ISSN 2965-1557
http://doi.org/10.1590/2965-1557.037.e202532177

Scientific article

Revista de Filosofia Aurora

periodicos.pucpr.br/aurora

PUCPRESS

Edu-eco-communities: designing sustainable and community based learning environments

Edu-eco-comunidades: conceber ambientes de aprendizagem sustentáveis e comunitários

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Como citar: DI PAOLO, Laura Desirèe. Edu-eco-communities: designing sustainable and community based learning environments. *Revista de Filosofia Aurora*, Curitiba: Editora PUCPRESS, v. 37, e202532177, 2025. DOI: https://doi.org/10.1590/2965-1557.037.e202532177

Abstract

The Anthropocene era, marked by limited resources and shared responsibility for their use, calls for educational settings to model eco-sustainable practices against resource misuse and waste. To achieve this, learning environments should mirror the ecological realities of the Anthropocene by offering limited resources to be shared and preserved across generations. They should also foster democratic, participative practices to distribute the responsibility of resource conservation. Given the urgency of redirecting educational practices toward sustainability, we draw on the well-established Montessori Method, which exemplifies eco-sustainable learning by integrating local resources with specially

[1] Funding: ERC SYNERGY GRANT *XSCAPE* - Material Mind. **ERC-2020-SyG 951631.**

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designed educational tools. Additionally, its principles of freedom, organisation, care, and rituals demonstrate democratic participation in governance.

Keywords: Eco-sustainable education. ecological redirection. Montessori Method. Limited resources.

Resumo

A era do Antropoceno, marcada por recursos limitados e responsabilidade compartilhada pelo seu uso, exige que os ambientes educacionais sirvam de modelo para práticas ecologicamente sustentáveis contra o uso indevido e o desperdício de recursos. Para isso, os ambientes de aprendizagem devem espelhar as realidades ecológicas do Antropoceno, oferecendo recursos limitados a serem compartilhados e preservados entre as gerações. Eles também devem promover práticas democráticas e participativas para distribuir a responsabilidade pela conservação dos recursos. Dada a urgência de redirecionar as práticas educacionais para a sustentabilidade, nos baseamos no bem estabelecido Método Montessori, que exemplifica o aprendizado eco-sustentável ao integrar recursos locais com ferramentas educacionais especialmente projetadas. Além disso, seus princípios de liberdade, organização, cuidado e rituais demonstram a participação democrática na governança.

Palavras-chave: *Educação ecossustentável. Redirecionamento ecológico. Método Montessori. Recursos limitados.*

Introduction

When we think of 'schools' (at least in Western societies), we might envision buildings that accommodate pupils in classrooms, separated by corridors. In each classroom, children and young adults of approximately the same age sit at desks and listen to lessons delivered from the front of the room by a teacher. Pupils are expected to listen to these lessons, take notes, and memorise as much information as possible, supported in their at-home work by books or other provided materials. While there is obviously a certain level of (required) independent work, such as writing essays or building science projects, pupils are evaluated through standardised tests that 'demonstrate' how much of the information supplied by the teachers during the lessons has been retained. Although there are differences among schools and teachers, this traditional or - more correctly - teacher-centred approach is still dominant in contemporary formal education[2]. This is despite the increasing amount of data provided by multiple parties (ranging from quantitative and qualitative research to self-attestations by instructors and students) reporting the preference for the opposite, student-centred approach. This latter not only enhances information retention but, most importantly for the aim of the present work, stimulates motivation, participation, and fosters a more democratic engagement of pupils in their learning journey (e.g., Marking; Garcia Mollá, 2022; Harris *et al*., 2013; Smit *et al*., 2014; Bature; Campus, 2020; Souleles, 2017; Mullamaa, 2017; Di Felice, 2018; Zucconi, 2016; Helmi, 2019; Elen *et al.,* 2007; Starkey, 2019; Rappleye; Komatsu, 2024; Yilmaz, 2007; Altinyelken, 2015; Jahan *et al.,* 2022).

This paper's topic is an attempt to depict how schools and formal education could transform in the face of the global climate challenges brought about by our new Anthropocene era, and it is naturally related to how educational systems run and are organised. Facing the challenge of turning schools into more eco-friendly institutions and designing materials and spaces that allow the use, reuse, and recycling of resources - instead of abusing and wasting them - implies exploring how society can transform education to prepare students to become effective global citizens. This transformation involves promoting eco-ethical behaviours and practices that empower students to address the increasingly urgent ecological challenges of the future. While we will discuss these two aspects separately for analytical purposes, they are deeply interconnected. Integrating eco-sustainable behaviours, design, and materials into formal education also requires the adoption of democratic and participatory practices (e.g., Ferreira, 2017; Engdahl & Furu, 2022; Wals *et al*., 2014; O'Brain *et al.,* 2013). It has been pointed out, in fact, that eco-sustainability policies aiming to assure the capacity of the Earth's system to support humanity are effective only if upheld by socio-political actions driving toward more democratic, horizontal, and participative forms of governance (e.g., Rockström; Gaffney, 2021; Steffen *et al*, 2018; Donges *et al*., 2017; Steffen & Smith, 2013; Steffen *et al*., 2015; Griggs *et al*., 2013; Westley *et al*., 2011; Biermann, 2012; Biermann *et al*., 2012; Galaz, 2014; Lade *et al*., 2020; Sterner *et al*.,

[2] It is quite challenging to find comprehensive data on this specific teaching approach, even limiting the research to European countries. However, sources such as the European Commission (https://education.ec.europa.eu/resources-and-tools/education-and-training-statistics), UNESCO (https://www.unesco.org/en/articles/global-report-teachers-what-you-need-know), the Eurydice Network, which provides data and analyses on European education systems (https://eurydice.eacea.ec.europa.eu/publications/learning-sustainability-europe-building-competences-and-supporting-teachers-and) suggest that the teacher-centred approach is still the most widespread educational methodology across Countries. This data strictly contrasts with the necessity to modify educational systems, which, at least in Europe, has been established since the Bologna Process report in 2009 (see: Bologna Process, 2009; Bologna Secretariat, 2010; see also: Geven & Attard, 2012.

2019). Educational settings, as the primary locations where eco-sustainable practices should be implemented, must then absolve a leading position toward global ecological redirection of human behaviour also in terms of democratic participation in governance (e.g., Komatsu *et al*., 2023; Ledley *et al*., 2017; Lutz *et al*., 2014; Lee *et al*, 2015; Bengtsson *et al*., 2018). This immediately raises the question of who steers the gears of the educational practices: the pupils - as in the student-centred approach -, or the teachers - in the more well-known traditional system described above. We propose a third approach, where students, teachers, and learning ecologies work synergistically in education, simultaneously fostering eco-sustainable practices as a byproduct.

Given space constraints, the vagueness of concepts such as the student-centred approach, and the urgency[3] of the matter at hand (i.e., eco-sustainable redirection of educational practices), in this paper we look at established and globally spread pedagogies which have the "purpose of educating planetary citizens to adopt life-long caring and appreciation for nature" (Kopnina, 2020: 284), and already adopt eco-sustainable, collaborative, and low-tech educational tools (See also: Geven; Attard, 2012; Bayram-Jacobs; Hayırsever, 2016; Tangney, 2014; Zairut, 2020; Starkey, 2019). In particular, we take inspiration from the Montessori Method (MM), which has been longly recognised as having a leading position in eco-sustainable educational practices (Sutton, 2009). This is a practical choice. We assume that different practices as well as the implementation of up-to-date technologies (e.g., virtual tools, 'Smart' environments, Large Language Models), along with their re-design for collaborative activities (e.g., Yuill, 2021) are also crucial to transforming educational systems in the face of ecological challenges (e.g., Ronaghi, 2023; Kövecses-Gõsi, 2019; Negi, 2024, Contreras-Taica *et al*., 2022; Grajewski *et al*, 2015; McWhorter; Delello, 2016).

In the following, we will briefly analyse the MM, a form of student-centred approach that grounds its methodology on pupils' interests, skills, and abilities, in terms of community and democratic participation in educative policies (Sec. 3). Thus, the MM inherently relates to different educational theories such as the 'Philosophy for the Children' or the 'Democratic School' (Scarpini, 2020; Furtschegger, 2024; Oprescu *et al*., 2011; Goldshmidt, 2021; Thayer-Bacon, 1996; Carnie, 2017. See also: De Stefano, 2022; Frierson, 2016b; 2019). We will also look at MM's employment of low-tech, eco-friendly, and collaborative resources (Sec. 2). In this sense, the practical preference for MM turns into theoretical. Two foundational aspects of the methodology, the freedom of choice and the limitedness of resources - that are property of the ecological embedding, the classroom - better equip the MM to mimic the ecological conditions of the Anthropocene, in which resources are limited and citizens are invited to re-use them, without abuse or waste, acting as *communities* for their preservation.

[3] Cosidering also the significant ecological impact of schools on the environment, primarily through energy use, transportation, waste production, and material consumption. See, e.g.: https://www.gse.harvard.edu/ideas/usable-knowledge/21/11/why-schools-need-look-their-own-carbon-footprint]

1. The Montessori Method

Conceived by the Italian physician Maria Montessori at the beginning of the twentieth century, the MM is organised around the idea that development and learning are embodied and enacted processes, in which sensorimotor system and cognition are intertwined, and knowledge, concepts and high cognitive abilities dynamic result from the interaction between children's autonomous exploration and their material embeddings[4]. In the MM, teaching happens indirectly, through the design and organisation of the materiality of learning, the classroom and its artefacts, known as 'prepared environment'. Education occurs when pupils interact with their 'prepared environment', an immersive ecology of purposely designed educational objects, organised in hierarchical complexity and presented by the teachers at the appropriate time. Being a test-free environment, teachers evaluate students' understanding and readiness for learning by observing their engagement with the material, especially their accurate use of it. 'Frontal' lessons—if they can be called that in the MM, especially in the lower grades—occur when a teacher presents the material and demonstrates its use to a single student or a small group of up to 4 or 5 pupils. Mostly, pupils work alone or in self-established groups around a material or a task, at their own pace and following their own inclinations. While a detailed description of the MM is beyond the scope of this work, it is important to note that much of the educational practices occur through interaction with the material environment. This has three key implications First, certain material and pupils' cognitive functions are strongly coupled, at least for a certain time, forming a complex bio-ecological, extended system in which pupil and material cannot be separated (e.g., Frierson; Di Paolo, 2024). Secondly, the classroom serves as an example of distributed cognition, where - for instance - the connections between different subjects of inquiry are physically manifested through the arrangement of materials and their placement within the space (Di Paolo *et al*., 2024; Lillard, 2017). Finally, materials are respected and cared for in their own right, deserving treatment similar to that of other human and non-human agents (e.g., plants, animals). A significant portion of the MM curriculum is dedicated to 'Exercises of Practical Life,' such as sewing, cooking, and tidying up. Students are also expected to use materials properly and return them to their designated places, ensuring availability for their peers (Lillard, 2017). These simple behaviours transform educational materials into ecological resources. Unlike single-user, annually replaced textbooks and artefacts in traditional education, MM materials are shared, collective resources that must be preserved for future generations.

In the next sections, we will explore the eco-sustainable and community-based selection and interaction with educational materials. It is important to note that in a typical MM school, the educational artefacts can be categorised into three types: traditional, local, and 'method-specific'. By "traditional", we refer to the various educational materials and resources that are commonly available in learning environments. These include physical books, computers, tablets, paper, art supplies such as colours, and other tools that can

[4] In order to avoid weighting down the conversation, we do not quote all references in the text for what concerns the MM method. However, for references, see: e.g., Montessori, 1994; 1996a; 1996b; 1997; 2011; 2017; 2023; Ahlquist, 2023; Saha; Adhikari 2023a; 2023b; Lawrence; Staehli, 2023; Müller; Schneider, 2002; Moretti, 2021; Lillard, 2017; 2019; Catherine *et al.,* 2020; Ponticorvo *et al.,* 2019; Frierson, 2022; 2015; Denervaud, 2023; Laski; Wang, 2023; Murray *et al.,* 2023).

be used for consultation or creative projects. These resources are often utilised in specific classes such as language studies, digital literacy, art, etc. (e.g., Lillard, 2017; Blackwell, 2013). 'Method-specific' materials are those that are characteristic of the MM, used in all MM schools, and predominantly designed by Maria Montessori herself (Lillard, 2011; 2017; Lillard; McHugh, 2019). They range from devices for literacy and mathematics to those used in the "Education of the senses" curricula, the history 'Long Strips', the 'Puzzle Earth Map', and the botany, biology, and anthropology 'Cards', etc. By 'local,' we refer to elements from the surrounding eco-social niches that are incorporated into the classroom, such as local fauna and flora that are observed, collected, and often brought in (e.g., plants, stones, flowers, snails), or contributions from parents and other community members who share their expertise as learning opportunities for the students.

2. Educational ecologies and sustainability

The first aspect that sets the MM classroom apart from more traditional educative settings is its organisation[5]. Each classroom is an organised, immersive learning environment where all materials have a specific, clearly defined place within child-friendly furniture. Classrooms are not strictly divided by individual ages but are grouped by age ranges (e.g., 1st to 3rd grade or 1st to 6th grade, 7th to 9th grade), allowing younger and older students to work together in the same space with shared materials. Shelves, tables, chairs, and other furniture are appropriately sized for each age group, enabling both younger and older students to interact with them effectively. Additionally, the classroom is physically organised by subjects, with 'method-specific', 'traditional', and 'local' materials designated for each area. Materials not in use are always stored in a specific location, such as on shelves, in drawers or boxes. If stored out of sight, like in a drawer or box, a label always indicates its contents (e.g., 'large brushes,' 'small brushes,' 'pencils,' 'paper,' or mathematical operation symbols such as 'subtraction,' 'multiplication,' etc.). This organisation supports the development of cognitive skills and the construction of abstract categories. More relevant to this discussion, it also mirrors the structure of environmental resources: materials are available in designated locations and can be accessed as needed, with the expectation that they are returned to their proper place after use (e.g., Di Paolo *et al.*, 2024; see also: Vatansever; Ahmetoğlu, 2019; Lillard; Taggard, 2019; Lillard; McHugh, 2019). These resources are limited in quantity. There is usually just one item for each category of materials: one for 'method-specific' materials (e.g., one Botany Cabinet, one Puzzle Globe, one Spindle Box), one for 'local' items (such as a tree branch, a specimen of a specific plant, or a small terrarium), and only one or a few for 'traditional' materials (e.g., a couple of books, a few computers or tablets, a set of brushes). This limitation supports cognitive development by encouraging children to explore different materials when their preferred one is in use or by promoting collaborative activities. Relevant to this work, this system fosters eco-sustainable behaviours and forward-thinking. As children expect to find materials in their designated places, they understand the responsibility of returning them after use, ensuring availability for others. Similarly, knowing that materials should be in good condition (without missing parts or damage), they learn to take care of them and use them responsibly. As we will explore later (sec. 3), in the absence of restrictive policies, these behaviours are sustained collectively through rituals, explicit agreements, and group discussions.

[5] For the organisation of the classroom, please refer to: Lillard, 2017; Montessori, 1996b; Lillard; McHugh, 2019; Müller; Schneider, 2002.

2.1 Traditional and local educational artefacts

Amongst the traditional materials, we consider books, computers and tablets, brushes, colours, scissors, glue, chemistry and physics experimental tools, etc. Unlike in traditional, teacher-centred schools, these resources are not limited to single-discipline, single-year, or single-user purposes. All of them are meant to be shared and passed down, as resources of the learning ecologies. While MM schools might tend to acquire high-quality and durable materials, pupils take responsibility for their preservation, through collaborative participation in the daily cleaning, taking turns in performing certain roles (such as vacuuming, brooming, or dusting), and engaging in the daily general discussions at the end of the workday. During those discussions, pupils act as a community, reciprocally evaluating the use and misuse of resources, leading to a distributed form of responsibility. Each pupil independently learns to respect and share the available resources while being personally accountable to the community for any misuse or waste.

This approach to materials is also evident in other – also traditional – educational methodologies, where they are used as ecological and collective resources in specific subjects like physics, chemistry, or art labs. However, in the MM, this approach to materials is an explicit part of the curriculum, known as 'Exercises of Practical Life.' These exercises involve self-care, environmental care, grace and courtesy, and control of movement (e.g., Lillard, 2017). They range from specific skills, such as sawing and cooking, to more general tasks like washing hands, polishing shoes, sweeping floors, cleaning tables, arranging flowers, folding napkins, sharpening pencils, and cleaning tools. For younger pupils, these activities help them learn body control, counting, and the proper names of objects. For older pupils, they strengthen their connection to their learning environment, fostering self-determination, self-regulation, and agency (Lillard, 2019; Tiryaki *et al*., 2022; Frierson, 2016b; 2019; 2022). By performing everyday activities within the school, pupils create connections between learning and daily life, blurring the distinction between the school environment and the outside world.

Additionally, the MM's scientific curriculum extends beyond the traditional classroom setting, incorporating direct observation and interaction with local environments like forests and gardens. Students gather natural materials, referred to as 'local,' which include bio-ecological elements such as plants, branches, wood pieces, leaves, and stones. These items are brought into the classroom, organized on shelves, and integrated into daily learning activities, particularly within science and art (Russell, 2014; Yates, 2024; Rathunde, 2014; Rinke *et al.*, 2013). For example, leaves collected from the environment might be used for artistic projects, such as creating stamps, studying symmetries, or learning botany by comparing them to the cards in the 'Botany Cabinet'. Although the use of local, low-tech, eco-friendly educational materials is not exclusive to this methodology and can be observed in various educational settings, what distinguishes the MM approach is how these materials are systematically reorganized within the classroom to facilitate learning.

In MM, teaching occurs indirectly through students' interaction with their environment, curated by an "invisible" teacher (Quarfood, 2022). However, teachers play a key role in organising and reorganising the classroom space to stimulate curiosity, enhance memory, and allow students to re-enact and connect their outdoor observations to scientific disciplines (Macià-Gual; Domingo-Peñafiel, 2021). For instance, placing a branch on the science shelf enables students to draw connections between a walk in the park and scientific inquiry and the acquisition of subject related knowledge. In practical terms, this means integrating abstract concepts,

such as 'Science' as an academic discipline, with the practice of 'doing science,' which encompasses activities like repeated observation, data collection, and comparison (e.g., Weisberg; Sobel, 2022). For the purpose at hand, this also entails establishing connections between classroom activities and the local ecological niche, especially when aligned with the general pedagogical principles of the MM, which emphasize care and respect for learning materials. Consequently, pupils may not only comprehend the relationship between scientific practices and their local environment but also extend the principles of care and respect for classroom materials to the natural world around them. Since these local elements brought into the classroom are treated according to the same principles as other learning materials, they become collective resources that facilitate collaborative activities and are governed by mutual agreements about their use, fostering democratic interactions (see sec. 3).

Consequently, the classroom becomes more than just a site of instruction; it actively fosters and stimulates the development of competencies, knowledge, and collaborative activities. It serves as a carefully designed epistemic ecology, where students navigate and resolve uncertainty throughout different stages of learning (Di Paolo *et al.*, 2024). Teachers are instrumental in creating these learning ecologies, ensuring that both local and traditional materials are not only tools for cognitive development but also means to promote sustainable practices and democratic interactions (Whitescarver; Cossentino, 2007).

2.2 'Method-specific' educational artefacts

What truly distinguishes the MM approach to educational artefacts is its adoption of low-tech, eco-friendly devices designed for shared use among generations of students. These artefacts employ sustainable, durable materials such as wood and natural pigments as part of the educational methodology (for an in-depth analysis of MM materials, see Mueller; Schneider, 2002; Lillard, 2011, 2017). Without delving deeply into the intricacies of pedagogy, it is sufficient to note that Montessori emphasized the role of the senses in cognitive processes—a perspective that aligns closely with modern cognitive science (e.g., Di Paolo *et al.*, 2024; Politi, 2023). As a result, she carefully crafted her materials and curricula to stimulate cognitive development through sensory interaction, while also considering durability and accessibility. Young learners, particularly those at the beginning of their formal education, engage in an "Education of the Senses," where different materials are used to fulfil distinct cognitive functions. To enhance the sense of touch, for example, children handle collections of fabrics, smooth papers, and sandpaper with varying textures and grit. Often, they explore these materials blindfolded to focus exclusively on tactile perception. In addition, collections of wooden cubes and blocks—such as the 'Pink Tower,' the 'Brown Stair,' and the 'Blue and Red Rods'—are incorporated into learning due to wood's warm tactile quality. These blocks, varying in shape and size, not only help children distinguish forms but also introduce basic counting, combining tactile feedback with the muscle movements of the hand (Lillard, 2017).

Even in the upper classes, where more advanced educational tools are introduced, low-tech artefacts made from accessible, eco-friendly, and durable materials are prominent. For example, in teaching foundational academic skills like writing, pupils do not initially encounter letters on a board or paper. Instead, they begin by practising the thumb-index finger grip using sets of 'Wooden Cylinders' with small knobs that mimic the feel of holding a pen (Lillard, 2017). Following this, students engage with the 'Movable

Alphabet'—wooden letters that can be arranged to form words—or explore letters engraved on wooden blocks or made from sandpaper (the 'Sandpaper Letters'), enabling them to distinguish letters from their surrounding contexts, such as a page or line. Additionally, students learn the correct finger and wrist movements for writing through the use of the 'Geometry Cabinet,' which contains several natural wood trays, each holding six blue, two-dimensional wooden shapes (e.g., rectangles of varying dimensions in one tray, triangles in another). Wood is the preferred material for Montessori tools due to its ease of availability and its warm tactile quality (Lillard, 2017).

Other materials, such as metal, are also utilised for their durability. For instance, pupils practice using pencils with the '10 Metal Insets,' a series of geometric shapes designed for tracing on paper. The use of metal, rather than wood, prevents wear from repeated handling by novice learners and allows these tools to be used across generations. Although markers were not available when Montessori developed her pedagogy, modern Montessori schools continue to prefer natural coloured pencils and water-based paints. This preference is not only rooted in eco-friendliness but also aims to avoid exposing children to potentially harmful, alcohol-based markers (Lillard, 2017). Another notable material is sand, employed in the 'Sand Tray,' where children practice handwriting without the need for paper.

When studying grammar, students use the 'Grammar Box', which contains 'Grammar Symbols'—wooden shapes that vary in geometry (e.g., triangles, circles), colour (e.g., dark blue, light blue, red), and size. Each variation represents a different part of a sentence (e.g., subject, verb, adverb). These symbols are paired with 'Word Cards', which students arrange to form sentences. The colours and sizes of the symbols aid memorisation by drawing attention, while their abstract shapes help students understand the conventional nature of language. This method also allows connections between languages, as the same symbols can be used to learn a second language with a different set of word cards, and across subjects, such as geometry and grammar. Children often study grammar collaboratively, sitting on the floor to add symbols representing different sentence parts or to categorise word cards next to the appropriate symbols, offering corrections to one another. After completing the activity, they return the cards and symbols to their boxes and place them back on the shelves, ready for the next group.

The mathematics curriculum in the MM is among the most developed, featuring numerous sustainable tools. Examples include the 'Red and Blue Rods,[6]' 'Spindles Box,'[7] 'Long Bead Chain,'[8]

[6] The 'Red and Blue Rods' or 'Arythmetic Rods' are ten wooden rods, which arranged side by side, form a stepped triangle. Each rod is a solid prism, with the first rod colored blue and measuring 10 cm in length—referred to as the 'unit.' The second rod is 20 cm long, painted half blue and half red, with both colors spanning equal lengths. Positioned beneath the first prism, the blue portion of the second rod aligns perfectly with the first, while the red section extends outward. The third rod, adhering to the same pattern, is 30 cm long, divided into blue, red, and blue sections, with the blue segment protruding this time. This pattern is consistent across all rods, which are constructed and organized according to the same principle, ranging from 1 to 10. The final rod is one meter long and is again segmented into alternating 10 cm sections of blue and red (see, e.g.: Montessori, 1994: 5-6).

[7] A wooden box, divided in 9 compartments and containing 45 identical wood spindles, adopted for learning basic arithmetic (e.g., Montessori, 1994; Lillard, 2017).

[8] It consists of a series of coloured beads, each representing a specific quantity, which can be combined to form a continuous chain and it is used for learning abstract mathematical operations in a tangible way (Montessori, 1994; Lillard, 2017).

'Binomial and Trinomial Cubes,'[9] 'Geometric Solids,'[10] 'Fraction Insets,'[11] 'Pythagorean Theorem Materials,'[12] and 'Multiplication Board.'[13] These materials are considered sustainable not only because they are primarily made of wood but also because they are designed for use across generations, contributing to a stigmergic prepared environment. Their collaborative use encourages eco-friendly behaviours, such as returning items to their original locations and maintaining them in optimal condition for future students. It is no coincidence, then, that the MM is often seen as a leader in ecological sustainability (Sutton, 2009; Schmidt, 2017; Gynther; Ahlquist, 2022). In the next section, we will explore how the combination of learning ecologies and pedagogical practices fosters the development of eco-sustainable behaviours, emphasising both individual and community responsibility.

Responsible communities

The MM is not only a model for the adoption of low-tech, eco-sustainable materials but is also recognised for its leadership in sustainable practices (Sutton, 2009; Emerson; Siraj-Blatchford, 2017; Schmidt, 2017; Lide, 2018; Misheva, 2020). It is historically grounded in a person-centred, child-centred approach that values multiple forms of intelligence, individual agency, pupil participation, collaborative learning, and resource sharing (Cartwright *et al.,* 2022; Mavric, 2020; Oprescu *et al.,* 2011; Frierson, 2016, 2018, 2019; Williams; Keithnot, 2000; Thayer-Bacon, 2011; Lillard *et al.,* 2021; Hallumoğlu *et al.,* 2023; Bavlı; Kocabaş, 2022; Macià-Gual; Domingo-Peñafiel, 2021). The MM's resilience and adaptability have contributed to its global diffusion across diverse socio-political, economic, and ecological contexts (Holmes, 2018; Debs, 2023; Cadis; Busu, 2022; Debs *et al.,* 2022; Johnson, 2022; Joyce Pickering, 2015; Murray *et al.,* 2023; Kasour *et al.,* 2023; Malhotra *et al.,* 2023; Chen; Guo, 2021; Vettiveloo, 2008; Parham *et al.,* 2023; Ackerman, 2019; Lillard *et al.,* 2017, 2023; Debs; Brown, 2017; Gross; Rutland, 2019). Ultimately, it aims for optimal development, guiding children to grow into global citizens (Raimondi, 2018; Leonard, 2015; Gynther; Ahlquist, 2015; Brunold-Conesa, 2010; de Brouwer *et al.,* 2023; Baligadoo, 2020).

In our view, one of the reasons the MM stands out when redefining formal education in the Anthropocene is its understanding of education as an interplay between three key actors: students, teachers, and classrooms. Each plays a pivotal role, and education would be incomplete without any of them. Teachers act as mentors, collaborating with pupils and making democratic decisions about daily activities and long-term goals as peers (Bavli; Kocabaş, 2022). While teachers are expected to have more knowledge, such as the use of certain materials or how to perform tasks, they are not presumed to always know 'better.'

[9] The binomial and trinomial cubes are made up of red, yellow, blue and black cubes and rectangular prisms that fit neatly together into a wooden box, and they are used for learning volumes. There is only one correct way to assemble the puzzle in order for it to fit back in the box, and so it is *self-correcting* in nature.

[10] 10 3-D shapes made of dense wood that are sanded smooth and painted shiny blue, to be plasant to handle and resistant. They are housed in a wooden box along with stands for the solids that may roll, and they demonstrate how 3D shapes are related to 2D shapes, for instance observing how the base is related to the sides.

[11] That is a beautiful set of metal templates resting on slanted wooden trays. The insects are geometrical figures (circles, triangles, and squares) ranging from the whole to the tenth, each piece having a small knob facilitating its moving (Montessori, 2011).

[12] It consists again of a (green) tray with metal insects, coloured white (the triangle), red, blue, and yellow the squares build on the sides. Each construction is composed of little metal insects with knobs, that allow the comprehension of the Pytagoras Theorem (Montessori, 2011).

[13] Consistent of a square wooden board with 100 indentures in each of which a bead can be placed, a small wooden box containing 100 beads, numbered cards 1-10, and multiplication series 1, 2 and 3 [...].

Unlike traditional schools where teachers dictate content, much of the MM curriculum is self-directed, emphasising independent and collaborative activities (Koh; Frick, 2010; Siswanto; Kuswandono, 2010).

The classroom serves not only as a space for knowledge and skill development but also as an ecology of limited resources that pupils must share, choose from, and care for. Students engage in self-selected activities, make long-term educational decisions based on their preferences and abilities, and freely choose collaborators. A defining feature of the MM is the absence of a standardised and estrisec system of feedback, such as grades or notes, for evaluating performance. The learning environment remains relatively neutral regarding performance, and pupils are not judged or compared based on their success in specific tasks or across subject areas (Denervaud *et al.*, 2020a, 2020b). There is no need to overuse a material for achieving something, that is. A pupil or group of pupils autonomously research topics at their own pace and present their findings to the entire class in a peer-review format, where classmates and teachers can ask questions, offer suggestions, and propose alternative views (Murray, 2011; Mallett; Schroeder, 2015; Alburaidi; Ambusaidi, 2019; Richard-Bossez, 2023; Koczela; Carver, 2023).

Students actively participate in regulating their classroom environment. While formal evaluation is not part of the school's pedagogy, social and community judgment remains an essential aspect of the learning process. Norms are democratically established and discussed within the community, allowing for indirect evaluation during 'circle time' at the end of each day, where pupils and teachers reflect on key events and openly discuss challenges (Wasson; Boyles, 1988; Lillard, 2008; Koczela; Carver, 2023). Moreover, the exploitation of resources is addressed both informally and formally throughout the day. Pupils, never bound to a chair or task unless by choice, are free to point out when a classmate has monopolised or misused a device. During the end-of-day circle, they are encouraged to bring up issues and collaboratively seek solutions within their community. Prevention of resource exploitation is also embedded in the structure of activities, as pupils are encouraged to start collaborations around devices whenever needed. In one MM school frequently visited by one of the authors, a list of educational devices is maintained in the classroom. When a pupil decides to use specific materials, they write their name next to the item on the list. This transparency allows others to see who is using a particular device, facilitating collaborative opportunities and ensuring equitable access. By creating a shared responsibility for resources, the system naturally prevents overuse and fosters cooperative learning (Lillard, 2021; Laski *et al.*, 2015). This practice also encourages responsibility for resource use, as each pupil removes their name from the list once the device is returned to its place and made available to others.

An essential aspect of the MM approach is that material use and management are directly experienced by each pupil. In multi-age classrooms, children take turns performing various roles, such as cleaning and reorganising at the end of the day, while ensuring tasks are completed properly. This hands-on involvement is crucial for ecological redirection, fostering a sense of individual responsibility for their learning environment and the materials within it. The MM highly values autonomous engagement, not only for its impact on academic and learning achievements but also for its primar role in raising future citizens who actively participate in global democratic governance and their local communities (Koh; Frick, 2010; Lillard, 2019; Leonard, 2015; Жусипбек; Нагаева, 2022; de Brouwer *et al.*, 2023; Duckworth, 2006; Siraj-Blatchford; Emerson, 2017; Moretti, 2021; Basargekar; Lillard, 2023).

These direct experiences redefine not only the relationship between pupils and their educational resources—used responsibly, not exploited—but also the concept of community. The classroom community

becomes a local group where individuals share responsibility for governance and access to resources. Within this larger community, smaller, fluid groups form daily around specific devices or tasks. Students are thus continuously prompted to reflect on their behaviour within their working group, their interactions with other groups, and their role in the broader classroom community. Since these working groups are flexible, pupils must negotiate access to resources, participation in activities, and collaboration with one another. Conversely, the circle time at the end of each day ensures that norms are established collaboratively and fairly, creating guidelines for resource use and group collaboration that work for everyone. Importantly, these norms are not extrinsically imposed but are continuously re-evaluated grounding their re-definition on the hands-on, direct experiences of each student across their multiple communities, and across time (e.g., Stairs Vaughn, 2002; Khan, 2006; Lillard; Else-Quest, 2006; McNamara, 2014; Murray, 2011. See also: Livstrom *et al.*, 2019; Guinan; Hansell, 2014).

Within the local ecology constituted by the multiage classroom, pupils in the MM spend from three to six years. This allows them not only to develop ownership of, and sense of individual responsibility for their learning ecology, but also to redefine norms at various stages of development, and in relationship with other pupils at different stages. For instance, it might help to understand the difficulties of a younger child not only in dealing with a task or a subject but also in carrying around or repositioning a device. On the other hand, it allows the cultural transmission of norms and values without the necessity to involve superimpose and extrinsically given rules, or punishments. An older child can simply suggest to a younger classmate how to perform a task or where to reposition a device, allowing a horizontal, democratic transmission of norms and values (Ahmad; Reba, 2018; Frierson, 2022; Randolph *et al.*, 2023; O'Donnell, 2012. See also: Lillard *et al.*, 2021; Lillard, 2017).

In this way, the MM redefines the relationship between agents and their contexts. Rather than serving as mere backdrops, contexts actively participate in learning activities, mediating cooperation and other social interactions. Consequently, pupils learn to respect both their peers and their learning environments, fluidly transitioning between animate and inanimate partners throughout their learning journey (Leonard, 2015; Misheva, 2020; Ozgen, 2023; Frierson, 2016; Cossentino, 2017; Bertolino; Filippa, 2021). Thus, the MM powerfully mirror the geopolitical and ecological realities of the Anthropocene era, characterized by limited resources that require countries and communities to find responsible solutions for their preservation, sharing, and appropriate use. This framework implies a fluid distribution of responsibility and governance across various stakeholders, including individuals, communities, and states.

Conclusions

In conclusion, three key elements can be drawn from Montessori schools. The first is the limitation of resources, reflecting the constraints of ecological resources, particularly in the Anthropocene. Although these educational resources are specifically designed to stimulate and enhance cognitive functions—differing from natural resources—they are provided in limited quantities and require attention and care, which are cultivated by the pedagogy. The second element is the freedom of choice. In contrast to teacher-centered approaches, Montessori schools empower children to make their own learning decisions. This encouragement of agency not only nurtures individual responsibility toward the learning environment but also fosters democratic, participative interactions within a fluid eco-social community. The third point is the

use of low-tech and durable resources, intended for collaborative use and shared as an ecological inheritance within the classroom. 'Low-tech' encompasses two aspects: the use of long-lasting devices for teaching foundational skills such as reading, writing, and arithmetic, and the integration of locally available socio-ecological tools and traditional devices as shared resources. These tools support students' learning within their immediate context, aligning with Montessori principles that emphasize respect for nature and context-based education.

Data availability statement

The main focus of this article is contributions of a theoretical or methodological nature, without the use of empirical data sets. Therefore, in accordance with the journal's editorial guidelines, the article is exempt from being deposited in SciELO Data.

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Editores responsáveis: Léo Peruzzo Júnior e Jelson Oliveira.

RECEBIDO: 04/10/2024 *RECEIVED: 10/04/2024*
APROVADO: 04/05/2025 *APPROVED: 05/04/2025*
PUBLICADO: 09/06/2025 *PUBLISHED: 06/09/2025*