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Perceptual drivers of undergraduate students' engagement in digitally-enabled transformative sustainability education in Tanzania

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Abstract. This quantitative cross-sectional survey examined undergraduate students' perceptions and engagement in digitally-enabled transformative sustainability education (TSE) in a university context in Tanzania. It explored the influence of perceptual factors – the perceived usefulness, relevance, and accessibility of digital tools – on students' cognitive, behavioural, and emotional engagement in TSE. Grounded in the technology acceptance model and educational engagement theory, data were collected from 699 students using a non-probabilistic sampling approach and analysed with descriptive and inferential statistical techniques. Perceived usefulness ($M = 4.06$) and perceived relevance ($M = 4.01$) were the most highly rated factors, while perceived accessibility ($M = 3.93$) received slightly lower ratings, pointing to persistent challenges in digital facilitating conditions. Correlation analyses revealed moderately strong and significant relationships among the perceptual factors ($r = 0.45$–0.55, $p < .0001$), the strongest being between perceived relevance and perceived usefulness ($r = 0.55$), which underscores their interdependence in shaping technology adoption for TSE. Students' engagement was generally high ($M = 3.92$), with cognitive ($M = 4.03$) and emotional ($M = 4.04$) engagement surpassing behavioural engagement ($M = 3.71$) and so revealing a participation gap. The engagement domains were moderately correlated ($r = 0.48$–0.56, $p < .0001$), indicating distinct yet interconnected constructs. Multiple regression identified perceived accessibility as the strongest predictor of engagement ($B = 0.270$, $p < .0001$), followed by perceived usefulness ($B = 0.253$, $p < .0001$) and perceived relevance ($B = 0.218$, $p < .0001$). The findings emphasise the interplay of perceptual factors in fostering engagement in TSE, with accessibility emerging as a critical driver despite its lower rating. To advance TSE, the study recommends strengthening digital infrastructure and improving access to sustainability-related digital resources to close behavioural engagement gaps and support the United Nations 2030 Agenda in resource-constrained contexts.

Keywords: transformative sustainability education, digital tools, digital pedagogy, educational engagement, university students, technology acceptance

1. Introduction

1.1. Background and context

Education for sustainable development (ESD) has become a central focus in contemporary educational reforms, responding to intensifying global sustainability challenges. ESD is widely recognised as a key instrument for cultivating sustainability agency, empowering individuals to act intentionally and serve as sustainability practitioners [66, 86–88]. Building on the foundational work of early pioneers [41, 65, 82], 21st-century scholars in sustainability education [19, 22, 48, 80] emphasise the transformative potential of education, and of ESD in particular, for addressing complex contemporary realities.

Scholars such as McCowan [56] and Sezen-Barrie, Windschitl and Nxumalo [78] advocate a strategic pedagogical shift from content-based teaching to transformative, action-oriented approaches to address escalating sustainability concerns. This evolving discourse reinforces the synergy between

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sustainability education and transformative learning, giving rise to transformative sustainability education (TSE) as an emergent and integrative educational model. Proponents of TSE contend that transmissive approaches are inadequate to equip learners with the competences and critical consciousness required to respond to global sustainability challenges [19, 22, 86].

As an alternative, they advocate TSE as an educational approach that does not merely transmit knowledge but transforms the learner's mindset by promoting action-oriented responses to global challenges [19, 22]. TSE thus emerges as a promising pedagogical approach that fosters innovation, adaptability, and social transformation, vital for addressing complex sustainability challenges [68, 78]. Integrating TSE into curricula is therefore crucial for cultivating the competencies undergraduate students need to drive sustainable change.

TSE integrates the development of sustainability skills with critical reflection, the core component of transformative learning [48], and occupies a dynamic and complex space that fosters innovative pedagogy, deep learning and informed action [59, 74, 82]. It offers learners meaningful opportunities to reflect on personal challenges while cultivating the agency to address them. Embedding digital technologies such as social media and learning management systems into this synergy represents a critical step towards enhancing students' engagement with TSE [58, 81].

1.2. Alignment with global frameworks

This renewed emphasis on the role of education in addressing sustainability crises aligns with both the United Nations Sustainable Development Goals (UN-SDGs) and UNESCO's Education for Sustainable Development (ESD) within the 2030 Agenda [87, 88]. SDG 4, Target 4.7 of the 2030 Agenda states that by 2030 all learners should acquire the skills needed to promote sustainable development, and thereby foster sustainable lifestyles, human rights, gender equality, peace, global citizenship and cultural diversity [88]. TSE is education of precisely this kind, since it focuses on transforming learners' socio-cognitive and emotional engagement in order to address sustainability challenges.

The importance of TSE for the transformation and localisation of global challenges is echoed in the UNESCO ESD for 2030 framework, whose core goal is transformative action [87]. The framework underscores the significance of an education that combines knowledge of sustainability challenges with the ability to act on them, and it draws attention to the gap between global sustainability crises, such as climate change, and their local manifestations, which learners must comprehend and address [68]. It therefore underscores the need for context-responsive learning that links global sustainability issues to learners' lived experiences.

1.3. Challenges in TSE implementation

Although TSE is widely recognised as a vital pathway towards a sustainable future [19, 78, 86], its implementation within higher learning institutions remains limited [1]. Studies from China [31], England [66], and India [45] highlight a persistent disconnect between international TSE frameworks and the lived realities of teachers and students. Commonly cited barriers include pedagogical limitations, institutional constraints, limited engagement and insufficient teacher preparedness on sustainability-sensitive topics such as climate change and social inequalities [69].

Similar challenges are reported across African contexts, including Tanzania, where inadequate support conditions, limited pedagogical and digital competencies, financial and technological barriers, partial curriculum integration and language issues impede TSE implementation [33, 62, 93]. In university contexts, TSE is marginalised in pedagogy [15, 18] and is often confined to isolated courses or programmes rather than serving as a foundational educational approach [91]. These recurring obstacles underscore the urgent need for context-responsive strategies, localised professional development and systemic support to embed TSE effectively in teacher education and beyond.

1.4. Role of digital tools in TSE

Recent empirical studies highlight the growing role of digital tools – social media, mobile apps, learning management systems and virtual simulations – in sustainability education [40, 58, 63, 81]. These studies suggest that digital pedagogy, defined as the purposeful use of digital tools in teaching and learning, can substantially enhance TSE by enriching interaction, deepening reflection, and fostering learner agency.

Digital tools also reshape how learners engage with sustainability issues, promoting cognitive, motivational and behavioural engagement with sustainability content [40, 63]. Lee, Byers and Powell [50], however, found that although university students are interested in campus sustainability initiatives, barriers such as institutional context and insufficient information about sustainability may hinder their participation. While scholars remain optimistic about the potential of digital tools for advancing sustainability education, their effective integration into TSE remains an evolving area of inquiry, particularly with respect to pedagogy, educator readiness, and digital alignment.

The mechanisms by which university students perceive and engage with TSE through digital tools remain underexplored, especially within the Tanzanian context. Existing studies have approached sustainability education primarily through the lens of competence development, overlooking students' lived perceptions and patterns of engagement in the digital era [7, 43, 94], even as the integration of transformative learning tenets into sustainability education gains recognition worldwide as a pedagogically sound approach [19, 29, 80].

1.5. Importance of learners' perceptions and engagement

While the affordances of digital tools can enrich learner-centred and engaging experiences, they cannot substitute for the relational and dialogical dimensions of learning [61]. Examining how learners perceive and engage with digitally enabled TSE is therefore crucial for shaping pedagogical strategies that meaningfully integrate emerging technologies and empower the next generation to act as transformative sustainability leaders.

Grounded in the technology acceptance model (TAM) [23] and the unified theory of acceptance and use of technology (UTAUT) [92], perceptions are understood as subjective beliefs shaped by cognitive appraisal – what individuals see, feel and sense. Perception functions as a lens that directs action, underscoring that learning is not simply knowledge transmission but a perceptually guided process [2]. Hyytinen et al. [42] emphasised the centrality of learners' perceptions of transformative learning, such as critical thinking and values-based reflection, in building sustainability competences among university students. Leal et al. [49] argue that students' perceptions and attitudes towards sustainability shape their understanding and behavioural engagement, and Uzorka, Akiyode and Isa [90] showed that behavioural engagement through practical, hands-on activities enhances the personal relevance of sustainability topics and fosters participation in sustainability initiatives. Together, these studies underscore the pivotal role of learners' perceptions and engagement in meaningful sustainability education.

In Sub-Saharan Africa, the adoption of digital learning has grown rapidly among university instructors and students [4], making it timely to explore how such practices influence engagement in TSE. Accordingly, this study examines students' perceptions of digital tools in TSE across three domains: perceived usefulness, perceived relevance, and perceived accessibility (or ease of use) [23, 92]. These constructs, defined in section 2.1, are essential for understanding learners' subjective interpretations of their digital learning experiences [8, 72, 75].

1.6. Research purpose and objectives

This study examined university students' perceptions and engagement with digitally-enabled TSE in Tanzania. Specifically, it investigated how undergraduate students' perceptions of the relevance, usefulness and accessibility of digital tools shape their cognitive, behavioural, and emotional engagement in TSE. The study pursued three objectives: to identify the key perceptual factors that influence undergraduate students' engagement in digitally-enabled TSE, to assess their perceived levels of engagement, and to analyse the impact of these factors on that engagement.

2. Theoretical considerations

2.1. Technology acceptance model

Developed by Davis [23], TAM is an integrative perspective that explains technology adoption through perception-based acceptance pathways. The theory posits that users' acceptance and actual use of technology are primarily determined by perceived usefulness (PU) and perceived ease of use (PE). The present study employed TAM to explain undergraduate students' perceptions of digitally-enabled TSE.

PU refers to the degree to which users believe that using a particular technology will enhance their performance or outcomes [35]. In this study, it aligns with perceptions of the utility of digital tools in TSE, including their role in supporting comprehension of sustainability content, real-world application and self-reflection; it thereby supports the practical application of knowledge needed to achieve transformative learning outcomes.

PE is the extent to which users believe that technology use will be free of effort [23]. When technologies are user-friendly and present minimal technical barriers, learners are more likely to accept and engage with them. This study operationalises PE as perceived accessibility (PA) – students' perceived ability to navigate and use digital tools for TSE effectively – covering perceptions of independence, confidence, organisation, and the reliability of digital sustainability content. PA is used throughout the remainder of the article to denote the measured construct.

Perceived relevance (PR), though not explicitly a TAM construct, is conceptually related to attitudes towards use and influences both PU and PA [75]. Here, it refers to the extent to which students view digitally enabled TSE as meaningful for their personal lives and broader communities, and as aligned with transformative sustainability goals. PR shapes students' willingness to engage with digital TSE tools, since higher perceived value strengthens their motivation to adopt and use such platforms effectively.

Previous applications of TAM in sustainability education support its utility in these domains. Almulla [8] found that students' adoption of e-learning for sustainability was shaped by PU, PE and attitudes towards use, while Saroia and Gao [75] and Rosli et al. [72] provided empirical evidence linking TAM constructs with sustainability education outcomes. More broadly, studies consistently associate TAM premises with relevance, efficacy and ease of use [9, 25, 73].

The model nevertheless has limitations: it has been applied only sparingly to sustainability-specific digital tools, it carries contextual and cultural biases, and its constructs are difficult to operationalise. Addressing these gaps is essential to capturing the transformative potential of digitally-enabled TSE, and broader empirical validation would enhance the model's relevance across diverse learning environments and its capacity to address rapidly evolving sustainability challenges.

2.2. Educational engagement theory

Educational engagement theory (EET) provides a framework for technology-based teaching and learning [44]. While engagement can occur in traditional settings, EET postulates that technology enhances participation and social interaction in ways difficult to achieve through stand-alone pedagogical practices [16, 76, 79]. The theory is thus best understood as a pedagogical model suited to technology-mediated learning [20].

EET shares core features with constructivist learning: an emphasis on meaningful learning [3], on collaboration and community learning as in situational learning theory [53], and on the importance of experiential learning in sustaining motivation [46]. It is a multidimensional theory grounded in social, cognitive, behavioural, and emotional perspectives, and its principles are structured around three pillars: relating, creating and donating.

The relating pillar involves collaboration through group-based learning, fostering social and communication skills [44]. In digitally enabled TSE, this is facilitated through platforms such as Google Workspace or Moodle, which promote collaborative problem-solving and behavioural engagement. Collaboration also stimulates cognitive engagement by requiring critical thinking and problem-solving, and supports emotional engagement through peer interaction and shared sustainability action [67]. Digital tools such as social media extend this pillar by enabling emotionally resonant connections beyond formal learning contexts.

The creating pillar entails active, purposeful and project-based learning [44]. Within TSE, this includes initiatives such as virtual campaigns addressing environmental issues or digital models for climate action. Such hands-on, digitally mediated projects foster behavioural engagement through action while strengthening emotional engagement, as learners feel personally invested in and inspired by sustainability initiatives amplified through digital platforms.

The donating pillar extends learning beyond the classroom by emphasising authentic, real-world applications [44]. It aligns with service learning, which cultivates academic and civic responsibility in addressing real problems [13, 39]. In TSE, this principle highlights students' application of digital skills to tackle sustainability challenges, fostering cognitive engagement through reflection and critical analysis, behavioural engagement through applied action, and emotional engagement through meaningful contribution.

2.3. Dimensions of students' engagement

Students' engagement is widely recognised as a key determinant of active learning and improved educational outcomes [47, 64, 97], yet the concept remains inconsistently defined and measured [64, 95]. Wong and Liem [95, p. 19] define engagement as "students' psychological state of activity, that affords them to feel activated, exert effort and be absorbed during learning activities". This definition aligns with Zepke's [97] psychological domain of engagement, which highlights the influence of motivation, attention and passion on cognitive engagement.

Systematic reviews show that engagement research in digital contexts such as social media, video and collaborative platforms often relies on self-reported measures and overlooks contextual variation [64], prompting calls for more nuanced, context-sensitive approaches [64, 95]. The principles of EET [44] complement this need by realising the related, creating, and donating pillars through collaborative, project-based, and socially relevant digital learning experiences, which can boost motivation and nurture deeper, sustained engagement.

Kuh [47] identified four major perspectives on student engagement: social-psychological, viewing engagement as internal processes of thought and feeling; behavioural, focusing on observable student actions; socio-cultural, emphasising conditions such as identity, equity and inclusion; and holistic, which integrates multiple dimensions of students' experiences. Zepke [97] outlined five perspectives: psychological, psychosocial, socio-cultural, socio-ecological (highlighting social and cultural capital [51]) and political, informed by critical pedagogy and linked to student emancipation [57]. These perspectives underscore both the richness and the conceptual ambiguity of engagement research, which is applied inconsistently across contexts.

Reschly and Christenson [71], however, view this diversity positively, as it enriches scholarly evaluation of engagement. To capture this multidimensionality, the present study integrates EET (relate, create, donate) [44] with the three-dimensional model of engagement (behavioural, cognitive, emotional) [30]. In digitally-enabled TSE, behavioural engagement includes observable actions such as accessing resources, participating in online discussions and promoting sustainability awareness through digital platforms [14, 64]. Cognitive engagement entails critical thinking, problem-solving and the reflective application of sustainability knowledge in digital spaces, whereas emotional engagement involves the motivation, values and sense of purpose that sustain participation in digitally mediated sustainability initiatives. This integrative approach provides a robust framework for examining how digital tools influence student engagement in sustainability education, particularly in Tanzanian higher education, where digital adoption is expanding but remains constrained by limited resources.

As shown in figure 1, cognitive engagement involves cultivating intellectual skills, including the deep processing of information through critical thinking and problem-solving. This domain is observed when students define, comprehend and evaluate what they are learning [64], and it is linked to persistence, a defining factor of self-regulated learning and of the learning-to-learn model of lifelong learning [26, 52]. In the present study, cognitive engagement refers to the extent to which students intellectually apply digital tools to engage with TSE and develop sustainability competencies.

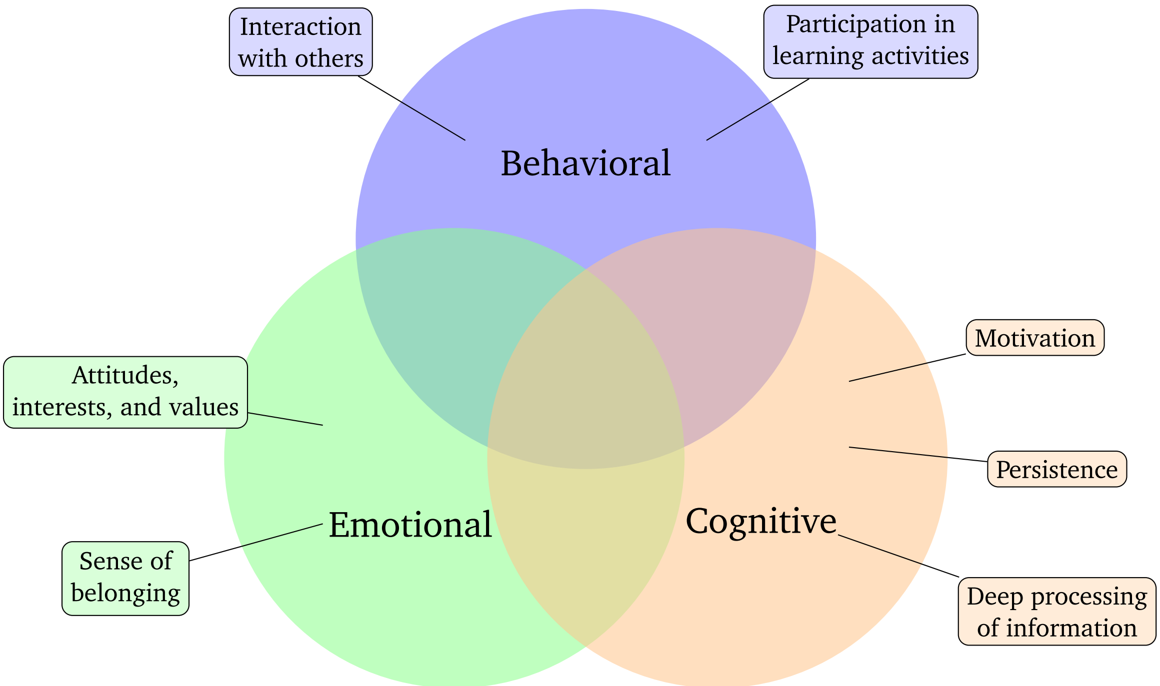

Figure 1: The framework of students' engagement [76, p. 5].

Emotional engagement focuses on affective connection and internal drives, including attitudes, interests, values and a sense of belonging [26, 76]; it is the extent to which learners display affective reactions in learning settings [30, 64]. In the present study, this domain captures how effectively connected undergraduate students feel through digitally-enabled TSE, and how their use of digital technologies shapes their emotional attachment, sense of digital belonging, and hope for a sustainable future.

In virtual spaces, tools such as simulation software or collaborative platforms can promote cognitive engagement, for example, using a simulation to understand a complex sustainability challenge such as climate change, and emotional engagement, typified by a feeling of belonging to the wider global community and of being part of sustainability solutions. Although these domains are treated separately here, in practice they overlap considerably.

2.4. Conceptual framework: TAM–EET integration

This study was guided by a conceptual framework that integrates TAM [23] with EET [44] to explain how digital tools enhance undergraduate students' engagement with digitally-enabled TSE. The framework comprises three interrelated sections: TAM, EET and TSE engagement outcomes. Together, these illustrate how perceptions and engagement with technology shape students' digital learning experiences.

The TAM constructs – PU, PE, and attitudes towards use – serve as the foundation for digital tool adoption [72, 75]. PU influences students' engagement with the actual use of digital tools through the relate, create and donate principles of engagement, while the belief that digital tools are easy to use enhances efficacy, motivation and active participation in digital learning. Attitudes towards use, in turn, bear on the perceived relevance of digital tools for TSE, since such tools link sustainability to practical life and to real-world applications (figure 2).

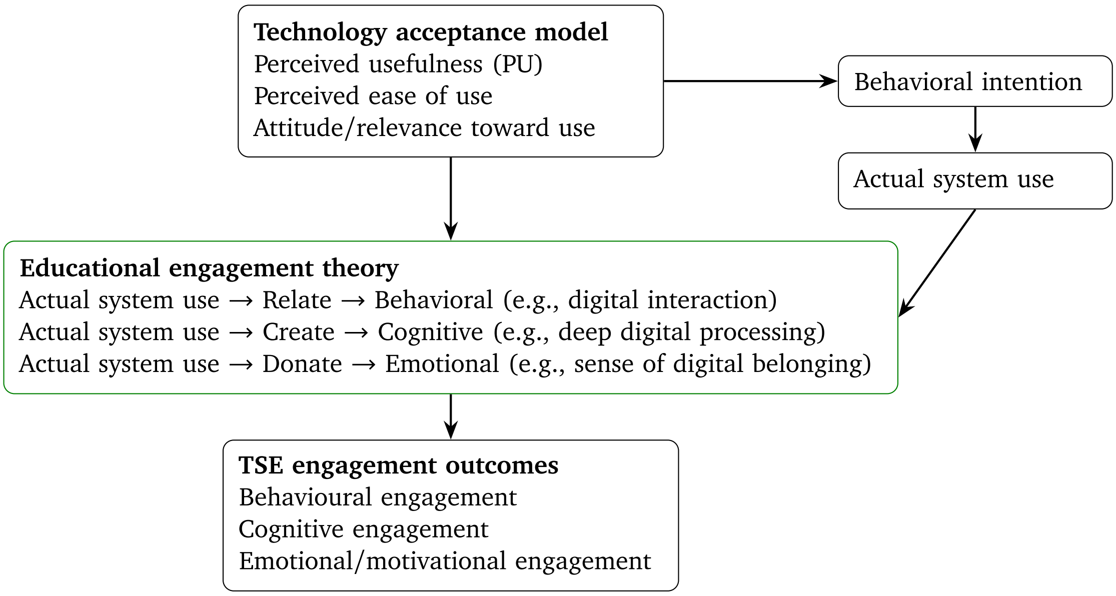

Figure 2: The study conceptual framework.

The model then presents the EET constructs, adapted to digital contexts: behavioural, entailing active participation and digital interaction with others; emotional, involving positive feelings and a sense of belonging in relation to digital tools; and cognitive, comprising the critical processing and analysis of digital sustainability data. These constructs provide a pedagogical framework for examining undergraduate students' engagement during actual system use, and the relate, create and donate principles support digitally mediated learning experiences when applied effectively [44].

The final section presents engagement outcomes, with the TAM constructs as the model's foundation and the educational engagement principles as mediating factors. The model holds that cognitive, behavioural, and emotional engagement are bound up with digitally-enabled TSE and implies that digital environments can be leveraged to foster engagement through collaboration, creativity, and active participation in real-life sustainability challenges.

3. Research methodology

3.1. Research approach and design

This study employed a quantitative research approach, using numerical data to examine undergraduate students' perceptions and engagement with digitally-enabled TSE [21]. A cross-sectional descriptive survey design was used to collect data and analyse associations between variables, supporting the exploration of predictive relationships between perceptions and engagement [32, 38]. This design is well-suited to investigating social and psychological dimensions such as perceptions and engagement in TSE contexts [34, 54].

3.2. The study area context

This study was conducted at the University of Dodoma, a public institution in central Tanzania. The university participates in national initiatives such as the Education Sector Development Programme (ESDP) and the Higher Education for Economic Transformation (HEET) project, led by the Ministry of Education, Science and Technology (MoEST) and the Tanzania Commission for Universities [83].

These initiatives aim to enhance access, quality and digital infrastructure in higher education while fostering ICT integration and sustainability competencies.

They align with the UN Sustainable Development Goals (SDGs) and with national policy frameworks, including the Education and Training Policy [89] and the National Digital Education Strategy 2024–2030 [85]. The university's commitment to sustainability education made it a suitable setting for examining TSE, although its structural conditions, shaped by ongoing reforms and digital constraints, may limit the generalizability of the findings. Those conditions nonetheless offer insight into how institutional environments influence sustainability-oriented learning, illustrating the importance of context in shaping undergraduate students' experiences and outcomes.

3.3. Participants and sampling

The participants were undergraduate students enrolled in two education degree programmes, the Bachelor of Adult Education and Community Development and the Bachelor of Education in Arts, both of which explicitly integrate sustainability themes into their curricula. Core courses such as "Lifelong Learning for Sustainable Development" and content from community development modules address key social sustainability issues. Participants were recruited from these two programmes using non-probabilistic convenience sampling.

This strategy is practical for quick, low-cost data collection and is commonly used in cross-sectional educational surveys, particularly in low-resource settings [4, 33]. Non-probabilistic sampling, however, limits the reproducibility and generalizability of findings to broader populations [12, 28]. The relatively large sample ($N = 699$) supports meaningful inferential analysis within the target group. The resulting sample is described in table 1.

Table 1
Demographic features of the respondents.

Variable	Frequency	Percent
Gender		
Male	373	53.36
Female	326	46.64
Age categories (years)		
20–24	486	69.53
25–29	87	12.45
30–34	54	7.73
35 and above	72	10.30
Frequency use of digital tools		
Daily	484	69.24
Two times per week	70	10.01
More than three times per week	143	20.46
Never	2	0.29

As shown in table 1, 53.36% of the respondents were male and 46.64% female, closely reflecting the national bachelor's degree enrolment trend in Tanzanian universities for the 2024/25 academic year, where 54.8% of students were male and 45.2% female [84]. Regarding age, the largest proportion of respondents (69.53%) fell in the 20–24 cohort, a pattern consistent with national statistics for 2024/25, which indicate that 143,346 students (67.7%) of the 211,720 enrolled at bachelor's degree level were aged 21–24 [84]. They were followed by respondents aged 25–29 (12.45%) and 35 and above (10.30%), while the smallest group, 7.73%, were aged 30–34.

More than two-thirds of respondents (69.24%) used digital tools daily. Overall, the sample's demographic profile aligns closely with national enrolment trends, and its members had sufficient digital exposure to provide reliable accounts of their perceptions and engagement with digitally enabled sustainability education.

3.4. Analytical framework and data collection tool

The research tool was a self-developed structured questionnaire with scaled items, informed by TAM [23] and by the assumptions of EET for technology-supported teaching and learning [44]. Its development began with a comprehensive review of the literature [23, 24, 26, 44, 52, 58, 63, 72, 75, 81, 97] in order to establish a theoretical and empirical foundation for the study.

Key constructs and dimensions were selected from the reviewed literature, and content validity was established by two experts in digital pedagogy and sustainability education. A descriptive non-experimental design was used to confirm the instrument's validity, and reliability was assessed using Cronbach's alpha (table 2). Following validation and reliability testing, the finalised questionnaire was administered to the target sample, and the collected data were prepared and analysed to address the research objectives.

Table 2
Reliability test.

Variable	Number of items	Cronbach's alpha	Interpretation
Perceived relevance (PR)	7	0.750	Acceptable
Perceived usefulness (PU)	7	0.789	Acceptable to Good
Perceived accessibility (PA)	6	0.702	Acceptable
Cognitive engagement (CE)	7	0.747	Acceptable
Behavioral engagement (BE)	7	0.831	Good
Emotional engagement (EE)	7	0.782	Acceptable to Good

As shown in table 2, Cronbach's alpha exceeded the recommended threshold of 0.70 [38] for every construct, indicating acceptable to good reliability: PR ($\alpha = 0.750$), PU ($\alpha = 0.789$), PA ($\alpha = 0.702$), CE ($\alpha = 0.747$), BE ($\alpha = 0.831$) and EE ($\alpha = 0.782$). Based on expert input, the questionnaire was refined into a 46-item instrument comprising three sections: demographic information (5 items), perceptions of digitally enabled TSE (20 items), and engagement with TSE (21 items).

The first section captured respondents' demographic characteristics. The second assessed students' perceptions of digitally-enabled TSE through three latent variables drawn from TAM [23] and adapted from prior studies [55, 72, 75]: PR evaluated the relevance of digital tools for understanding TSE, PU assessed their utility for TSE learning, and PA examined students' ability to access and apply these tools.

The third section measured engagement with TSE using three latent variables [70]: cognitive engagement, focused on critical thinking and deep understanding of sustainability concepts; behavioural engagement, concerning actions such as sustainability agency and the application of lessons in real-life contexts; and emotional or motivational engagement, reflecting enjoyment and emotional connection to sustainability challenges. All items were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

3.5. Data collection procedures and ethical considerations

Data were collected through an online survey administered via Google Forms. Before administering the questionnaire, the researcher met with prospective respondents to explain the aims of the study and provide a brief orientation on completing the online survey. The questionnaire was distributed via a link on WhatsApp and in other social media groups of which prospective respondents were members. Respondents were periodically reminded to complete the questionnaire and were explicitly informed that participation was voluntary.

Respondents were also assured that their information would be kept confidential. Ethical approval, reference number MA.84/261/90/128, was obtained from the Institutional Research Ethical Committee (IRREC). Data were collected over four weeks during the first semester of the 2024/25 academic year, then cleaned and coded for statistical analysis. Because recruitment was through open invitations to social media groups, no response rate can be computed, and self-selection into the sample may limit the external validity of the results.

3.6. Data analysis

Data were analysed using SPSS ver. 25. Descriptive analysis summarised the collected data, yielding frequencies, means, and standard deviations. Inferential analysis comprised analysis of variance, correlation, and multiple linear regression, testing the relationship between undergraduate students' perceptions and their engagement with digitally enabled TSE. Diagnostic analysis included a reliability test (Cronbach's alpha above 0.7; table 2), fit diagnostics, and multicollinearity testing.

Panels A–H of figure 3 present the regression diagnostic plots used to check the key assumptions of the linear model: linearity, homoscedasticity and normality of residuals.

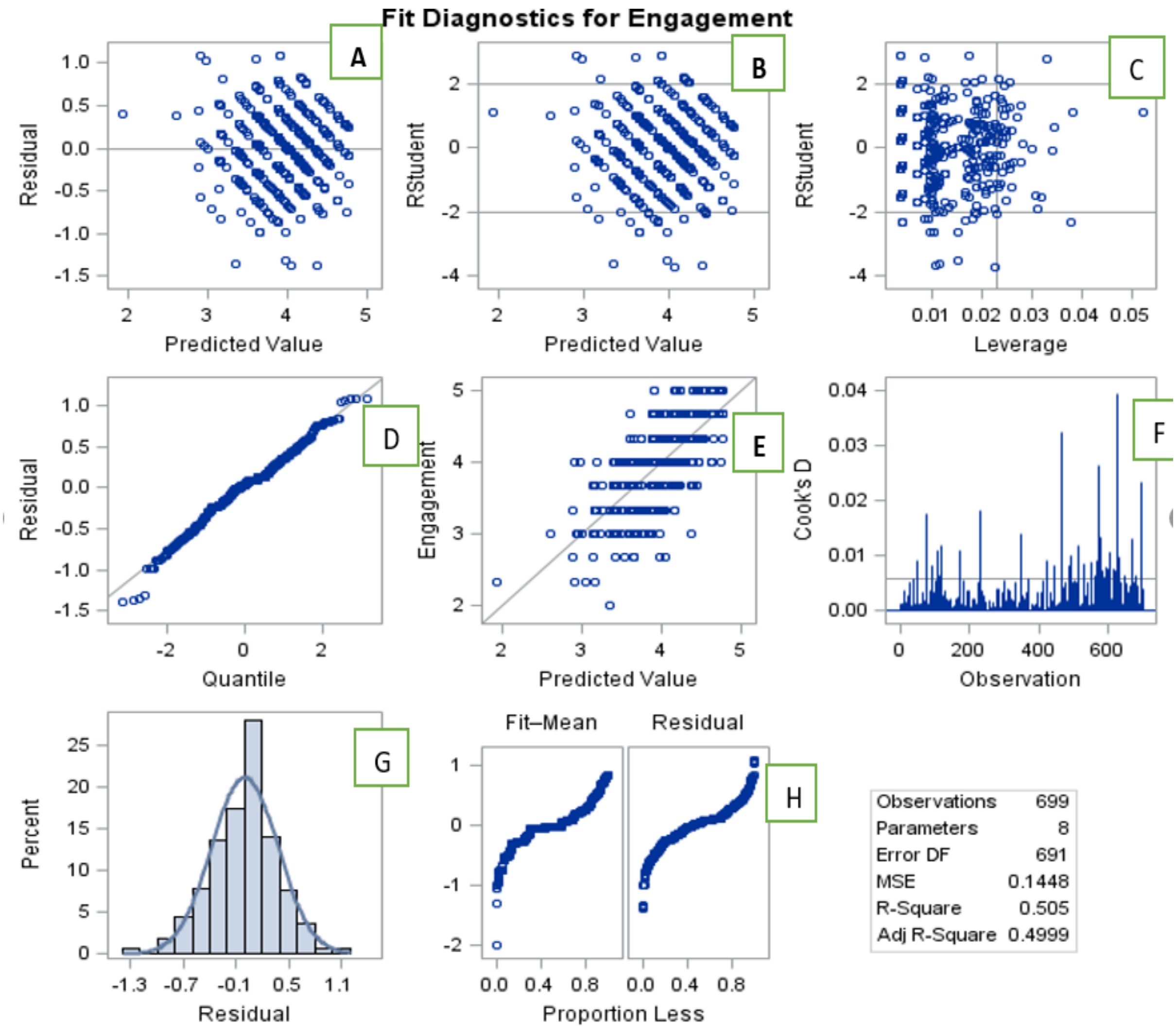

Figure 3: Fit diagnostics for engagement: regression diagnostic plots. Panel A: residuals vs. predicted values; B: RStudent vs. predicted values; C: RStudent vs. leverage; D: Q–Q plot; E: engagement vs. predicted value; F: Cook's D; G: residual histogram; H: fit–mean and residual proportion plots. (Observations = 699; parameters = 8; error DF = 691; MSE = 0.145; R^2 = 0.505; adjusted R^2 = 0.500.)

The plots indicate that the model's assumptions are reasonably met. Panels A and B, plotting residuals against predicted values, show linearity and homoscedasticity with no evident patterns or major outliers. Panel C, studentised residuals against leverage, shows no high-leverage points, indicating a stable regression. The Q–Q plot in panel D confirms that residuals are approximately normally distributed, and panel E shows a positive trend between predicted and observed engagement, reflecting an acceptable model fit. Panel F (Cook's D) reveals no influential outliers, while the residual histogram in panel G and the fit–mean residual plot in panel H further support normality and a consistent residual distribution.

3.7. Analysis of variance

Analysis of variance (ANOVA) was conducted to assess the model's robustness by testing whether the combined effects of the independent variables significantly predict the outcome variable. The fitted regression included the three perceptual predictors (PR, PU and PA) and four additional terms, which were treated as covariates for control purposes: gender, age, prior use of digital tools for sustainability learning, and frequency of accessing sustainability content online. The covariates were included to adjust the perceptual estimates for background variation among respondents; their individual contributions were not the focus of the analysis and are therefore not reported in the main results. Given the model degrees of freedom reported in table 3 (model DF = 7), the complete set of covariates accounts for the four non-perceptual terms in the model.

Table 3
Analysis of variance.

Source	DF	Sum of squares	Mean square	F	p	Adj. R^2
Model	7	102.048	14.583	100.69	<.0001	
Error	691	100.045	0.145			
Corrected total	698	202.093				0.500

The model yielded a highly significant result ($F = 100.69$, $p < .0001$), indicating that the set of predictors collectively explains a reliable portion of the variance in students' engagement with digitally enabled TSE. The relatively low mean square error (MSE = 0.145) indicates a good model fit [38]. The model accounts for 50.5% of the variance in students' engagement ($R^2 = 0.505$; adjusted $R^2 = 0.500$), reflecting substantial explanatory power.

4. Findings

The findings are presented in the order of the study objectives.

4.1. Perceptual factors and perceived engagement with digitally-enabled TSE

The first objective was to identify the key perceptual factors influencing undergraduate students' engagement with digitally enabled TSE. Three perceptual factors, each measured by multiple items, are reported in table 4. Mean scores were interpreted against five bands: very low (1.00–1.79), low (1.80–2.59), moderate (2.60–3.39), high (3.40–4.19) and very high (4.20–5.00).

Table 4
Perceptual factors influencing engagement with digitally-enabled TSE.

Perceptual construct	Mean	SD	Interpretation
Perceived relevance (PR)	4.01	0.57	High
Perceived usefulness (PU)	4.06	0.63	High
Perceived accessibility/ease of use (PA)	3.93	0.64	High
Overall perceptual factors	4.00	0.61	High

Table 4 shows that overall perceptions of the factors influencing students' adoption of digital tools for sustainability education were high ($M = 4.00$, SD = 0.61). Within a narrow band (3.93 to 4.06), PU received the highest rating ($M = 4.06$), closely followed by PR ($M = 4.01$), while PA recorded the lowest of the three ($M = 3.93$) and the largest dispersion (SD = 0.64). Table 5 gives sample items for each construct.

Table 5
Sample items for the perceptual constructs.

Construct	Sample item	Mean	SD
PR	Digital platforms help me understand sustainability issues more clearly	4.18	0.72
	I can relate to sustainability content better when it is presented digitally	3.86	0.84
PU	I find digital tools useful for exploring sustainability solutions	3.96	0.86
	Digital resources improve my comprehension of sustainability topics	4.09	0.79
PA	I find it easy to access sustainability materials online	3.96	0.86
	I feel confident using digital platforms for learning sustainability	3.52	1.13

For the distributional analysis, responses on the five-point scale were collapsed into three categories: "negative" for strongly disagree and disagree, "neutral" for neutral, and "positive" for agree and strongly agree. Figure 4 presents the resulting ratings of the perceptual factors.

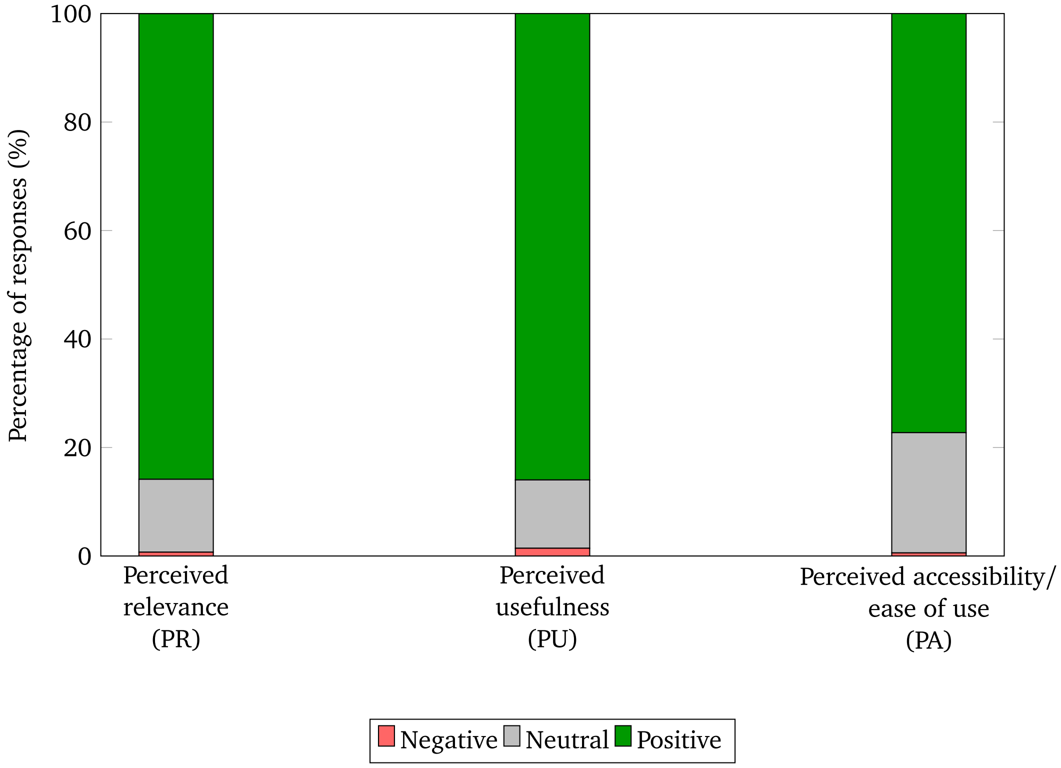

Figure 4: Distribution of undergraduate students' ratings of the digitally-enabled TSE perceptual factors.

As shown in figure 4, fewer than 2% of responses fell into the negative category in any of the three perceptual domains. Neutral responses accounted for 13.43% of ratings for PR, 12.59% for PU and 22.17% for PA. Positive perceptions predominated throughout, exceeding 85% for PR and PU and reaching 77.26% for PA. This pattern aligns with the overall mean of 4.00 and reinforces the generally favourable attitudes towards the relevance, usefulness, and accessibility of digital tools in TSE, while marking PA as the domain in which students were most equivocal.

These descriptive statistics, however, do not capture the extent to which the three perceptual factors are interrelated. A Pearson correlation analysis was therefore carried out to assess their interdependence; the results are presented in table 6.

As table 6 shows, all correlation coefficients were moderately strong ($r \approx 0.45$–0.55) and statistically

Table 6
Pearson correlations among the digitally-enabled TSE perceptual factors.

	PR	**PU**	**PA**
PR	1	0.555 <.0001	0.450 <.0001
PU	0.555 <.0001	1	0.487 <.0001
PA	0.450 <.0001	0.487 <.0001	1

significant at $p < .0001$. The strongest correlation was between PR and PU ($r = 0.55$), followed by PU and PA ($r = 0.49$); the weakest, though still significant, was between PR and PA ($r = 0.45$). These results indicate a mutually reinforcing relationship among the perceptual factors, with each supporting and amplifying the others in shaping students' adoption of digital tools for TSE.

4.2. Perceived engagement in digitally-enabled TSE

The second objective was to assess undergraduate students' perceived levels of cognitive, behavioural, and emotional engagement in digitally-enabled TSE. Table 7 presents sample items for each construct.

Table 7
Sample items for the engagement constructs.

Construct	Sample item	Mean	SD
CE	I challenge ideas using digital sustainability content.	3.85	0.75
	I link digital learning to global sustainability challenges.	4.01	0.80
BE	I share sustainability content online.	3.71	1.01
	I join online forums about sustainability topics.	3.71	0.89
EE	I feel inspired by digital sustainability stories.	4.09	0.86
	I am emotionally affected by digital content on sustainability challenges.	3.68	0.81

CE = cognitive engagement; BE = behavioural engagement; EE = emotional engagement.

Table 8 shows that undergraduate students reported relatively high engagement in digitally-enabled TSE, with an overall mean of 3.92. Emotional engagement scored highest ($M = 4.04$), closely followed by cognitive engagement ($M = 4.03$), while behavioural engagement was comparatively lower ($M = 3.71$). This disparity underscores the multidimensional nature of students' engagement in technology-enhanced environments.

Table 8
Perceived engagement with digitally-enabled TSE.

Latent variable	Mean	SD	Interpretation
Cognitive engagement (CE)	4.03	0.59	High
Behavioural engagement (BE)	3.71	0.75	High
Emotional/motivational engagement (EE)	4.04	0.63	High
Overall	3.92	0.65	High

Figure 5 presents the distribution of perceived engagement across the three domains. CE and EE showed the strongest positive trends, at 84.98% and 84.69% of students respectively, consistent with their mean scores of 4.03 and 4.04. Students thus appear both cognitively and emotionally prepared to engage with sustainability education through digital tools.

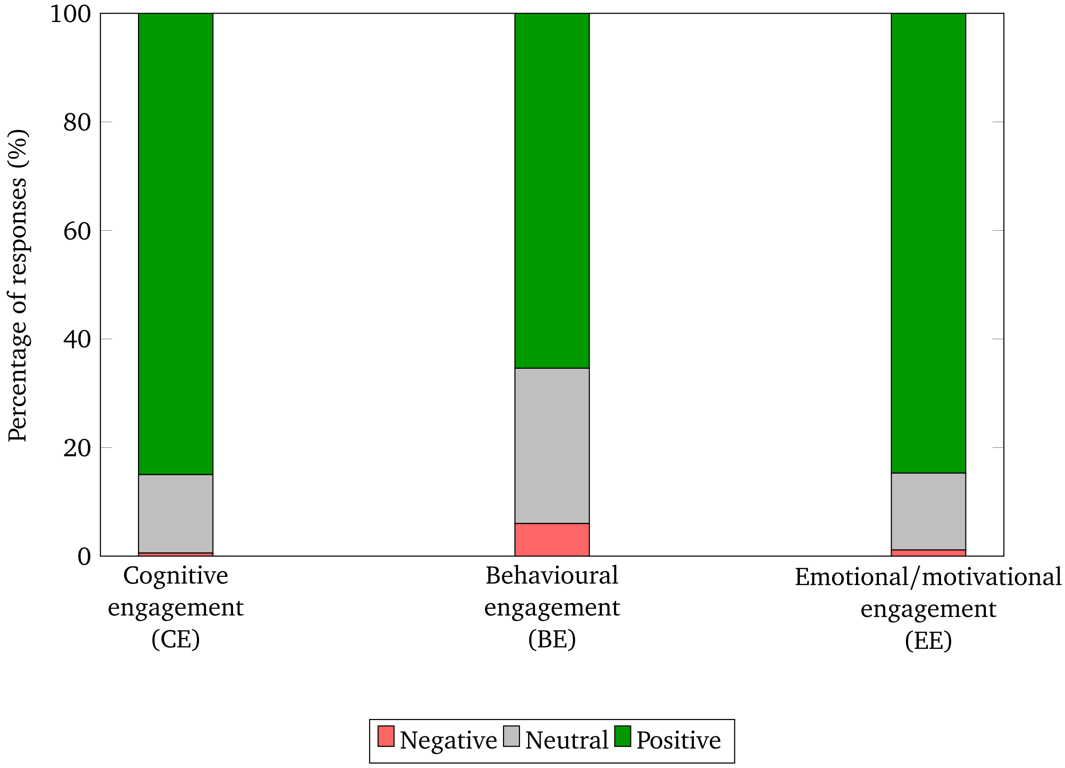

Figure 5: Distribution of undergraduate students' perceived engagement in TSE.

BE, by contrast, drew a lower positive response rate of 65.38%, alongside a notable 28.61% neutral and 6.01% negative responses. Pearson correlation analysis was then conducted to assess the interdependence of the three engagement domains; table 9 presents the results.

Table 9
Pearson correlations among the perceived engagement domains in digitally-enabled TSE.

	CE	**BE**	**EE**
CE	1	0.486 <.0001	0.561 <.0001
BE	0.486 <.0001	1	0.481 <.0001
EE	0.561 <.0001	0.481 <.0001	1

As table 9 shows, all correlation coefficients were moderately strong ($r \approx 0.48$–0.56) and significant at $p < .0001$. The strongest was between CE and EE ($r = 0.56$), followed by CE and BE ($r = 0.49$); the association between BE and EE ($r = 0.48$) was the weakest, though still moderate and positive. These moderate associations suggest that the three dimensions of engagement, while interrelated, remain distinct constructs.

4.3. The impact of perceptual factors on engagement in digitally-enabled TSE

The third objective examined the impact of perceptual factors on students' engagement in digitally enabled TSE. Multiple linear regression was employed; table 10 reports the coefficients for the perceptual predictors.

All three perceptual factors were statistically significant predictors of students' engagement in

Table 10
Parameter estimates for the perceptual factors associated with student engagement in TSE.

Variable	Estimate	SE	*t*	*p*	VIF
Intercept	1.055	0.132	8.00	<.0001	—
Perceived relevance (PR)	0.218	0.031	6.97	<.0001	1.547
Perceived usefulness (PU)	0.253	0.029	8.70	<.0001	1.632
Perceived accessibility (PA)	0.270	0.027	10.02	<.0001	1.411

Estimates are unstandardized. The fitted model comprised seven terms (table 3); the four non-perceptual terms were included as covariates (gender, age, prior use of digital tools for sustainability learning, and frequency of accessing sustainability content online) and are not reported here.

digitally-enabled TSE. PA carried the largest coefficient ($B = 0.270$, $p < .0001$), followed by PU ($B = 0.253$, $p < .0001$) and PR ($B = 0.218$, $p < .0001$); because all three predictors share the same five-point metric, their coefficients are directly comparable. Variance inflation factors ranged from 1.41 to 1.63, well below the commonly accepted threshold of 5.0 [36], indicating no serious multicollinearity and therefore stable, reliable coefficients.

5. Discussion of the findings

5.1. Perceptual determinants of digital engagement in TSE

Undergraduate students expressed strong positive perceptions of the digital tools used in TSE, particularly regarding PU and PR. These findings support TAM's key proposition that users' beliefs about usefulness and ease of use are principal determinants of the acceptance of technological tools for learning [23]. Previous studies [8, 72, 75] likewise support TAM's utility for explaining the uptake of digital technologies in sustainability education.

PU emerged as the most highly endorsed construct, reflecting students' appreciation of the cognitive benefits of digital tools for exploration, critical thinking and problem-solving. This is in line with recent meta-analyses confirming PU as the strongest predictor of acceptance [25, 73]. Contrasting views exist, however: Alqahtani et al. [9] found that system quality, particularly ease of use and interface design, outweighed PU in predicting user acceptance. Such findings underscore the interdependence of the TAM constructs: while PU is foundational, it operates in tandem with ease of use and system quality.

PR also scored highly, but its slightly lower mean suggests that students may find digital tools useful without always aligning with the communication needs of sustainability content. The adoption of digital tools for TSE thus depends on both perceived functionality and contextual meaningfulness for students' learning goals. Consistent with this, the strongest observed correlation, between PR and PU, indicates that students who recognise the relevance of digital tools to TSE are also more likely to perceive them as useful.

PA, though still positive, showed the greatest variability, pointing to disparities in how accessible or easy to use students find the tools. This echoes patterns of digital inequality: some respondents may face barriers to poor internet connectivity, platform complexity, and inadequate digital literacy, all defining features of the digital divide in developing countries, including Tanzania [33, 62]. Such barriers could impede students' sustained adoption and engagement with digitally enabled TSE.

These results highlight the importance of aligning digital technologies with students' academic and sustainability goals, reinforcing the theoretical assumption that relevance enhances perceived value and functional utility within TAM [5, 98]. The alignment between technology and student objectives cultivates more intrinsically motivated learners and calls on educators to design digital experiences that address immediate academic needs as well as broader environmental concerns.

The positive correlation between PU and PA indicates that the more accessible and easier to use digital tools are, the more useful they are perceived to be, which aligns with TAM's predictions and with usability research in educational technology: Han and Sa [37] report a positive effect of ease of use on perceived usefulness. The weakest but still significant correlation between PR and PA similarly suggests that when digital tools are easy to use, students are more likely to see them as relevant to their work in TSE.

5.2. Perceived engagement with digitally-enabled TSE

Undergraduate students reported relatively high perceived engagement in digitally enabled TSE across the cognitive, emotional, and behavioural dimensions. This accords with Schindler et al. [76], who confirmed that technology has positive effects on multiple indicators of student engagement across all three dimensions. The present findings also reveal a cognitive-emotional alignment among participants, alongside a behavioural engagement gap, evidenced by the lower positive response rate and the substantial proportion of neutral and negative responses for BE.

The gap is consistent with Schnitzler, Holzberger and Seidel [77], who found that cognitive engagement is not always matched by behavioural engagement. A lack of opportunities for hands-on involvement and digital learning environments that encourage passive rather than active participation may explain the lower behavioural scores. This contrasts with the systematic review by Bond et al. [16], which examined the relationship between digital technology and student engagement and found that behavioural engagement was the most frequently identified dimension, followed by affective and cognitive engagement. That review, however, did not examine discipline-specific applications of technology, whereas the present study focuses specifically on engagement in TSE.

The weaker association between behavioural engagement and the cognitive and emotional dimensions shows that, while behavioural engagement remains a key dimension, it does not directly follow from the other two. ElSayary, Mohebi and Meda [27] and Ye et al. [96] likewise report a disparity between students' behavioural engagement and their cognitive and emotional engagement, and Borup et al. [17] notes that the emphasis on cognitive over behavioural engagement in virtual learning is long-standing. This disparity points to a gap between students' cognitive and emotional alignment with TSE and their actual participation, highlighting the need to address the contextual and motivational barriers that hinder active engagement in sustainability-oriented action.

5.3. The effect of perceptual factors on engagement with digitally-enabled TSE

The perceived accessibility and ease of use of digital tools were the strongest predictors of undergraduate students' engagement with digitally-enabled TSE. This concurs with Altawalbeh et al. [10], who found that learners with good access to digital tools tend to perceive those tools as more useful and so form stronger engagement intentions, and with Alyoussef [11], who concluded that accessibility, favourable facilitating conditions and ease of use all positively affect e-learning use in higher education. Reducing technological barriers is, therefore, critical to promoting active participation in sustainability practices among instructors and students alike.

The statistical significance of PU and PR further shows that students recognise both the functional benefits and the contextual importance of digital tools for sustainability-related learning. Accessibility alone may have only a limited effect on learners' behavioural intention to engage in sustainability practices [6, 60]; the pathway to engagement is instead mediated by several perceptual factors acting together.

Taken together, the results illustrate that engagement in digitally mediated TSE is shaped by an interplay of psychosocial perceptions and contextual affordances rather than by any single determinant. This supports calls for digitally-enabled sustainability learning environments that are intuitive, contextually meaningful, and conducive to active participation – environments that use technology to bridge personal motivation and situational relevance, so that learners are more likely to internalise sustainability principles and apply them across contexts, which is crucial for long-term behavioural change.

6. Conclusions

This study yields three conclusions regarding perceptual factors, engagement levels, and predictive relationships. First, regarding perceptual factors in digital tool adoption, undergraduate students rated perceived usefulness and relevance highly, while perceived accessibility and ease of use received slightly lower, though still positive, ratings. Students therefore view digital tools as valuable and pertinent for advancing TSE, yet challenges in creating conducive conditions – particularly access to sustainability-related digital content – persist. The moderate to strong correlations among these factors highlight their interdependence, forming a reinforcing cycle that shapes technology adoption in TSE.

Second, at the level of engagement, overall engagement in digitally-enabled TSE was high, with the cognitive and emotional domains surpassing behavioural engagement. This reveals a cognitive-emotional alignment alongside a behavioural gap: students are intellectually and emotionally invested, but practical participation remains unrealised. The moderate correlations across domains underscore their interconnected yet distinct nature. Bridging this gap requires pedagogical strategies that translate cognitive and emotional investment into concrete digital action.

Third, regarding the predictive relationships between perceptions and engagement, multiple regression showed that PA was the strongest predictor of engagement, followed by PU. Although accessibility was rated lowest descriptively, it exerts the greatest influence on engagement, underlining its role in translating perceptions into action in TSE. These findings contribute to the empirical understanding of the relationship between perceptual factors and engagement in digitally enabled TSE, as framed by TAM and EET, and offer educational stakeholders insight into how undergraduate students engage with sustainability education through digital tools in resource-constrained settings.

7. Recommendations

To advance TSE and support the United Nations 2030 Agenda, this study recommends prioritising improvements in digital infrastructure and accessibility. Because perceptual factors are interconnected rather than siloed, strengthening accessibility and ease of use can amplify perceived usefulness and relevance, thereby raising overall engagement, particularly in its behavioural domain. Universities should invest in reliable access to sustainability-related digital resources, such as learning management systems and open educational content, and provide training that reduces technical barriers.

Several delimitations bound these conclusions. The study assessed undergraduate students' perceptions of and engagement with digitally enabled TSE rather than other digitally enabled outcomes. It was conducted at a single public university, and the unit of analysis was undergraduate students enrolled in teacher education degree programmes. That setting, combined with the drawbacks of non-probabilistic sampling, limits the generalizability of the findings beyond this context; further studies could adopt a multi-institutional design to enable broader comparative analysis.

Quantitative data captured measurable patterns of engagement, but not the personal narratives, motivations and challenges that underlie them. A mixed-methods approach using a sequential explanatory design could therefore assess both the perceived and lived experiences of university students as they take up digital tools in TSE.

Finally, a cross-sectional survey based exclusively on self-reported data collected online may be affected by social desirability bias. A mixed methods longitudinal study would help minimise this bias and would track how the cognitive–emotional–behavioural relationship evolves. A qualitative investigation is also needed to uncover the reasons for the behavioural gap, examining both students' perceptions and institutional barriers; such an inquiry would inform more targeted and effective digital pedagogy.

Conflicts of interest

The author reports no competing interests.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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