive programme applying an interdisciplinary and intercultural approach to maximise creative self-efficacy and creativity levels. This study and another study (Zguir et al., 2022) build the notion of developing an early understanding of preparing students for TDE before entering higher education. It is also pivotal to determine when these students progress to higher education and why they consider doing transdisciplinary research (Guimarães et al., 2019).

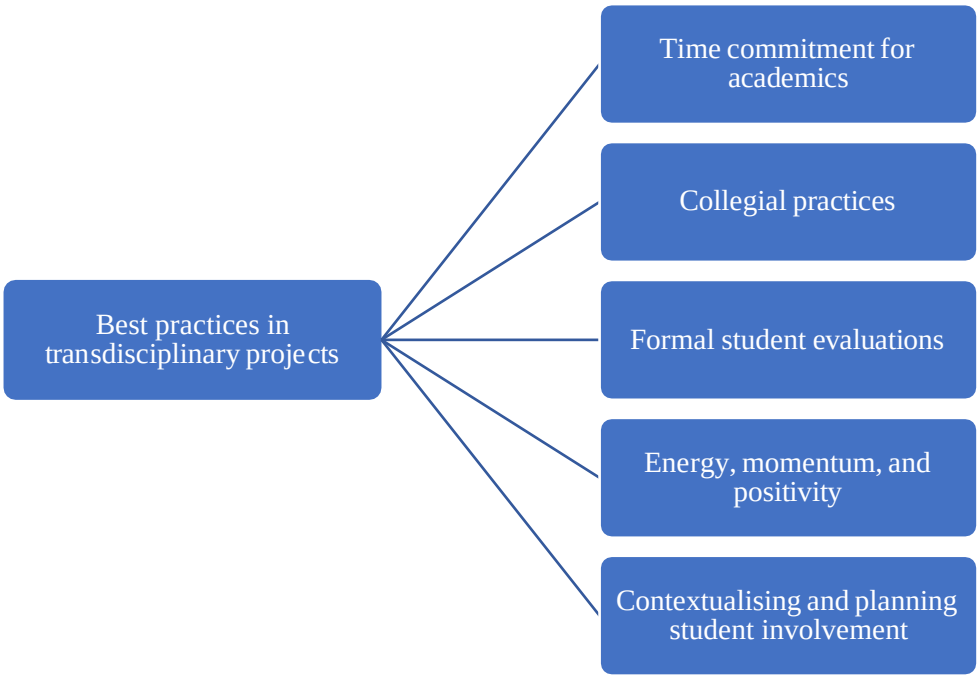

Figure 3: Best practices in transdisciplinary projects.

Interdisciplinary and transdisciplinary researchers (ITDR) form due to a variety of motivations, attitudes, skills, and behaviours and often develop through quadrangulation of disciplinary depth, multidisciplinary breadth, interdisciplinary integration, and transdisciplinary competencies (i.e., T-shaped training) (Guimarães et al., 2019). While this can be a possible career path, the academic environment is not prepared and adapted for ITDRs and requires the exploration of interdisciplinarity or transdisciplinarity to be more conducive for this type of research and education (Guimarães et al., 2019). Higher education institutions (HEIs) also have an essential role in co-creation of social innovation by encouraging collaborative learning tools focused on open platforms and systemic change to engage society and strengthen social stakeholders' collaboration (Kumari et al., 2020). Their framework model for co-creation for social innovation stems from internal and external changes, while the former contributes to learning theories, whereas the latter links to a systemic approach. These changes combine with several new roles of HEIs, which include facilitating learning from each other; blurring the boundaries; collaborative research and entrepreneurship; network facilitation and proactive collaboration and new collaborative physical spaces (Kumari et al., 2020). Other recent advancements include the creation of sustainability-oriented labs entailing (1) fix and control; (2) (re-)design and optimize; (3) make and relate; (4) educate and engage; (5) empower and govern; and (6) explore and shape (McCrory et al., 2022). Sustainability-oriented labs not only have the potential to inform TDE initiatives aimed at promoting sustainability in the AEC industry but also led to three new dimensions of sustainability related to focused sustainability object; overall sustainability orientation; and lab properties (McCrory et al., 2022). Building further from the concepts delineated by Russell, Dolnicar, et al. (2008) and Tang and Werner (2017); Vidergor (2023) presented the proposal of a novel transdisciplinary subject called "Future Studies" related to a novel literacy called future thinking literacy – a literacy that integrates language, digital/information, and scientific/critical literacies and can enable elementary and secondary school learners to explore any topics or disciplines that they study taught in a learning environment named LIFTS (Learning in Future Thinking Societies. Multidimensional Curriculum Model (MdCM) allows the implementation of a transdisciplinary curriculum for students to propose sustainable futures due to its basic three dimensions (content – multidisciplinary/transdisciplinary; process – teaching-learning strategies; and product – multi-categorical, creative, and innovative) and three additional dimensions (personal, creative, and time) as these facilitate learners to view and examine topics from various aspects and angles (Vidergor, 2023).

3.1.3 Systemic advancements for achieving TDE

Systemic advancements focused on top-down or bottom-up approaches influence progress to achieve TDE. Universities need reward IDR generated from IDC and problem-oriented approaches (Kueffer et al., 2012). Additionally, various HEIs must integrate sustainability into their curricula and embrace transition management concepts to inculcate cultural and institutional changes. Supportively a framework called the radically inter- and transdisciplinary environment (RITE) framework was designed by Holm et al. (2013) to advocate the combination of natural, social, human, and technical sciences from the commencement of research projects. Transdisciplinary frameworks in AEC education have the potential to enhance educational programs to innovate solutions for reducing environmental impacts (Holm et al., 2013).

Overarching examples include UNESCO Chairs and UNITWIN Networks to foster inter-university cooperation that can bridge current gaps related to evaluating sustainability performance and advocacy of integrated methods (Wals, 2014). HEIs continue to reorient themselves and make systemic changes to enable increased sustainability awareness through education; research; operations; and community outreach activities due to UNESCO ESD Chairs' role of conceptualizing learning, competence and systems change (Wals, 2014). To enable this evaluation and reorientation, researchers have attempted to answer the questions of how to evaluate a scientist's knowledge transfer in a project; and how can the "*transdisciplinary effect*" of scientific projects, and/or publications be evaluated (Kogtikov et al., 2016). Their study formulated successful quantification of knowledge transfer and integration among participants in collaborative projects leading to potential evaluation of compliance of a scientific team working on a TDR project and also assessing students' skills and abilities in transdisciplinary environments (Kogtikov et al., 2016).

Assessing students in transdisciplinary environments in several graduate programs may contribute to the development of the next generation of sustainability scientists (Figure 4), although this transdisciplinary environment may not be available in all graduate programs that support integrative approaches, usually requiring external opportunities (Güvenen, 2016; Killion et al., 2018). An experiment entailing a group of doctoral students from universities across the United States of America with numerous disciplinary backgrounds who participated in integrative research training to learn and develop socio-environmental research skills showed that students faced common barriers such as lack of exposure to epistemological frameworks and team-science skills; challenges to effectively include stakeholder perspectives in their research; and variable levels of committee support to conduct integrative research (Killion et al., 2018).

The tendency to offer training to graduate or doctoral students to inculcate sustainability competencies is associated with socio-economic structure of the related HEI potent to any possible systemic change (Demssie et al., 2019). Contexts with low per capita income, limited infrastructure, and rural populations need different systemic changes for TDE to promote sustainability competencies than other countries (Demssie et al., 2019). Their Delphi study related to experts from academia and industry led to the identification of eight sustainability competencies related to the Ethiopian context, which included: (1) transdisciplinary competence to collaborate with diverse sustainability experts; (2) flexibility and continuous learning; (3) communication and information acquisition; (4) stakeholder and policy coordination; (5) resource utilization; (6) social justice and inclusion; (7) competence to balance sustainable development dimensions; and (8) competence to utilize indigenous resources for sustainability (Demssie et al., 2019).

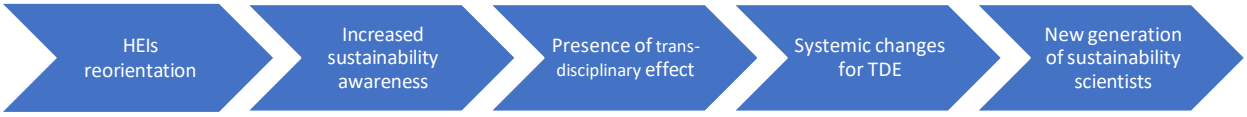

Figure 4: Developing the next generation of sustainability scientists.

Systemic changes for TDE in AEC curricula may rely on SDG 4 (Quality Education) in combination with SDG 12 (Responsible Consumption and Production) (Dhara & Singh, 2021).

However, this study reflects that this combination conflicts with SDG 8 (Decent Work and Economic Growth). Therefore, a successful systemic change towards TDE in AEC curricula will need the development of a deeper awareness of empathy and consequences of inequalities at various scales to encourage the discussion between social inequality, sustainability, climate change, and economic growth, bringing students and staff closer to the intersection of SDGs 10 (Reduced Inequalities) and 13 (Climate Action) (Dhara & Singh, 2021). This approach enables students to question their lifestyles and relationships with the concepts and sub-concepts of sustainability to design sustainable buildings and define a sustainable lifestyle. This pathway to TDE incorporated in AEC curricula will allow rethinking, reinventing, and renegotiating taken-for-granted concepts related to endless growth to understand wellbeing for responding to the troubled relationship humans have with nature.

TDE towards complex societal challenges such as rising sea levels also needs indigenous knowledge (Richmond et al., 2023). When inculcating similar scenario-based design projects in AEC curricula, it is essential to embed the concepts of creating partnerships between academia, local communities, and tribes to face climate change for contributing to sustainable practices in the AEC industry (Richmond et al., 2023). The outcome of the inclusion of local tribes enriches educational outcomes and empowers communities to participate in environmental stewardship actively. Similarly, if AEC degree programmes are designed to support the development of a sustainability mindset, sustainability literacy, and creative confidence, they can develop sustainability changemakers who are people with strong sustainability values, wide range of skills and competencies who can apply sustainability transitions on individual, organisational, and system levels (Macagno et al., 2024). The development of a new generation of sustainability scientists (Killion et al., 2018); and sustainability changemakers (Macagno et al., 2024) has a synergetic relationship with the combined transformative potential of Industry 5.0, University 5.0, and Education 5.0 (Hashim et al., 2024). This combination was further explored using a tetra-dimensional empirical model to integrate 5.0 in higher education, comprising a theoretical dimension, application dimension, technical dimension, and practice dimension (Hashim et al., 2024). The education of meta-competencies can be an output of this model, which may prevail due to diverse perspectives from system and innovation research, management science, engineering, arts, and humanities encouraging iterative learning, resilient improvisation, dynamic viability, and sustainable innovation (Zenk et al., 2024).

3.2 Best practices from built environment and related disciplines

Best practices from built environment and related disciplines identified various research findings linked to educational innovation in environmental studies and green building studies; implicit knowledge co-creation supporting TDE for the future of AEC curricula; and scenarios of interdisciplinary teaching approaches.

3.2.1 Educational innovation in environmental studies and green building studies

Evidence of innovative ideas stemming from environmental studies and green building studies prevails in academic literature for over two decades (Gruenewald, 2004). This study used a Foucauldian lens to explore what causes environmental education to often become a disciplinary

practice evading its purpose of addressing ecological and social issues. Signposting to the Earth Charter, it is proposed as a visionary text to guide educational theory and practice to prevent any neglect faced by environmental education (Gruenewald, 2004). Evidently, an experimental course called "Angles of Green Building" at the Centre for Interactive Research on Sustainability, Simon Fraser University (Holden et al., 2008). Instructors and lecturers must be transformative learners themselves to ensure transformative learning among students to design, run and implement courses in sustainability topics that enable students from various backgrounds and levels to engage and take responsibility to transform their behaviour in favour of sustainability (Holden et al., 2008). In a similar effort at California State University, Northridge, USA, seven faculty members partnered to develop and teach a 15-week undergraduate course on sustainability (Kurland et al., 2010). The course showed that the inclusion of practicum experiences, e.g., hands-on projects reinforces integrative learning to allow students to apply theoretical knowledge to real-world sustainability issues therefore reinforcing organisational change and faculty commitment as vital elements for the development of interdisciplinary courses (Kurland et al., 2010). Comparable attempts have also been made at a doctoral level, e.g., the curriculum of Integrative Conservation (ICON) at the University of Georgia, Athens, USA, intertwining integrative approaches, experiential learning, and strategic communication (Welch-Devine et al., 2014). The study proves that the ICON programme could be an example worthy of replication as it was able to overcome several hurdles for inter- and transdisciplinary teaching (Welch-Devine et al., 2014), however campus planning, students' departmental obligations need to be aligned for TDE in the AEC to succeed.

Therefore, architectural education needs a readjustment to assimilate practice-based learning in design studios and utilise new methods and tools beyond disciplinary types of knowledge production for future architects to respond optimistically, alternatively and creatively to establish future career paths oriented towards sustainability (Charalambous & Christou, 2016). The research findings of Sahakian and Seyfang (2018) on sustainable consumption education emphasize the importance of transdisciplinarity in teaching sustainable practices, aligning with your review on reducing the environmental impact of the AEC industry through interdisciplinary approaches. Their identified challenges, such as the complexity of sustainability issues and the need for a broader systems perspective, resonate to integrate transdisciplinary methods in education. Similarly, Boarin and Martinez-Molina (2022) highlight the shift from content-focused curricula to pedagogical approaches that foster active engagement and practical application within architectural education. This approach aligns with the principles of TDE, advocating for a holistic, multidisciplinary framework that equips future professionals with the skills to address complex environmental challenges (Butt & Dimitrijević, 2022, 2023). Both studies reveal the need for integrating sustainability into educational practices to enhance environmental outcomes and support sustainable development within the AEC sector.

3.2.2 Implicit knowledge co-creation supporting TDE for the future of AEC curricula

TDE plays a pivotal role in shaping the future of curricula within the Architecture, Engineering, and Construction (AEC) sector by integrating diverse knowledge systems and fostering collaborative learning. Evely et al. (2010) highlight the importance of engaging both academic and non-academic stakeholders, emphasizing that transcending traditional disciplinary boundaries is crucial for addressing complex problems. This aligns with TDE's core principle of collaborative

learning through multiple perspectives, essential to tackle the multifaceted challenges prevalent in the AEC industry. Fortuin et al. (2011) further this notion by advocating for an educational framework that combines physical and social sciences. Their emphasis on integrating these disciplines facilitates a structured response to environmental challenges and resource management, emphasising the need for cross-disciplinary collaboration and stakeholder engagement.

In architectural education, Salama (2012) advocates for a systemic pedagogy that aligns with TDE principles by focusing on human behaviour and sustainable planning. This approach highlights the need for integrating various knowledge domains to mitigate environmental impacts. Lozano et al. (2013) extend this argument by proposing that sustainability competencies should be embedded across all curricula, rather than being confined to specialized programs. This holistic approach enhances systems thinking, preparing future professionals to effectively address sustainability challenges.

The role of co-creation and inclusive design in addressing urban challenges is emphasized by Rizzo and Galanakis (2015), who stress the importance of engaging diverse knowledge systems and stakeholders. This is consistent with TDE's focus on collaborative problem-solving and knowledge co-production. Tejedor et al. (2018) reinforce this by exploring how TDE can foster practical problem-solving skills and stakeholder collaboration, highlighting the need for such approaches in engineering education. Lazzarini et al. (2018) contribute to this discussion by emphasizing the interdisciplinary profile of academics engaged in Sustainable Human Development (SHD) practices. Their findings highlight the importance of integrating sustainable development principles into academic activities and promoting these principles beyond universities.

The imperative for integrating sustainability into educational frameworks is further supported by Murtagh et al. (2020), who advocate for a transdisciplinary approach to sustainable construction. Their findings demonstrate the necessity of breaking down disciplinary silos to develop comprehensive solutions that address environmental impacts. Similarly, Perpignan et al. (2020) identify a gap in current curricula regarding cross-disciplinary competencies and stress the need for a holistic approach that incorporates economic, social, and ethical considerations.

Bedewy and Lavicza (2023) contribute to this discussion by incorporating cultural and historical contexts into TDE, proposing a STEAM + X framework. This approach enhances interdisciplinary connections and provides innovative solutions to complex issues like coloniality, which can indirectly impact environmental considerations in the AEC sector. Finally, Ikudayisi et al. (2023) highlight the critical need for integrated practices within the AEC industry, pointing out that current curricula often lack adequate training for effective multidisciplinary collaboration. By incorporating advanced technological tools and integrated design processes into educational frameworks, TDE can equip future practitioners with the necessary competencies to address sustainability challenges and improve project efficiency.

In summary, the integration of diverse disciplines, the promotion of co-creation, and the emphasis on sustainability are essential components of TDE that can significantly enhance the effectiveness of AEC curricula. Aligning educational frameworks with these principles will better prepare professionals to address the complex environmental issues facing the industry and contribute to the development of more resilient and sustainable built environments.

3.2.3 Scenarios of interdisciplinary teaching approaches

Interdisciplinary teaching approaches are gaining traction in universities worldwide as they prepare future professionals in the Architecture, Engineering, and Construction (AEC) industry to address complex environmental challenges (Ertas, 2012). At the American University of Beirut in Lebanon, Asmar and Mady (2013) implemented an interdisciplinary design program that integrated various design disciplines. This program broadened students' perspectives, encouraging them to think beyond their specific fields and embrace sustainability as a core principle. The success of this approach highlights the importance of fostering a learner-centred environment that promotes the development of new interdisciplinary knowledge.

Similarly, Arizona State University in the United States has been at the forefront of implementing problem- and project-based learning (PPBL) in sustainability education (Brundiers & Wiek, 2013). Their approach emphasizes the importance of defining sustainability challenges clearly and building effective teams to address these issues. This method aligns well with the AEC industry's need for collaborative problem-solving and the practical application of sustainable practices, equipping students with the skills needed to tackle real-world environmental challenges.

In Europe, Charles University in the Czech Republic, through initiatives like the Virtual Campus for a Sustainable Europe (VCSE), has been instrumental in creating transdisciplinary, multi-stakeholder learning environments (Dlouhá et al., 2013). These virtual platforms enable international collaboration and the integration of diverse perspectives, essential for addressing the AEC industry's global environmental challenges. This approach demonstrates how universities can transcend traditional academic boundaries (Mureşan, 2013) to foster innovative solutions. Julien et al. (2018) mentioned the importance of future-oriented thinking in education for sustainable development (ESD). Their approach encourages students to develop foresighted thinking and anticipatory competence, essential for navigating the long-term environmental impacts in the AEC sector. This future-focused education is vital in preparing students to handle the complexities of sustainability.

In Spain, the Polytechnic University of Catalonia emphasized the role of continuous professional development in enhancing sustainability education (Pérez-Foguet et al., 2018). By integrating sustainability principles into teaching, educators are better prepared to foster interdisciplinary collaboration among students, which is crucial for addressing the environmental challenges faced by the AEC industry.

National Chiao Tung University in Taiwan illustrated the application of interdisciplinary teaching by developing a project-based online course for Building Information Modeling (BIM) (Tsai et al., 2019). This approach combines real-life cases and technology, equipping students with practical skills that enhance sustainability in construction projects.

The Delft University of Technology in the Netherlands responded to the evolving role of design education in promoting interdisciplinary collaboration (Voûte et al., 2020). Their approach focuses on equipping design students with the skills to work across disciplines, enabling them to develop innovative solutions that reduce the environmental impact of construction projects.

Lastly, NingboTech University in China implemented a transdisciplinary learning approach that combines engineering and design education (Ma & Jin, 2022). This curriculum focuses on urban water ecological restoration, demonstrating how integrating diverse disciplinary

perspectives can enhance sustainability literacy and prepare students to tackle environmental challenges effectively.

These universities illustrate the global adoption of interdisciplinary teaching approaches, which are crucial for preparing AEC professionals to innovate and implement sustainable solutions in the built environment.

3.3 IDC/TDC concepts from various disciplines

Due to the nature of the research, various IDC/TDC concepts can be borrowed from other disciplines, ranging from (1) natural and health sciences; (2) educational sciences; (3) engineering sciences; and (4) humanities and social sciences.

3.3.1 Natural and health sciences

IDC/TDC within the natural and health sciences offers critical insights for enhancing educational approaches across various fields, including the Architecture, Engineering, and Construction (AEC) industry. Walker et al. (1998) stressed the importance of collaboration and community-building in healthcare, advocating for a shift away from traditional disciplinary silos towards holistic, relationship-centered care models. This shift necessitates professionals to engage in creative dialogues and collaborative learning experiences, fostering a health-oriented rather than a purely medical model of education. Such emphasis on interprofessional collaboration provides a template for fostering similar cross-disciplinary teamwork in the AEC sector, where diverse expertise is essential for addressing complex environmental challenges. Christie et al. (2007) highlighted the benefits of transdisciplinary assignments in healthcare education, which promote collaboration among disciplines like nursing, nutrition, and physical therapy. These assignments not only enhance students' skills in communication, teamwork, and understanding of other disciplines but also specify the challenges of coordinating diverse schedules and ensuring cohesive team dynamics—challenges that are equally pertinent to interdisciplinary projects in the AEC industry. Pearson and Hubball (2012) explained the significance of systematic planning, implementation, and evaluation in interdisciplinary settings, drawing from their experiences in pharmacy education. Their emphasis on faculty leadership and professional development is particularly relevant for guiding transdisciplinary efforts in sustainability education within the AEC sector. Furthermore, Rahmawati et al. (2022) introduce the Ethical Dilemma STEAM Teaching Model, integrating chemistry education with learning in sustainability. This model emphasizes the development of transdisciplinary abilities and incorporates ethical considerations, encouraging students to engage with complex real-world problems and fostering transformative learning. The alignment of this approach with the goals of TDE highlights its potential to cultivate socially responsible citizens capable of contributing to environmental preservation, a crucial outcome for the AEC industry as it seeks to reduce its environmental impact. Together, these studies illustrate how the principles of interdisciplinary and transdisciplinary collaboration in natural and health sciences can inform and enhance educational strategies across different fields, equipping future professionals with the skills and knowledge necessary to develop sustainable solutions in their respective domains.

3.3.2 Educational sciences

IDC/TDC in education is increasingly recognized as critical in preparing students to tackle the multifaceted challenges of modern society, transferrable to fields such as the Architecture, Engineering, and Construction (AEC) industry. O'Hara (2007) calls for a radical shift from traditional education systems to transdisciplinary approaches that equip graduates with the skills necessary to address contemporary societal challenges. This shift is supported by Hui (2011), who advocates for combining constructivist, problem-based, and experiential learning approaches to engage students with real-world sustainability issues, thus fostering the problem-solving and critical thinking skills essential for mitigating environmental impacts in the AEC sector. Similarly, Tikly (2015) emphasizes the integration of diverse disciplinary perspectives, including indigenous and experiential knowledge, to create a more comprehensive understanding of sustainability, which is crucial for effective collaboration in reducing the environmental footprint of the AEC industry.

Practical applications of these interdisciplinary methods are highlighted by Urea (2015), who argues that hands-on learning experiences, such as case studies and portfolios, are more effective than traditional lectures in equipping students for the collaborative and problem-solving demands of the AEC industry. This is further echoed by Bilyatdinova and Klimova (2017), who stress the importance of developing both hard and soft skills, such as teamwork, communication, and technical expertise, through multidisciplinary programs. Derler et al. (2020) extend this notion by demonstrating how integrating societal values into the research process through participatory methods, like photovoice and design thinking, can enhance collaborative learning and promote sustainability. Berchin et al. (2018) and Bourgeron et al. (2018) also specify the role of interdisciplinary initiatives and international conferences in advancing sustainability within higher education and the AEC sector, by facilitating the exchange of innovative solutions and best practices.

In addition to fostering collaboration and practical skills, these educational strategies emphasize the development of sustainability competencies. Cincera et al. (2018) advocate for learner-centred, transdisciplinary, and real-world teaching methods that are crucial for empowering students to make a positive impact on the AEC sector through sustainable practices. Gómez-Ríos et al. (2023) and Holincheck et al. (2024) further demonstrate how curriculum reforms and transdisciplinary STEM learning engage students in real-world problem- solving, equipping them with the skills needed to innovate and address environmental challenges. Collectively, these studies mention the importance of integrating diverse pedagogical methods, fostering interdisciplinary collaboration, and implementing practical applications in education to prepare future professionals to tackle the sustainability challenges that may impact the AEC curricula effectively.

3.3.3 Engineering sciences

Transdisciplinary approaches in engineering education are necessary for fostering sustainability and addressing complex environmental challenges in industries which impact education in the AEC industry. Dlouhá and Burandt (2015) highlight the importance of creating collaborative learning environments that bring together students and faculty from diverse disciplines. Their study demonstrates that such environments are crucial for developing key competencies like

communication, cooperation, and the ability to work across disciplinary boundaries, which may be essential for delivering sustainable solutions in the AEC industry. This perspective aligns with Annan-Diab and Molinari (2017), who emphasize the need for educational frameworks that promote interdisciplinary learning and integrate sustainability concepts across curricula. They argue that effective solutions to sustainability issues require collaboration among professionals from different backgrounds, a principle particularly relevant to the multifaceted nature of environmental impacts in the AEC sector.

Further emphasizing the shift from traditional educational models, Dlouhá et al. (2017) discuss the transition from conventional environmental education to Education for Sustainable Development (ESD) in Central and Eastern Europe. They underline the importance of governance, policy support, and individual initiatives in implementing sustainability in higher education. Straub and Vilsmaier (2020) stressed that transdisciplinary processes in education, particularly in teacher education, can bridge the gap between academia and practice, ensuring that innovations are socially and culturally robust. This model of education not only improves academic outcomes but also promotes sustainable practices in the AEC industry by integrating diverse perspectives and fostering collaboration among stakeholders. The emphasis on transdisciplinary project-based learning (PBL) in engineering further supports this approach, highlighting how integrating multiple disciplines through PBL can enhance critical thinking, problem-solving, and design skills—key competencies for sustainable AEC practices (Farid et al., 2021).

The successful implementation of TDE is further exemplified by Huang et al. (2022), who developed a video-facilitated transdisciplinary STEM curriculum that integrated STEM education with social service and writing, fostering empathy and design competence among students. This curriculum highlights the importance of a holistic approach to education that prepares students to address real-world environmental challenges, particularly in the AEC industry. Similarly, Corrêa et al. (2020) illustrate how sustainability principles integrated into design education can develop essential skills like conflict resolution and project management while promoting cross-cultural understanding. de Oliveira et al. (2023) add to this by emphasizing the integration of transdisciplinary competencies into chemical engineering education, aligning to reduce environmental impact in the AEC industry. Krawczyk et al. (2023) and Lesseig et al. (2023) further highlight the role of interdisciplinary approaches in communicating sustainability issues and fostering integrated thinking, ultimately contributing to innovative and sustainable solutions in the AEC sector. These studies collectively show the transformative potential of TDE in preparing future professionals to tackle the environmental challenges inherent in the AEC industry.

3.3.4 Business, humanities, and social sciences

The integration of transdisciplinary approaches in the fields of business, humanities, and social sciences provides valuable insights that may be applicable to addressing environmental challenges in the AEC industry. Klein (2015) discusses the importance of transcending traditional disciplinary boundaries to tackle complex issues, a principle that may be beneficial in the AEC industry, where collaboration among diverse professionals is crucial. By fostering interprofessional approaches that bridge the gap between academia and industry, AEC

professionals might better navigate the multifaceted nature of environmental issues, potentially devising innovative strategies for sustainability. This transdisciplinary mindset could facilitate the integration of technical, social, and policy dimensions, aligning with the industry's need for holistic and collaborative frameworks.

Borges et al. (2017) explore the hidden curriculum within student organizations in a business school, revealing how these organizations can provide learning experiences that address gaps in the formal curriculum, particularly in areas like ethical concerns, corporate social responsibility, and sustainability. These insights may be relevant to the AEC industry, suggesting that similar informal learning platforms could enhance the professional development of future AEC practitioners by fostering a deeper understanding of sustainability beyond the formal educational framework. Additionally, Prinsloo (2018) mention the use of literature as a catalyst for critical thinking across disciplines, highlighting the potential for literature to foster a transdisciplinary approach to education. This could be particularly useful in the AEC sector, where integrating critical thinking and diverse disciplinary perspectives might promote a more holistic and innovative approach to sustainability challenges.

The concept of TDR presented by Vinz (2019) offers further insights into how TDE could address environmental challenges within the AEC industry. By integrating scientific research with creative approaches, such as "Science & Fiction," TR could bridge the gap between academic knowledge and practical application, possibly training future AEC professionals to become change agents in reducing the industry's environmental impact. Ajanovic and Çizel (2021) also discuss the evolution of tourism studies towards a transdisciplinary approach, which may have parallels in the AEC industry, where addressing complex environmental impacts could require similar interdisciplinary frameworks that transcend traditional disciplinary boundaries.

Rapanta (2021) accentuates the potential of student-centered dialogical argumentation methods in fostering critical thinking and collaborative skills. These skills may be essential for addressing the environmental impacts in the AEC industry, where informed discussions about sustainability and environmental stewardship are crucial. By promoting argumentative reasoning across various disciplines, this educational framework might enhance students' abilities to engage in complex problem-solving, potentially contributing to developing more sustainable practices within the AEC sector. Ming et al. (2023) highlight the complexities of interdisciplinary learning within Liberal Arts and Sciences (LAS) education, emphasizing the importance of integrating diverse disciplinary perspectives while maintaining individual academic identities. These findings suggest that TDE in the AEC industry could support students in navigating and blending knowledge from various fields, which may be crucial for effectively addressing environmental challenges.

Finally, Borowitz (2024) examines the teaching of social science aspects of space through a transdisciplinary approach, which may have implications for the AEC industry. By integrating knowledge from multiple disciplines, such as environmental science, policy, and engineering, educators could equip future AEC professionals with the skills needed to address the industry's ecological footprint. This approach could enhance student engagement and prepare them to navigate the multifaceted challenges of sustainability in their respective domains, potentially leading to innovative solutions that mitigate environmental impacts.

4 TDE framework to reduce EI aligned with SDGs for AEC curricula

The AEC industry aligns with several of the United Nations SDGs due to its significant influence on sustainable urbanization, resource efficiency, and environmental impact reduction. Among the most relevant SDGs is **SDG 3: Good Health and Well-Being**, as designing buildings and cities with features such as good air quality, natural lighting, green spaces, and safe infrastructure contributes to both physical and mental well-being. Additionally, **SDG 6: Clean Water and Sanitation** highlights the AEC industry's vital role in sustainable water management. This includes the design of water-efficient buildings and infrastructure that ensures access to clean water and reduces water pollution. Furthermore, **SDG 7: Affordable and Clean Energy** emphasizes the incorporation of energy-efficient systems, renewable energy technologies, and passive design strategies in buildings, which collectively reduce energy consumption and promote clean energy solutions. **SDG 9: Industry, Innovation, and Infrastructure** entails the industry's contribution to building resilient infrastructure while fostering innovation in construction materials and processes, ultimately promoting sustainable industrialization. The AEC industry is also central to **SDG 11: Sustainable Cities and Communities**, as it plays a crucial role in creating inclusive, safe, resilient, and sustainable urban environments through sustainable urban planning, affordable housing, and environmentally conscious design. In alignment with **SDG 12: Responsible Consumption and Production**, the industry adopts sustainable construction materials, implements efficient waste management practices, and conducts lifecycle assessments in building projects, which support the reduction of resource consumption and waste production. Moreover, the AEC sector contributes to **SDG 13: Climate Action** by reducing greenhouse gas emissions through sustainable building practices, energy-efficient systems, and innovative materials, thus playing a critical role in mitigating climate change. Lastly, **SDG 15: Life on Land** highlights the industry's potential to help reduce deforestation, preserve ecosystems, and minimize biodiversity loss by promoting the sustainable use of land and construction materials. Collectively, these SDGs guide the AEC industry in addressing environmental, social, and economic sustainability challenges, enabling professionals in the sector to design and construct in ways that benefit both people and the planet.

The proposed TDE framework for reducing EI in the AEC industry is presented through core inputs to desired educational outcomes. This framework aligns with the Sustainable Development Goals (SDGs) and emphasizes the importance of integrating sustainability, interdisciplinarity, and innovative educational strategies into AEC curricula.

The TDE framework is structured in three key levels (1) core inputs/foundations; (2) key education components; and (3) desired educational outcomes (Figure 5).

The foundation of the framework relies on (1) **IDC**, (2) **sustainability integration**, and (3) **SDG alignment**. These pillars form the basis of the educational strategies and ensure that the curriculum reflects the complexity and interconnectedness of environmental, social, and economic issues within the AEC industry. By aligning the curriculum with SDGs such as SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), the framework ensures that sustainability is embedded at every stage of the educational process, addressing the AEC industry's environmental challenges holistically.

The middle section outlines the seven key components of the transdisciplinary education model, forming a comprehensive and innovative approach to AEC education. These components include (1) **interdisciplinary curriculum design**: encouraging collaboration across AEC disciplines and beyond to create a more integrated, holistic learning experience; (2) **integration of sustainability across disciplines**: embedding sustainability principles throughout the curriculum to raise awareness of environmental impacts in every aspect of AEC practices; (3) **TDC and co-creation**: promoting partnerships with industry, communities, and global institutions to develop innovative, sustainable solutions to real-world challenges; (4) **systems thinking and reflective learning**: equipping students with tools to analyse and understand the systemic nature of sustainability issues in the built environment; (5) **Problem- and Project-Based Learning (PPBL)**: Engaging students with practical, hands-on projects that simulate real-world sustainability challenges in the AEC sector; (6) **development of foresight and anticipatory competence**: training students to anticipate and respond to future environmental challenges with innovative, forward-thinking design solutions; and (7) **global knowledge transfer and cooperation through international organisations**: facilitating international collaborations through networks such as UNESCO Chairs to foster knowledge exchange and promote global best practices.

The framework culminates in several desired educational outcomes, intended to produce graduates who are equipped to make meaningful contributions to sustainability in the AEC industry.

These outcomes include the development of sustainable solutions, skills to reduce environmental impacts, and the ability to contribute directly to the achievement of SDGs. By instilling these competencies, the framework prepares future AEC professionals to lead the industry toward more resilient and sustainable built environments, addressing critical global challenges such as climate change, resource depletion, and affordable housing.

Figure 5: TDE framework aligned with SDGs to reduce EI for AEC curricula.

5 Discussion

The AEC industry plays a pivotal role in advancing the United Nations Sustainable Development Goals (SDGs), particularly through frameworks that integrate sustainability into educational curricula. The proposed TDE framework emphasizes the alignment of AEC education with the SDGs, aiming to cultivate professionals capable of addressing pressing global challenges such as climate change (Klenk & Meehan, 2015), resource depletion (Russell, Wickson, et al., 2008), and affordable housing (Lawrence, 2004). This discussion compares the TDE framework with other existing frameworks, highlighting similarities, differences, and potential synergies. One notable

framework that aligns with the TDE framework is the roadmap for sustainable development through responsible sourcing in construction similar to Ball et al. (2021) findings. This framework emphasizes the importance of integrating corporate social responsibility (CSR) into the AEC sector, which is crucial for achieving multiple SDGs. The TDE framework similarly highlights the need for sustainability integration, reflecting the interconnectedness of environmental, social, and economic issues within the AEC industry. Both frameworks advocate for a holistic approach to education and practice, suggesting that responsible sourcing and sustainability are not merely add-ons but essential components of the AEC business model. Horry et al. (2022) provide another relevant perspective by discussing environmental management systems (EMS) in the AEC sector. Their research indicates that adopting ISO 14001 can facilitate a more sustainable approach within organizations, thereby contributing to the delivery of the SDGs. The TDE framework's emphasis on interdisciplinary curriculum design and sustainability integration resonates with the findings of Horry et al. (2022) as both frameworks advocate for systemic changes that enhance the AEC industry's capacity to address environmental challenges. The TDE framework's focus on co-creation and partnerships with industry further complements the EMS framework by promoting collaborative efforts to achieve sustainability goals. In contrast, the framework proposed by Zhang et al. (2021) focuses on building circularity assessment in the AEC industry. This framework emphasizes the importance of circular economy principles, which are crucial for reducing waste and enhancing resource efficiency. While the TDE framework incorporates sustainability across disciplines, it does not explicitly address circularity as a core component. However, integrating circular economy principles into the TDE framework could enhance its effectiveness in promoting sustainable practices within the AEC sector. This integration would align with the TDE framework's goal of producing graduates equipped to develop sustainable solutions, thereby addressing the need for innovative approaches to resource management. The TDE framework's focus on innovative educational strategies and the development of foresight and anticipatory competence aligns well with emphasis on technological integration. Both frameworks highlight the importance of preparing future AEC professionals to leverage technology in addressing sustainability challenges, thereby fostering a more resilient and environmentally conscious industry. Moreover, the framework developed by Caldas et al. (2022) explore the synergies between Construction 4.0 technologies and sustainable construction practices. This framework highlights the potential of emerging technologies to facilitate the transition towards sustainability in the AEC sector. The TDE framework's emphasis on interdisciplinary curriculum design and the integration of sustainability principles across disciplines complements these findings. By incorporating technological advancements into the educational process, the TDE framework can enhance the skill sets of future professionals, enabling them to implement innovative solutions that align with the SDGs. The mental health management framework proposed by Tijani et al. (2023) offer a unique perspective on the AEC industry, focusing on the well-being of project management practitioners. While the TDE framework primarily addresses environmental and economic sustainability, it also recognizes the importance of good health and well-being, as highlighted in SDG 3. Integrating mental health considerations into the TDE framework could provide a more comprehensive approach to sustainability, ensuring that the well-being of professionals is prioritized alongside environmental and economic goals. Liobikienė and Poškus (2019) emphasize the significance of environmental knowledge in fostering pro-environmental behaviour. Their

findings suggest that education plays a crucial role in promoting sustainability within both private and public spheres. The TDE framework's focus on developing competencies related to sustainability aligns with this perspective, as it aims to equip graduates with the knowledge and skills necessary to contribute to sustainable practices in the AEC industry. By fostering environmental knowledge, the TDE framework can enhance the effectiveness of AEC professionals in implementing sustainable solutions. Furthermore, the framework proposed by Caldas et al. (2022) highlights the role of circular economy strategies in mitigating climate change within the AEC industry. This framework emphasizes the need for tools that facilitate the integration of circular economy principles into construction practices. While the TDE framework does not explicitly address circular economy strategies, it could benefit from incorporating these principles to enhance its effectiveness in promoting sustainability. By integrating circular economy concepts, the TDE framework can provide a more robust educational foundation for future AEC professionals, enabling them to address the complexities of sustainability in their practices. In conclusion, the TDE framework presents a comprehensive approach to integrating sustainability into AEC education, aligning with various existing frameworks that emphasize responsible sourcing, environmental management, technological integration, and mental health considerations. While the TDE framework effectively addresses many aspects of sustainability, there is potential for further enhancement by incorporating circular economy principles and mental health considerations. By synthesizing insights from these frameworks, the TDE framework can better prepare future AEC professionals to navigate the complexities of sustainability, ultimately contributing to the achievement of the SDGs.

6 Conclusions

This research aimed to investigate the integration of Transdisciplinary Education (TDE) within the Architecture, Engineering, and Construction (AEC) industry curricula to enhance environmental sustainability and reduce environmental impact (EI). Through an interdisciplinary systematic literature review, the study identified core theoretical ideas aiding TDE; best practices from the built environment and AEC disciplines; and IDC/TDC ideas from other disciplines.

The findings indicate that TDE when effectively integrated into AEC education by being aligned with related SDGs, can significantly enhance students' understanding of complex environmental challenges. This education model may equip professionals with the necessary skills, knowledge, and competencies to create innovative solutions that contribute to sustainable development and become the next generation of sustainability scientists. Furthermore, the research highlights the importance of IDC, the incorporation of sustainability principles into curricula, and the adoption of problem-based and project-based learning approaches as essential strategies for fostering effective learning in the AEC industry.

The implications of these findings extend to both policy and industry practices. Policymakers are encouraged to support educational reforms that promote transdisciplinary approaches and align academic curricula with the Sustainable Development Goals (SDGs). By investing in such educational initiatives, governments can develop a better-equipped workforce to address pressing sustainability issues within the AEC sector. For industry stakeholders, adopting TDE principles

can lead to enhanced innovation, improved project outcomes, and a stronger commitment to sustainable practices.

Potential further research could focus on developing and testing specific TDE models tailored to the unique needs of different AEC disciplines. Investigating the long-term impacts of TDE on professional practice and its effectiveness in fostering sustainability-oriented mindsets among graduates is also critical. Additionally, exploring the role of technology and digital tools in facilitating transdisciplinary learning could provide valuable insights into modernizing AEC education. Both ideas and concepts are vital to advancing sustainability science. By integrating innovative ideas that emerge from TDE into broader conceptual frameworks of sustainability, we can cultivate a more holistic understanding of complex challenges. This approach not only enhances the curriculum but also drives the development of effective strategies for sustainable practices in the AEC industry. Overall, this research lays the groundwork for the ongoing exploration of TDE in the AEC industry, emphasizing the urgent need for educational transformation to meet the complex challenges of environmental sustainability.

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