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Learning in Evolving Ecologies: rethinking the relations between Humans, Nature and Technology

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Abstract: This contribution outlines a co-evolutionary pedagogical perspective by clarifying the foundations of an ecological approach to learning. Drawing on Bronfenbrenner's (1977) bioecological model, learning is interpreted as the outcome of a multilayered system in which individuals, natural environments and technological mediators continuously interact. The theoretical-critical investigation within this framework explores the potential of hybrid learning ecologies, understood as learning environments that integrate sensory immersion in nature, collaborative environmental engagement, and reflective technological mediation, to foster ecological understanding and transformative competencies. Drawing on a critical synthesis of the scientific literature, the study contends that understanding how ecological relationships shape learning processes is essential for reimagining education in an era of sweeping environmental and technological change. The analysis highlights how such hybrid ecologies can promote perspective shifts, embodied awareness and systemic thinking, thereby strengthening learners' ability to recognise interdependencies and to act within complex socio-ecological contexts. From this perspective, nature emerges as an active agent in the development of ecological sensitivity, while "slow" and intentional technologies function as reflective mediators without replacing direct environmental experience. The co-adaptive process between learners, tools and environments ultimately provides a conceptual basis for designing educational practices oriented toward sustainability and relational literacy.

Keywords: co-evolutionary pedagogy; hybrid ecologies; transformative learning.

1. Introduction

In the contemporary educational landscape, learning can no longer be interpreted as an isolated or purely cognitive phenomenon. This article proposes a theoretical framework of co-evolutionary pedagogy, defining learning as an emergent process arising from dynamic and reciprocal relationships between humans, nature, and technology. From this perspective, learners are not atomized individuals but active participants embedded in complex systems, where knowledge is co-constructed through continuous interaction (Tyrrell & Shalavin, 2023). Growing global challenges require overcoming the rigid distinction between digital and non-digital realities (Forsler et al., 2024). In such contexts, technology ceases to function as a neutral tool and instead becomes an integral component of meaning-making processes, actively shaping hybrid learning ecologies (Lacković et al., 2024; Niekerk & Schmidt, 2016). These ecologies integrate embodied and physical experience with digital mediation,

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calling for new forms of critical thinking and ethical awareness (Sung & Nathan, 2025). While traditional educational approaches have primarily focused on human systems (Shafi, 2020), this study reinterprets the role of non-human elements - such as ecosystems, climate, and artificial intelligence - as constitutive components of educational ecology (Sinnema et al., 2023), drawing on Bronfenbrenner's bioecological model. This perspective is essential for cultivating transformative competencies, including systemic thinking, ethical reasoning, and ecological literacy, which are increasingly necessary for navigating contemporary uncertainty (Redman & Wiek, 2021). This contribution offers a pedagogically generative analysis of education as a system of interdependencies and co-adaptations, emerging from the interaction between nature -understood as a co-educator - and technology, conceived as a mediator of reflection in individual development. To this end, a theoretical-critical analysis of existing literature in education, post-digital studies, ecological psychology, and sustainability was conducted. The document aims to contribute by (i) framing nature as a co-educator, (ii) conceptualising 'slow' technologies as reflective mediators, and (iii) proposing a perception–action–reflection continuum to guide the design of hybrid learning ecologies. Furthermore the article intends to develop this framework by first outlining co-evolutionary pedagogy in postdigital ecologies, then reframing Bronfenbrenner's bioecological model for contemporary learning environments, and finally articulating key dimensions and illustrative pathways for designing hybrid learning ecologies oriented toward ecological understanding and transformative competencies.

2. Co-evolutionary pedagogy and bioecological development in post-digital ecologies

Co-evolutionary pedagogy conceptualises learning as a relational and non-reductionist process in which knowledge emerges through dynamic interactions rather than through purely representative accounts of an objective external reality. This orientation aligns with ecological and post-digital paradigms, which challenge linear causality and instead focus on interdependence, uncertainty and co-adaptation as distinctive features of learning and development (Niekerk & Schmidt, 2016). In post-digital contexts, the boundaries between digital and non-digital realities become increasingly difficult to maintain, giving rise to hybrid learning ecologies that integrate embodied experience, social relationships and digital mediation into interconnected educational ecosystems that require critical reflection, ethical awareness and equitable participation (Forsler et al., 2024; Lacković et al., 2024). In this framework, interdependence and reciprocity emerge as key principles: learning arises from the reciprocal relationships between humans, nature and technology, transcending simple cause-and-effect models (Laat et al., 2020; Tyrrell & Shalavin, 2023). Hybrid ecologies therefore combine physical, digital and ecological spaces to enable context-sensitive learning (Sangrà et al., 2019), while promoting a clearer understanding of distributed action and power dynamics between human and technological actors. Studies suggest that such approaches can support student action, resilience, and sustained engagement over time (Gulikers & Visscher, 2025), although their complexity has been criticised; nevertheless, relational pedagogies have the potential to address integrated challenges such as digital inequality (Herodotou et al., 2019); ultimately promoting post-digital growth and environmental responsibility (Sung et al., 2024). Building on these considerations, Bronfenbrenner's bioecological model further clarifies how development occurs in these hybrid conditions, namely as a dynamic process shaped by ongoing interactions between individuals and their evolving environments (Bronfenbrenner, 1977; Bronfenbrenner & Morris, 2007), and organised through nested systems – microsystems, mesosystems, exosystems, macrosystems and chronosystems – that interact over time (Sinnema et al., 2023). Recent studies redefine this

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model for post-digital contexts, recognising digital infrastructures, virtual microsystems, and technological subsystems as constituent elements of contemporary developmental ecologies (Johnson & Puplampu, 2008; Navarro & Tudge, 2022; Spencer, 2024). From this perspective, learning emerges through reciprocal and proximal processes within a network of physical, social, technological, and ecological systems (Schlüter et al., 2025), not simply by adding technology as an additional layer, but by reinterpreting development itself as co-evolution within distributed, socio-ecological, and technology-mediated relationships.

3. Key dimensions of co-evolutionary learning ecologies

Starting from this theoretical framework, which interprets learning and development as co-evolutionary processes situated within hybrid and interdependent systems, it becomes necessary to clarify the operational dimensions through which co-evolutionary learning ecologies take shape in post-digital educational contexts. The dimensions that characterise co-evolutionary learning ecologies highlight the intertwined roles of nature, technology and embodied cognition in shaping learning processes in post-digital contexts. In particular, four key dimensions can be identified and articulated as follows: *a) Nature as an active co-educator*, where nature is understood not as a passive backdrop, but as an active participant in learning. Direct engagement with natural environments can foster ecological awareness, ethical understanding, and the development of ecological identity, while supporting cognitive and emotional development through immersion in ecological complexity (Vossoughi et al., 2023); b) *technology as a reflective mediator*, highlights that technology, when used with critical reflection, enhances observation and collaboration without replacing direct sensory experience (Van Kraalingen, 2021, 2022); conversely, when digital tools are used without educational intent, they risk weakening the richness of the experience. Careful design is therefore essential to ensure that technology supports reflection rather than inhibiting ecological connection. In line with post-digital education, technology is thus conceived as an integral part of learning rather than as an external element of discontinuity. Challenging the rigid distinctions between online and offline, hybrid models that integrate digital tools into physical and ecological contexts (Forsler et al., 2024) are favoured, while paying attention to ethical risks such as data practices and algorithmic biases (McLay & Reyes, 2019); c) *Embodied and ecological cognition within hybrid learning ecologies* emphasises the centrality of sensorimotor experience in learning and the emergence of understanding through physical engagement with the environment (Ionescu & Vasc, 2014; Kiefer & Trumpp, 2012). From an ecological psychology perspective, learning arises through continuous interactions between organisms and their environments (Raab & Araújo, 2019), a process that becomes particularly evident in hybrid learning ecologies, where understanding is constructed through interconnected physical and digital spaces (Abrahamson & Mechsner, 2022), supported by the 4E cognitive framework:embodied, embedded, extended, and enactive (Lebert & Vilarroya, 2024); d) *the perception-action-reflection continuum* brings these dimensions together by clarifying how embodied encounters within hybrid ecologies transform into reflective and meaningful learning, strengthening ecological understanding and transformative competence.

4. Hybrid Learning Ecologies and the Perception–Action–Reflection Continuum

Hybrid learning ecologies conceptualise learning as distributed across physical spaces, digital platforms and social relationships, where hybridity is not just a modality

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but a constitutive condition that reshapes participation and meaning-making (Raes, 2022). Based on sociocultural theory, HLEs frame learning as situated in historical, cultural, and institutional contexts (Goodyear & Carvalho, 2014), while embodied approaches emphasise how cognition emerges through the continuous coupling of perception, action, and environment (Gomez Paloma, 2017). From a networked learning perspective, knowledge is distributed across people and tools, requiring learners to develop advanced interpretation skills in complex environments (Gourlay et al., 2021). In such ecologies, action is not individual but distributed across learners, educators, and technologies (Bandura, 2001; Zimmerman, 2002), supporting participation, identity development and collective knowledge creation (Hutchins, 1995). The perception-action-reflection continuum for co-transformative learning (Mezirow, 2018) translates as an iterative process within co-evolutionary pedagogy. Encountering ecological systems generates dilemmas that challenge existing assumptions and stimulate reflection, promoting transformative learning based on ecological identity and ethical commitment (Burns, 2011). Within this continuum, technology can enhance awareness and reflection by enabling a shared understanding of complex environmental contexts, strengthening systemic thinking and supporting students in navigating uncertainty. Co-evolutionary pedagogy thus offers educators a framework for designing learning environments that integrate sensory experience, technology, and ecological responsibility (Berglund, 2024), while promoting inclusive participation. In this approach, educators act as co-designers of learning environments, facilitating dialogue and inquiry rather than transmitting content, in line with transformative learning theories that emphasise reflection and action (Webb et al., 2023).

This conceptual framework is reflected in a growing number of educational initiatives, both nationally and internationally, demonstrating how the principles of post-digital education and co-evolutionary pedagogy can be effectively implemented in real learning environments. In all these contexts, practices consistently emphasise the responsible and reflective use of technology to support, rather than replace, direct engagement with the natural world, fostering ecological awareness, critical reflection and transformative learning. In Nordic countries such as Finland and Sweden, outdoor education programmes are increasingly adopting hybrid learning ecologies that combine immersive experiences in natural settings with digital tools, including augmented reality applications, mobile biodiversity mapping, and geolocation-based learning platforms (Rustamova, 2023). These practices are in line with post-digital principles, as they integrate technology into learning processes in ways that support situated observation and collaborative inquiry without compromising embodied experience. Similarly, in the UK, urban eco-pedagogical initiatives such as Nature in the Digital Age engage students in monitoring local environmental conditions through digital sensors, mobile applications, and participatory mapping, promoting ecological literacy and collective understanding. In these examples, the perception-action-reflection continuum becomes clearly visible through cycles of field observation, participatory investigation, and shared reflection supported by digital mediation.

Similar approaches are also emerging in the Italian context. The educational project Sulle tracce della natura (On the Trails of Nature, Autonomous Province of Trento, 2022) offers students the opportunity to explore local ecosystems through interdisciplinary fieldwork supported by digital tools such as mobile applications for species identification, collaborative map creation and digital storytelling. In Emilia-Romagna, networks of schools committed to sustainability and health promotion (Scuole che Promuovono Salute) have developed learning pathways that integrate environmental education with digital literacy, encouraging students to document and critically reflect on their experiences in nature (Emilia-Romagna Region, 2021). In all these pathways, the perception-action-reflection continuum is again evident, as direct

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ecological encounters lead to situated actions and reflections structured through documentation, dialogue, and collaborative meaning-making (Jandrić & Ford, 2022).

5. Conclusion

This article has proposed a co-evolutionary pedagogical framework for understanding learning and development in post-digital educational ecologies, conceptualising them as emergent processes arising from dynamic and reciprocal relationships between humans, nature and technology. Moving beyond reductive and anthropocentric models of learning, the framework positions education as a system of interdependencies in which knowledge, agency and identity are continuously co-constructed within hybrid and evolving environments.

By reframing Bronfenbrenner's bioecological model for contemporary contexts, the contribution highlights how learning unfolds through proximal processes situated within nested socio-ecological and technological systems. Rather than treating technology as an external addition to educational settings, the analysis underscores its constitutive role in shaping developmental ecologies, while simultaneously emphasising the need for critical, ethical and reflective engagement. In this sense, post-digital learning environments are not defined by the mere presence of digital tools, but by the quality of the relationships they mediate and the meanings they enable.

A key contribution of the article lies in articulating four interrelated dimensions of co-evolutionary learning ecologies: nature as an active co-educator, technology as a reflective mediator, embodied and ecological cognition, and the perception–action–reflection continuum. Together, these dimensions provide a coherent pedagogical lens for designing learning environments that foster ecological understanding, systemic thinking and transformative competence. The perception–action–reflection continuum, in particular, offers a generative model for translating embodied encounters with ecological complexity into reflective learning and ethical commitment, supporting learners in navigating uncertainty and cultivating ecological responsibility.

The illustrative educational practices discussed demonstrate that co-evolutionary pedagogy is not merely a theoretical construct, but an emerging orientation already informing educational innovation across diverse contexts. These initiatives show how hybrid learning ecologies can sustain meaningful engagement with the natural world while leveraging digital mediation to enhance observation, collaboration and collective sense-making, without displacing embodied experience.

From an educational perspective, the framework redefines the role of educators as co-designers of learning ecologies, responsible for orchestrating conditions that enable dialogue, inquiry and reflection rather than transmitting predefined content. Such a shift has important implications for teacher education, curriculum design and educational policy, particularly in relation to sustainability education, digital ethics and inclusive participation.

Future research is needed to empirically investigate the impact of co-evolutionary learning ecologies on learners' ecological identity, agency and long-term engagement, as well as to explore how these approaches can be adapted across educational levels and socio-cultural contexts. Nonetheless, this contribution argues that embracing co-evolutionary pedagogy is not simply an option, but a pedagogical necessity in addressing the intertwined ecological, technological and educational challenges of the contemporary world.

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