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Sustainable Practices in Education: Virtual Labs

Maryam Sharifkhani, Jonathan Davidson, Kathryn MacCallum, Jan Evans-Freeman, Cheryl Brown, Chris Bullsmith and Brodwyne Richards
University of Canterbury

The adoption of Virtual Labs (VLs) as a pedagogical tool in higher education is rapidly increasing, especially with the recent shift towards remote learning during the COVID-19 pandemic. VLs offer a digital alternative to traditional laboratory settings, employing computer graphics, simulations, and interactive models to create immersive and interactive learning experiences. While the pedagogical benefits of VLs are well-established, their potential contribution to sustainability within Higher Education Institutions (HEIs) remains ambiguous. This paper aims to address this ambiguity by conducting a literature review to examine the sustainability implications of adopting VLs in HEIs.
This literature review reveals that VLs have the potential to enhance sustainability in HEIs across multiple dimensions. However, the literature highlights challenges and limitations associated with implementing VLs despite the positive indications. These include issues related to usability, technical challenges, and the potential costs associated with the adoption of VLs.
This literature review suggests the need for further research on the adoption of VLs in HEIs, specifically in relation to achieving the SDGs. It emphasises the importance of considering pedagogical aspects and implementing innovative teaching practices to maximise the long-term effectiveness of VLs. By shedding light on the intersection of VLs and sustainability in HEIs, this research contributes to a broader understanding of how adoption of VLs, can foster a stronger connection between people, the environment, and pedagogy, creating the way for a more sustainable and inclusive future of education.

Keywords: Virtual Labs, Sustainability, Higher Education Institutions (HEIs), Sustainable Development Goals (SDGs)

Introduction

The adoption of Virtual Labs (VLs) as an effective pedagogical tool to replace or supplement real lab contexts is growing (Bhute, et al, 2021). While the COVID pandemic has amplified adoption and the move from in-person experiential learning activities to learning that can now occur as a remote or virtual experience, the use of VLs has been growing for some time (Glassey & Magalhães, 2020). Virtual labs take many forms but generally employ computer graphics, simulations, and interactive models to create a ‘digital twin’ to the equipment, environments, and procedures commonly seen in traditional labs (Singh et al., 2021). A range of activities are included under the umbrella of VLs, encompassing individual and group-based experiences. This may involve the inclusion of virtual labs, virtual field trips, virtual simulations, 3D simulations, online labs, and other related activities.

Researchers and educators are increasingly recognising the pedagogical benefits of incorporating VLs into the teaching and learning process and noting the positive impact on various aspects of learning (Chen & Hsu, 2020; Suri et al., 2023; Yu et al., 2023; Yudintseva, 2023), including improving learning outcomes (Phillips et al., 2023), and increasing student engagement with course materials (Chen & Hsu, 2020; Davidson et al., 2022; Ryan et al., 2022).

Alongside these stated pedagogical benefits, VLs have also been heralded as being a more sustainable option compared to in person labs. Often physical labs suffer from limitations that add to the overall cost and availability of conducting laboratory work. Institutions face constraints around the availability of space and resources, access to potentially dangerous chemicals, the cost of expensive equipment and materials, the liabilities of using these tools and the amount of classroom time it takes to set up and conduct experiments (Kapici et al., 2019). As an answer to these constraints, VL have been highlighted as a valid alternative that supports effective learning that is safe and comparatively cost effective (Hsu & Thomas, 2002). In particular, VLs have highlighted the benefits of economic, social, and environmental sustainability. The use of VLs have been highlighted as a valid approach to reduce the need for physical resources, resulting in cost and environmental savings (Anyanwu et al., 2012; Palmarini, 2018; Salmerón-Manzano & Manzano-Agugliaro, 2018). VLs are seen as ways to promote inclusive and equitable quality education (Jones, 2018), and support teaching that is innovative, accessible and safer in many cases (Suri et al., 2023; Zhang et al., 2023).

Although some studies indicate that VLs can support a range of different sustainable benefits in HEIs (Anyanwu et al., 2012; Jones, 2018; Salmerón-Manzano & Manzano-Agugliaro, 2018), there is still ambiguity surrounding the sustainability implications of adopting VLs in HEIs context. In many cases sustainability is mentioned only in passing and not something that is explored as being a primary motivation for the research.

The University of Canterbury (UC) has recently embarked on an initiative that sits within UC's Sustainability Hub to explore more sustainable ways of teaching. With the goal of being carbon net neutral by 2030, UC is exploring innovative practice across all our activities including teaching and research. One of the primary goals of the projects has been to explore how VLs may contribute to key Sustainable Development Goals (SDGs). These SDGs represent a set of 17 global goals aimed at addressing global challenges and promoting sustainable development across various domains.

In order to understand how VLs may be more explicitly linked to wider sustainability goals we have undertaken a review of the literature to determine how sustainability is viewed in terms of VLs. This paper analyses these findings along with a discussion of how we see various VLs initiatives engage with sustainability. We explore the following questions:

- What work has been done to determine the impact of virtual lab educational practices on sustainability?
- How can virtual labs promote sustainability?

By examining various dimensions of sustainability and the literature in relation to how VLs can be adopted in the HEIs context to support sustainable practices we can relate this back to our context to explore how sustainability is driving our universities approaches to teaching and learning.

Concept of Virtual Labs

Virtual Labs (VLs) are a specialised form of virtual learning environment that centre around supporting practical learning activities within a digitally simulated environment. VLs fall under the broader concept of extended reality (XR), which involves the creation of immersive and interactive digital representations of reality (MacCallum, 2022). The term VLs specifically emphasises the aspect of conducting experiments and practical activities in virtual settings (Fridman & Mahajan, 2014). In the context of HEIs, integrating VLs offer an engaging and immersive learning experience for students. Students have the opportunity to engage in hands-on activities and perform experiments virtually, using the immersive and interactive virtual environments (Fridman & Mahajan, 2014). For example, students can manipulate virtual objects, actively participate in practical activities, and observe simulated outcomes within a secure and controlled environment. This facilitates the performance of experiments, the conduction of research, and the exploration of course-related concepts virtually, thereby fostering hands-on learning opportunities (Mohamed et al., 2021; Pathania et al., 2023). It also enhances the laboratory skills of students and fosters positive attitudes towards physics laboratory work. Numerous research studies have explored the use of VLs and related pedagogical strategies in wide range of disciplines and educational programs (Calvert & Hume, 2022; Nagdee et al., 2022; Ray & Srivastava, 2020; Shorey & Ng, 2021; Xue & Crompton, 2022). These include a variety of disciplines including health science and medical education (Silberman et al., 2013; Teles et al., 2020; Wright et al., 2018; Zackoff et al., 2023), engineering (Mohamed et al., 2021), science (Engel et al., 2023; Watson et al., 2022; Zahid Iqbal & Campbell, 2023) psychology and consultancy (Neden, 2020), and art (Yu et al., 2023).

Concept of sustainability

Sustainability is based on the principle that our survival and well-being are interconnected with the natural environment. The pursuit of sustainability involves preserving and striving to create and protect conditions that allow humans and nature to coexist harmoniously, meeting the needs of both current and future generations (United Nations, 1987). Although sustainability is widely recognised in literature, there is still complexity and ambiguity about what it exactly means (Harvey et al., 2022; Owens & Legere, 2015). In educational contexts, the term "sustainability" is described as a flexible and powerful concept, encompassing a wide range of perspectives, beliefs, and goals (Hong & Hardy, 2022). Hong and Hardy (2022) and Weisser (2017) claimed that there is no universally agreed-upon definition of sustainability in HEIs. Instead, these institutions formulate and utilise the term in diverse ways according to their own perspectives and goals. This means that sustainability can be understood and put into practice in various ways by the various stakeholders involved in HEIs (Vargas et al., 2019; Barlett & Chase, 2013).

Economical sustainability encompasses a system of economic processes (e.g., production, consumption, and distribution) that aim to ensure long-term financial performance (Lobo et al., 2015; Madu & Keui, 2012). Within HEIs, this holds significant importance, as HEIs are committed to maximising their current resources in order to advance the quality of education while ensuring the preservation of these resources for future generations (Warr Pedersen et al., 2017). This could include activities and projects aimed at promoting sustainability in various areas such as education, research, campus operations, and community engagement (Marans & Callewaert, 2017).

The social dimension of sustainability emphasises the importance of individual and community interests and well-being. This concept also emphasises the importance of the people in development and incorporates concepts related to equity, empowerment, human rights protection, cultural identity, and social justice (Eizenberg & Jabareen, 2017; Guo, 2017). HEIs with social sustainability will position themselves as institutions that are prepared to contribute resources to the community and improve quality of life (Madu & Kuei, 2012). In addition to ensuring equal access to information, education, and equal opportunities, HEIs can also enhance the development of communities and individuals (Mathiasson & Jochumsen, 2022). Due to the complex nature of social dynamics, scholars argue that social sustainability is a multi-dimensional concept in comparison to economic and environmental sustainability (Deeming, 2021; Saner et al., 2020). As such, evaluating social sustainability is more challenging than evaluating economic and environmental impacts (Vargas et al., 2019; Wolff & Ehrström, 2021).

Environmental sustainability involves utilising natural resources from the environment for a variety of purposes, including energy production, manufacturing, and consumption. The key principle is to ensure that the rate of resource utilisation does not exceed their capacity for natural regeneration over time (Evers, 2018; Mensah, 2019). In HEIs, environmental sustainability is often associated with the management of campus operations (Harvey et al., 2022). This includes addressing various environmental impacts such as energy and water consumption, greenhouse gas (GHG) emissions, and waste generation (Christie et al., 2015). HEIs strive to implement sustainable practices to minimise their ecological footprint and promote environmental conservation within their campus operations. By reducing energy and water consumption, minimizing GHG emissions, and adopting effective waste management strategies, HEIs can contribute to environmental sustainability and demonstrate their commitment to sustainable practices (Findler et al., 2019; Harvey et al., 2022).

In 2015, the United Nations (UN) launched the 17 Sustainable Development Goals (SDGs) including three dimensions of sustainability– economic, social, and environmental--as a comprehensive framework with the aim of improving the well-being of people worldwide (UN, 2015). The purpose of these guiding principles is to encourage sustainable practices and foster a more equitable and environmentally conscious world (Purvis et al., 2019). These goals include making basic services such as water, sanitation, and sustainable energy accessible to everyone, supporting inclusive education and decent work, fostering innovation and resilient infrastructure, reducing inequality, caring for environmental integrity by protecting ecosystems, and promoting collaboration for peace and responsible consumption and production (Saner et al., 2020). HEIs have shown their commitment to sustainability by signing international agreements and engaging with SDGs (Findler et al., 2019). They put efforts to implement SDGs and assess the role of their institutes in promoting sustainable development. These efforts include evaluating education for sustainable development, examining sustainability reporting, and studying specific sustainability assessment tools (SATs) (Berzosa et al., 2017).

Virtual Labs and sustainability

In this section, we explore the role of VLs as digital alternatives to physical laboratories and their potential contribution to sustainable practices. We examine how VLs can impact sustainability in terms of the economy, society, and the environment. Additionally, we evaluate existing studies to identify the presence of sustainability aspects and determine any gaps in research related to specific areas of sustainable development.

The use of VLs can play a crucial role in improving the economic sustainability in terms of resource conservation (Anyanwu et al., 2012). The adoption of VL's reduce the need for physical resources, such as materials and equipment, which can be costly and have environmental impacts. As an example, Anyanwu et al.

(2012) conducted a study on the enhancement of learning objectives in cellular physiology through the use of simple virtual microscopic slides. Their research demonstrated a significant reduction in both time and costs associated with conducting examinations using these virtual slides. Studies also have shown that the use of virtual learning environments resulted in a reduction of face-to-face class time, which in turn increased the opportunity for independent learning (Bak et al., 2023). Incorporating VLs into subjects such as geology and tourism (Schott & Marshall 2018; Watson et al., 2022), which typically require field trips, can also help reduce transportation and logistical expenses (Jones, 2018). Furthermore, with virtual labs, universities can accommodate a larger number of students simultaneously and offer a broader range of experiments and simulations. This scalability and flexibility can lead to optimised resource utilisation and improved efficiency in the delivery of practical education. This aligns with the objectives of SDG 12, which aims to promote sustainable consumption and production patterns. Moreover, VLs require less maintenance than physical laboratories, resulting in cost savings (Palmarini, 2018; Salmerón-Manzano & Manzano-Agugliaro, 2018).

Adopting VLs can potentially lead to a reduction in costs associated with dropout rates and course repetition (Garzón et al. , 2019). By integrating virtual labs, students' comprehension of the subject can be improved, and their motivation to engage in the course can be increased as they have multiple opportunities to do experiments. This further supports the positive impact of integrating VLs into educational settings, particularly in terms of promoting economic sustainability.

Using VLs can promote the health and safety of students and educators. For example, in the context of construction induction, the adoption of VLs can significantly reduce the risk of errors or accidents, ensuring the safety of the students (Suri et al., 2023; Zhang et al., 2023). Also in chemical laboratories VLs provide learners with an opportunity to experience real-life experiments in a risk-free environment, eliminating the need for direct physical contact with toxic chemicals or pathogenic substances (Jones et al., 2018). These benefits can map to the goal of SDG4, which aims to ensure quality education for all individuals.

By integrating VLs into educational settings, HEIs can contribute to the social dimension of sustainability by promoting equitable access to education and fostering inclusive and collaborative learning environments. VLs can provide access to educational resources and experiences to individuals who may face barriers in traditional educational settings (Jones, 2018). Adopting VLs in education can contribute to meeting the SDG 4, which focuses on promoting inclusive and equitable quality education and lifelong learning opportunities for all. Students from remote or underserved areas, those with physical disabilities, or those facing socio-economic challenges can engage in interactive and immersive learning experiences and making education accessible to all through VLs.

Virtual labs provide educators with the ability to design educational activities that encourage student interaction, critical thinking, problem-solving, and collaboration within the virtual lab setting (Delgado et al, 2020). Adopting VLs into educational practices provides educators with the opportunity to explore innovative pedagogies that adopt the interactive nature of virtual environments (Bak et al., 2022). This approach meet SDG 9, which aims to promote innovative teaching methods, expand access to education, and prepare individuals for a knowledge-based and technologically advanced society.

While studies emphasise the adoption of VLs in HEIs and highlight the benefits of VLs in promoting sustainability and enhancing educational outcomes, it is important to acknowledge that some studies have raised concerns about adopting VLs in enhancing sustainability (Akçayır & Akçayır, 2017). There are limitations and challenges associated with the use of VLs in education (Garzón et al., 2019). One limitation is the complexity perceived by students and educators in using VLs (Fraga-Lamas et al., 2018). It can be challenging for students to navigate and use VLs without a well-designed interface and proper instruction. Also, educators need to put additional lecture time to provide guidance for the students on how to navigate and use VLs (Manuri & Sanna, 2016; Patiar et al., 2021). Another limitation in using VLs is the presence of technical issues (Palmarini, 2018). Technical issues can arise due to factors such as software compatibility , network connectivity, hardware performance, and system reliability (Manuri, & Sanna, 2016). These technical challenges can impact the functioning of VLs and disrupt the learning experience of students.

Depending on the specific course and context of using VLs, it is important to consider the potential costs involved. Some VLs may require specialised equipment (e.g. headset, simulator, computer, etc.), which can be expensive in terms of monetary value (Wang et al., 2018; Zendejas et al., 2013). These costs need to be taken into account when considering the feasibility and sustainability of using VLs into educational programs. The below table provides a summary of various aspects related to the adoption of VLs in HEIs settings based on existing literature. It highlights how these aspects can contribute to the SDGs in both positive and negative ways. It is important to note that this mapping is based on our understanding of the studies, and none of them directly map any of the aspects to the SDGs.

Table 1: Mapping the Adoption of VLs to SDGs: Summary and Potential Alignment

Aspects of Adopting VLs in HEIs	Positives and Negatives Contributions	Sustainable Development Goals (SDGs)
Cost	***Positives*** • Reduce in physical resources (e.g., lab materials and equipment) (Anyanwu et al., 2012; Palmarini, 2018; Salmerón-Manzano & Manzano-Agugliaro, 2018) • Reduce duplication and effort and time (Anyanwu et al., 2012; Bak et al., 2022) • Reduce transportation and logistics costs (Jones, 2018) • Reduce costs associate with dropout rates (Zhang et al., 2023; Suri et al., 2023) ***Negatives*** • Equipment Cost (Zendejas et al., 2013) • Maintenance and technical cost (Palmarini, 2018) • VLs training (Patiar et al., 2020; Manuri, & Sanna, 2016).	SDG 8: Promote inclusive and sustainable economic growth, employment and decent work for all SDG 12: Ensure sustainable consumption and production patterns
Student engagement and learning experience	***Positives*** • Enhance students' engagement and learning outcomes (Bak et al., 2022) ***Negatives*** • Complexity in learning (Patiar et al., 2020; Manuri, & Sanna, 2016)	SDG 4: Inclusive and equitable quality education and promote lifelong learning opportunities for all
Health and safety	***Positives*** • Reduce the risk of errors and accidents (Zhang et al., 2023; Suri et al., 2023) • Reduce in direct physical contact with toxic materials (Jones et al., 2018)	SDG 4: Inclusive and equitable quality education and promote lifelong learning opportunities for all
Inclusivity and equitability	***Positives*** • Access to educational resources to individuals with barriers in traditional educational settings (Jones, 2018)	SDG 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all SDG10: Reduce inequality within and among countries
Innovation and creativity	***Positives*** • Enhance students' critical thinking and problem-solving skills (Delgado et al., 2020). • Promote innovative teaching methods (Bak et al., 2022)	SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation

At UC

The UC Sustainability Policy (2021) emphasises the integration of Sustainable Operating Practices as integral elements within the University's operations, signifying its commitment to becoming a sustainable organisation. This section focuses on sustainable initiatives within the educational sector, with a focus on the benefits and outcomes derived from implementing sustainable practices in education.

UC has been using VLs as part of teaching practical activities since at least 2018 (Watson et al., 2022). In 2020 the ALSDO (Alternative Lab and Studio Development Options) was created to further develop and increase to use of remote/distance labs (including VLs) at our university. The work done by the ALDSO group identified VLs as an effective way to teach practical activities, especially those that involve repetitive tasks for the teaching staff, location-based learning and learning involving large datasets such as maps and high-resolution images (Engel et al., 2023; Watson et al., 2022). VLs were also identified as a way to achieve the university sustainability goals.

In 2021 a specialized dedicated position was created to further accelerate the adoption and use of VLs. Since then, VLs have been created for ~ 10 different classes in a wide range of practical teaching applications. Labs were created for geology, biology, mechanical engineering, chemical and processes engineering, speech and language pathology, and innovation in design (part of an MBA degree) courses. The VLs approach in these courses were chosen for a variety of factors, such as:

- Health and Safety inductions in classes with large numbers of students
- Difficult access to lab equipment due to small lab size
- Lack of budget and opportunity for traveling to off campus locations
- Destruction/removal of location where learning occurred.
- Labs where practical applications were too dangerous to run with students present.
- Developing specific skills that are re-used throughout the degree.

Project reporting on the development of the labs showed that the VLs were helping UC achieve improved learning outcomes for students, by providing unique content that overcame the challenges identified, but also but as a resource that can be revisited and self-paced. Success of the VLs in meeting the desired outcomes were measured using teaching staff and student feedback.

The labs also helped the university meet several SDGs. In the case of a geology course on volcanoes, the virtual practical exercises have been used to create a Massive Open Online Course (MOOC) (Watson et al., 2022). This meets, amongst other, the SDG targets 4.4. An exercise on video-fluoroscopy for dysphagia assessment can reduces the use of chemcials while teaching the same learning goals, helping meet SDG target 12.4. In general terms, the VLs enable cost saving and reduced UC footprint, as the VLs were able to provide location-based learning without the need for students to travel large distances each semester. Another benefit is that the same VLs can be reused in subsequent semesters and with other courses. The VLs also improved resilience in teaching, as the VLs can be used anywhere/any time/for any number of students. VLs also improved flexibility in timetabling and reduced the use of the demand on lab space, as there was a reduced need to book the labs for teaching or schedule external personnel to demonstrate concepts.

Discussion and conclusion

VLs have gained significant popularity in HEIs as they have been found to have a positive influence on the learning and teaching experience of both students and educators. In this literature review, we examined several studies on VLs and their relationship with sustainability and the SDGs and we demonstrated that the adoption of VLs can have both positive and negative impacts on promoting sustainability.

When evaluating sustainability on campus, it is crucial to consider HEIs as both a business entity and an educational institution. This perspective acknowledges that HEIs have operational and organisational aspects alongside their educational mission. While many studies focus on Education for Sustainable Development (ESD) and teaching sustainability (Adefila et al., 2021; Hourdequin et al., 2018) this work takes a broader perspective by examining how VLs can enhance sustainability when considering the university as a business entity that needs to align with the SDGs.

This research aims to address ambiguity around the terms “sustainability” in HEIs by examining various dimensions of sustainability and exploring existing research that links VLs with sustainability and the SDGs. Although some studies indicating that VLs can promote sustainable operation in HEIs (Anyanwu et al., 2012; Jones, 2018; Salmerón-Manzano & Manzano-Agugliaro, 2018) our research findings aligns with other studies (Harvey et al., 2022) indicate that the ambiguity surrounding the sustainability implications of integrating VLs in HEIs still persists. Also, the existing literature does not effectively demonstrate how the adoption of VLs in HEIs aligns with the SDGs. This may relate to how the impact of VLs can be measured and evaluated in terms of SDGs (Berzosa et al., 2017). This literature review suggests, taking a strategic approach to the SDGs, conducting an assessment on the current, potential, positive and negative impacts that VLs may have on meeting SDGs. This will help identify where positive impacts can be scaled up and where negative impacts can be reduced or avoided.While research has demonstrated the potential of VLs as a sustainable practice in HEIs, it is important to consider the pedagogical aspects of incorporating VLs. For instance, Neden (2022) highlighted that VLs are not widely adopted due to perceived usability, usefulness, and cost barriers. It is important to understand how this technology can enhance existing teaching and learning practices and align with sustainability goals. In another word, for VLs to be effectively used in HEIs, flexible and innovative pedagogies are required (Calvert & Hume, 2022). This literature review proposes the need for additional research to examine the importance of implementing pedagogies that ensure the long-term effectiveness of VLs in courses, both in terms of enhancing learning outcomes and promoting sustainability.

In conclusion, by adopting VLs in HEIs educators have the opportunity to establish collaboration with environment and use innovative pedagogies to create inclusive and equitable learning experiences for students. VLs offer a sustainable approach that promotes collaboration, engagement, and interactive learning, transcending geographical barriers and providing access to educational resources for all. Through the adoption of VLs, HEIs can foster a stronger connection between people, the environment, and pedagogy, creating the way for a more sustainable and inclusive future of education.

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