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A citizen science approach to model water and food circularity in schools

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ABSTRACT

Promoting circularity in schools for climate adaptation requires detailed assessments of their resource metabolism, which is typically challenging due to lack of data. This paper proposes a bottom-up methodology for mapping and quantifying water and food flows in schools that combines the principles of Material Flow Analysis (MFA) and citizen science. A rural school in Catalonia was selected to validate the framework, profiting from an already existing sustainability culture. The study followed a participatory design of the methodology and data collection process that culminated with an MFA of the water and food metabolism of the school and the modeling of circular strategies. The school's average daily water consumption per student was estimated at 10.5 L, with toilet demand as the main driver. Implementing strategies such as rainwater harvesting and urine-diverting toilets have potential to cover around 74% of the potable water demand. The school displays low food waste generation (13.7% of the total food served is wasted), suggesting there is less room for improvement than in the case of water. By focusing on disaggregated flows and community participation, this study provides new insights into the field of circular educational infrastructure. By involving the school community in every stage of the data collection process, the research strengthens local ownership of sustainability practices and equips participants with tools and knowledge to continue monitoring and improving their resource management independently.

1. Introduction

Recent extreme weather events have intensified longstanding demands to ensure access to water and food resources. Persistent droughts and extreme flooding, among others, challenge existing supply chains and compromise basic infrastructure and public services. Children are one of the population groups that have been at the receiving end of recent crises, as >75% of extreme weather events have resulted in school closures (Venegas Marin et al., 2024). Prolonged interruptions can thus disrupt both their learning process and their access to healthy food, with 400 million children included in school meal programs worldwide (Global child nutrition Foundation, 2024).

In this context, schools are essential services that need to be physically adapted to the changing climate conditions, especially regarding water and food management. Enhancing the climate resilience of educational buildings can not only ensure continuity when facing disruptions but also build long-term capacity for sustainability (Arceo-Gomez and López-Feldman, 2024; Lassa et al., 2023). To do so, schools could benefit from and contribute to the increasing municipal interest in the circular economy, which offers a breadth of possibilities to integrate circular resource management in all spheres of urban and rural life (Kopp et al., 2024; Petit-Boix and Leipold, 2018). A fundamental first step is understanding how water and food are embedded in the metabolism of educational buildings. Mapping and quantifying these flows can reveal inefficiencies in current management practices, facilitate the identification of resource synergies, and guide the design of circular strategies in a context of complexity (Morote et al., 2020; Luna-Nemecio et al., 2020; Virk et al., 2025).

The literature shows a scattered landscape of approaches for assessing water and food consumption in schools while generally focusing on single resource flows. In the case of water, the factors driving consumption have been determined through statistical analyses of samples of schools considering variables such as building typologies (Almeida et al., 2014; Nunes et al., 2019; Schultt et al., 2022). For instance, Farina et al. (2013) found that kindergartens in Italy used more water per student (up to 31.1 L/day) than primary and secondary schools due to age-specific needs. These water consumption profiles primarily rely on aggregated utility bill data and complementary questionnaires with the school board (Antunes and Ghisi, 2020; Gamarra et al., 2018; Visser et al., 2021). Regarding food consumption,

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literature mainly focuses on assessing and reducing food waste generation. Studies have developed methodological frameworks to measure food waste while raising awareness in schools (Derqui and Fernandez, 2017). For instance, Kasavan et al. (2021) used direct weighing to assess food waste across school canteens in Malaysia, finding an average of 12.2 grams of waste per day. Similarly, Malefors et al. (2022) demonstrated how targeted interventions, such as awareness campaigns and food waste trackers, can reduce waste generation in Swedish schools.

While these types of approaches generate insightful consumption profiles, they fail to capture the complete water and food metabolism of school buildings (i.e., from production to consumption and end of life). Research shows that circular strategies applied to buildings and neighborhoods hold large potential for a self-sufficient, resilient and environmentally sustainable urban transformation, with rainwater harvesting, greywater reuse or urban agriculture as notable examples (Ferreira et al., 2018; Gullberg and Eriksson, 2025; Rufí-Salís et al., 2024). Starting this transformation in schools requires a more systemic evaluation of water and food flows. In turn, this demands a high degree of data granularity to understand not only the physical infrastructure available but also human behavior toward resource consumption and conservation. However, there is a lack of granular approaches due to the challenges of measuring real-time water and food consumption, which are typically aggregated in utility bills and purchase orders.

To address this gap, participatory approaches to resource mapping and quantification are a powerful tool that needs to be further exploited in schools. In this sense, engaging the school community in the process not only improves data granularity but also serves as an environmental education activity that can equip students with the knowledge and skills needed to respond to ecological crises (Luna-Nemecio et al., 2020; Mochizuki and Bryan, 2015). Methodologies inspired by citizen science, which is research conducted by members of the public, often in collaboration with research institutions (Paul et al., 2020), offer a valuable framework in schools for tackling challenges requiring complex, evidence-based solutions. This approach has been increasingly applied in educational contexts, involving school communities as collaborators in data collection and knowledge generation (e.g., Araújo et al., 2022; Ballard et al., 2017; Farrell et al., 2021). Citizen science has also proven effective beyond the classroom, contributing to conservation research, resource management, and environmental decision-making (Aceves-Bueno et al., 2015; McKinley et al., 2017; Theobald et al., 2015). In the context of circular water and food management, little progress has been made to develop viable approaches for schools, although the integration of the circular economy into their curricula is starting to gain traction (Kosta et al., 2025; Laius et al., 2024; Tiippana-Usvasalo et al., 2023).

Our study proposes a citizen science approach for mapping and quantifying water and food flows in schools that can assist in their transformation into more circular and climate-resilient services. Our goal is to co-design the evaluation of the water and food metabolism, from conceptualization to data collection and analysis, by involving the entire school community to capture the school's infrastructure, consumption patterns and resource circularity potential. Unlike previous studies defining water and food consumption profiles, our approach breaks down the water and food metabolism following school activities. It relies not only on the school staff but also on students from all educational levels to increase environmental awareness from an early age and generate a greater sense of connection with local resource management. By doing so, circular economy and sustainable resource management can also be integrated into the classroom activities. A rural school in Catalonia served as a testbed for developing and testing the citizen science framework, which provided insightful recommendations. This framework can be used in collaborative projects between academics and schools but can be transformed into a standalone tool for educational centers interested in water and food monitoring with students.

In the following section (Section 2), we describe the proposed co-creation methodology, the case study and data modeling. Section 3 presents the results of the water and food mapping and quantification in the selected school, along with the main lessons learned from the citizen science approach applied to resource monitoring. In the discussion (Section 4), we further contextualize the results of this case study with existing literature and reflect on the school feedback and societal impact of our approach.

2. Methodology

2.1. A citizen science approach to modeling water and food

Our approach builds on the foundations of industrial ecology combined with the principles of citizen science (Fig. 1). Schools are thus viewed as human-made systems that "are not in isolation from their surrounding systems, but in concert with them" (Graedel and Allenby, 1995), and where material cycles can be traced and optimized. Material flow analysis (MFA) is a valuable tool for assessing the interrelations between schools and the environment following material balancing of their metabolic processes (Hinterberger et al., 2003), from the different inputs of water and food to their consumption and end of life. From this perspective, water and food flows can be mapped and quantified throughout a school's metabolism, evidencing their potential to model circular strategies. To reach this goal, we propose the integration of citizen science as a fundamental part of this quantitative approach.

Fig. 1 defines our proposed bottom-up methodology, which is divided into four main steps: (1) participatory design, (2) participatory data collection, (3) assessment of the food and water metabolism, and (4) circular scenario modeling. Following the 10 principles of citizen science defined by Robinson et al. (2018), researchers and the actors involved in school communities actively participate in different steps of the mapping, quantification and evaluation of water and food flows. The school community is composed of the school board, teaching and non-teaching staff, and students. Families were not included, since they are not the main occupants of educational buildings during opening hours. The most intense collaborations take place in the first two steps, as the school community is essential in the definition of the system and the data collection process. Feedback is an integral part of the process to refine the methodology according to actor needs and to share the results. Each step is described in the following sections using the selected testbed as an illustrative case.

2.2. Description of the testbed and actors involved

Our approach was co-designed and tested at a public school embedded in the education system of Catalonia, a region in northeastern Spain (see Supporting Information A). Les Vinyes elementary school (Escola Les Vinyes, 2025) is located in Sant Cugat Sesgarrigues (province of Barcelona), a rural municipality of 1028 inhabitants (Idescat, 2024). Built in 1969, the school is home to 97 students (ages 3–12), 15 teachers and 9 non-teaching staff, as per 2024–25 enrollment data. The school premises cover around 1000 m^2 which are surrounded by vineyards (in Catalan, "vinyes"), the region's typical crop. The actors involved in the design and application of the proposed methodology were the entire school community (121 people) and the researchers with expertise in industrial ecology and citizen science who co-author this paper. Their roles are defined in Fig. 1 and described in the following sections.

Les Vinyes school offers favorable conditions for involving the entire community in a novel scientific activity with societal impact. Next to its small student population, the school shows great commitment to participating in sustainability programs, such as the "Escoles Verdes" program by the Catalan Government (Generalitat de Catalunya, 2025). Additionally, small projects dedicated to water and food waste management could be identified on-site, including a vegetable garden, a composting system, and a small rainwater harvesting system. Les Vinyes

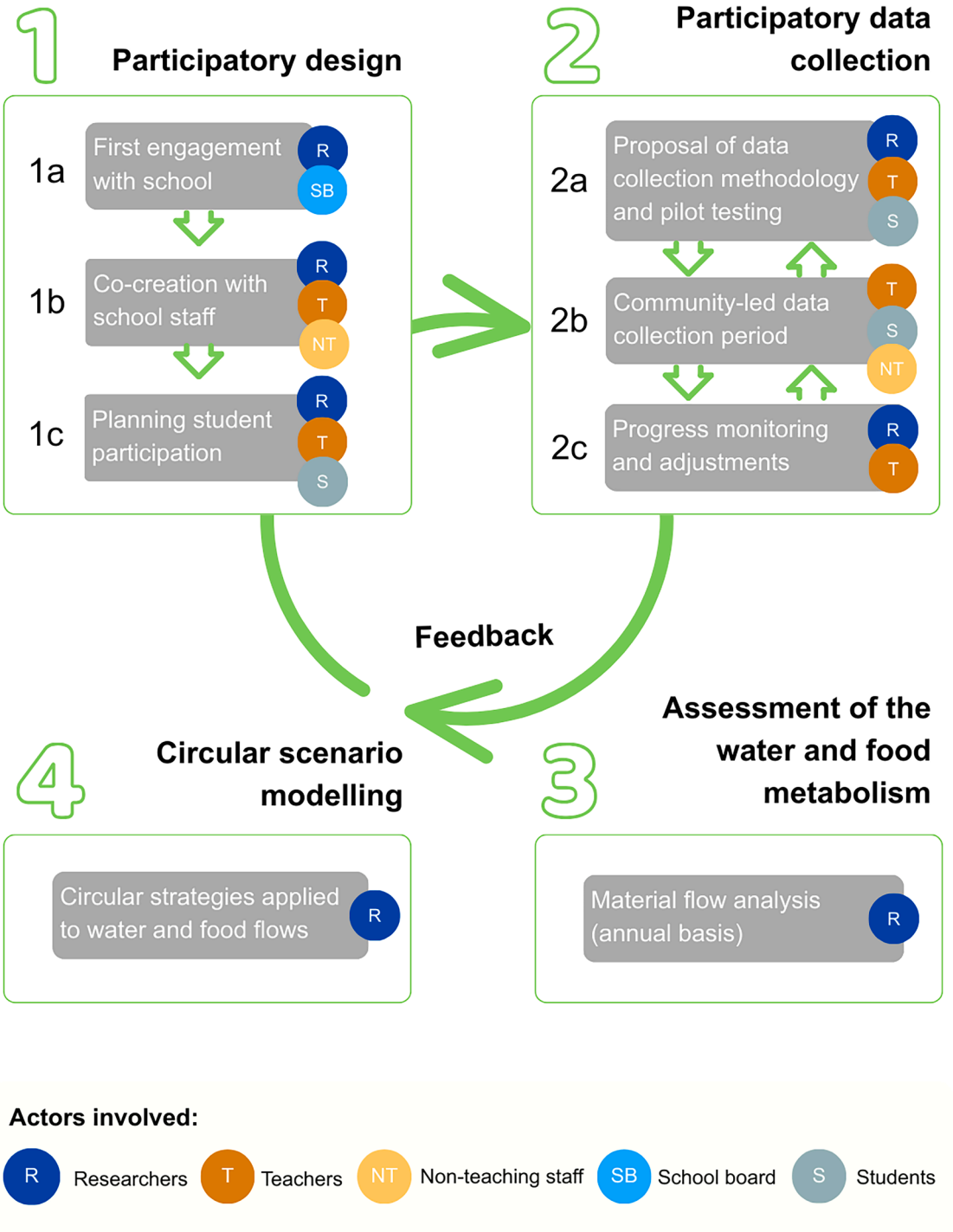


Fig. 1. Bottom-up approach for mapping, quantifying and modeling the water and food metabolism and circularity in schools following the principles of citizen science.

shares part of its infrastructure with municipal sports facilities, and the water utility bills cannot be disaggregated, rendering the study of the full water cycle more challenging. However, this can be a typical situation in public facilities, which makes our testbed a representative example of small educational institutions in similar contexts.

2.3. STEP 1: Participatory design

The first step involves key actions to gradually build trust among actors, i.e., establishing a connection with the school, integrating teachers into the research process, and subsequently involving students. The study was approved by the Research Ethics Committee of the Universitat Autònoma de Barcelona (see Supporting Information B).

Step 1a. First engagement with the school: The first contact with the school board aimed to define shared objectives, ensuring the research was integrated into the school's culture, schedule, and educational objectives. A tour of the school was conducted to understand its layout, inspect facilities, and observe daily dynamics.

Step 1b. Co-creation with staff: Engaging teaching and non-teaching staff from the start is essential for the project's success. Their

understanding and support are key to integrating the study into daily routines and ensuring its continuity. To this end, an in-person workshop was held with the teaching staff to present the study's objectives, gather insights, and encourage collaboration. During this session, all 15 teachers worked in teams to identify existing patterns of water and food consumption within the school, discuss initial monitoring strategies, and explore potential roles in the data collection process. In parallel, meetings with kitchen and cleaning staff enabled a joint definition of effective methods to measure lunchtime food flows, and water use during cleaning activities.

Step 1c. Planning student participation: Students were the most central element, as their cooperation was vital for meaningful data collection. Les Vinyes already has a formal sustainability group called the "Green Squad", which is composed of two students from each class (ages 5 to 12), totaling 18 children. The Green Squad was thus selected to participate in the co-design of the methodology with their teachers, lead the data collection process, and provide feedback to the research team. This autonomy within the student organization can foster their sense of ownership, engagement, and overall process effectiveness. Over the course of two of the Green Squad's biweekly meetings, the data collection methodology was refined and shared with the research team for validation. The whole student body (97 children) actively participated in the data collection process.

2.4. STEP 2: Participatory data collection

The second step began with a pilot definition and testing of the data collection methodology followed by the school-led data collection period. In parallel, data collection was continuously monitored for correctness and adjustments.

Step 2a. Proposal of a data collection methodology and pilot testing

Once feedback was gathered from the various members of the school community, the data collection methodology for water and food was established (Tables 1 and 2). Each flow was assigned to a specific group responsible for its monitoring, along with a tailored method for data collection. For water flows, a distinction was made between the frequency of use and the water consumption in each end-use facility, as each type of flow involved different use patterns. This distinction was not applied to food flows, since their frequency remained constant. The study focused on the school building and dining hall, excluding the adjacent outdoor area used for physical education. This scope was mutually agreed upon with the school community to align with available time and resources. Further details on the data collection methodology can also be found in Supporting Information C. The week before the data collection began, two test days were conducted. This allowed the community to adapt to the new routine and to validate the soundness of the methodology. Following these tests, a meeting with the Green Squad verified the implementation, while a discussion with a randomly selected class and teachers confirmed their understanding of the methodology. Data collected during the pilot test were not included in the results.

Step 2b. Community-led data collection period

Measurements took place over four consecutive weeks, from March 17 to April 11, 2025 (20 school days). Following the test days, students introduced a new routine into their daily activities that needed some time for adaptation. Following the inputs from the teaching staff, four weeks were considered sufficient to capture the behavior of the school and gave ample time for adapting to the data collection process. Sustaining a long-term monitoring process with the whole school community alongside the school's regular activities can become a burdensome task. For this reason, the selected period served to test the methodology and to keep all actors deeply engaged. All classes were present during this period, and no extraordinary activities were planned to avoid deviations in the regular practices of a school day.

Extrapolating a four-week period to a whole academic year comes with limitations. The number of students present every day may vary due to class excursions. Seasonality may affect water use, as summer conditions may increase the consumption of drinking water, and faucets may be used more frequently. However, many of the water and food flows included in the analysis may not vary across seasons (e.g., toilet flushing or lunch portions). Variations in irrigation were initially assumed to be negligible given the limited size of the vegetable garden ($< 20\ m^2$), but the effects of rainfall variability need to be further addressed in future studies.

Step 2c. Progress monitoring and adjustments

Throughout the data collection period, the research team ensured that the school community understood their roles and adjusted the methodology when needed. For example, kindergarten teachers (<5 years old) found standard tracking sheets difficult to fill in while being engaged in simultaneous tasks. Consequently, simplified tables, organized by day rather than by individual student, were created to better fit their classroom dynamics. Constant communication with the school and interviews with students facilitated weekly sharing of measurement results and clarification of inconsistencies.

2.5. STEP 3: Assessment of the water and food metabolism

At the end of the data collection period, the research team built the mass balances for the water and food flows to understand the metabolism of the school. A single-period mass balance was developed to facilitate the transfer of knowledge with the school community. The MFA was developed on an annual basis using the data collected by end-use facility or activity. This involved harmonizing the various tracking formats, such as handwashing logs and food waste records, into daily and weekly average data (see the whole dataset in Supporting Information G). This stage presented several challenges, since some data were recorded in slightly different formats or with missing details, requiring cross-checking with teachers. Inconsistent marks on tracking sheets (e.g., random symbols instead of "X") necessitated interpretation and, at times, assumptions were made about valid entries versus likely errors. Daily data were annualized considering the duration of an academic year (177 days).

Despite efforts for consistent data collection, limitations arose from the methodology's reliance on manual tracking. Inconsistent recording was noted for uses like handwashing or toilet flushing, particularly during busy times or in younger classrooms requiring adult supervision. The absence of automatic counters or sensors hindered the verification of data completeness and accuracy. Consequently, a standard deviation was calculated for each flow to reflect these estimated values, except for cleaning, which was assumed to be constant and only had one data entry (see Table 1). Irrigation's standard deviation was notably high due to significant rainfall during the measurement period, leading to large daily fluctuations from unused harvested rainwater.

Water and food flows were then categorized as production, consumption and end of life following mass balance principles and a metabolic perspective. The water metabolism was structured by source (i.e., potable water and rainwater), end uses (e.g., cleaning, toilets), resulting wastewater types (e.g., greywater, blackwater), and end of life (e.g., wastewater treatment plant (WWTP)). Wastewater flows were estimated by wastewater types. Greywater is generated in faucets, dishwashers and cleaning activities. Wastewater generation in toilets was divided into yellow water (i.e., urine), and blackwater. The food metabolism mapped the source (i.e., school meal deliveries, home-brought snacks), internal transformation (i.e., consumption times and locations), and end of life (e.g., organic waste, compost). The balanced MFAs were represented in Sankey diagrams using SankeyMATIC.

2.6. STEP 4: Circular scenario modeling

Taking the baseline MFA results from Step 3, the research team modeled circular scenarios to understand the school's circularity and

Table 1
Co-designed methodology for measuring water flows by end-use facility or activity.

End-use facility or activity	Data collection method		Participants in data collection	Data granularity	Assumptions and limitations
	Water consumption per use	Frequency of use			
Faucets, for handwashing	• Push-button faucets: flow per flush measured using a graduated container. Different faucet models were color-coded based on flow variability (Figure C2).• Threaded faucets: flow rate (liters/second) measured at an intermediate tap opening.	• Push-button faucets: each use was recorded with a colored "X" on a daily tracking sheet, allowing the identification of both the frequency and the specific faucet model used (Figure C1).• Threaded faucets: the number of seconds the tap was open was timed and noted in a separate table, providing a more precise estimate of individual water use (Figure C3).	Students and teachers	• Daily data• All uses of a person belonging to an age group (classroom)• All uses by faucet model	Tracking sheet was not anonymous as per the teachers' request to ensure data consistency in the classroom.
Faucets, for drinking water	Faucets in the dining room release the exact volume needed to fill table jugs during lunchtime. Each jug has a capacity of 2 L and is shared among students.	Each time a jug was filled, a "X" was marked on a tracking chart located in the kitchen.	Students and teachers	• Daily data• All uses of an age group (classroom)	• Water from personal bottles was excluded• Water remaining in jugs or glasses is used for watering plants but was not measured.
Toilet	The school has 12 toilets (Roca Kiwa and Roca Victoria 88,300 models), each consuming 6 L per flush.	Each toilet flush was recorded by marking a "X" on a daily tracking sheet, with one row per person per day.	Students and teachers	• Daily data• All uses of a person belonging to an age group (classroom)	• Tracking sheet was not anonymous as per the teachers' request to ensure data consistency in the classroom.• Urination and defecation were not differentiated.
Cleaning	A graduated container was used to measure the volume of water used in each cleaning task (e.g., mopping floors or cleaning furniture). Includes water from faucets to fill up the containers and water from toilet flushing for toilet disinfection.	At least one daily toilet flush per toilet unit for disinfection. Frequency of cleaning tasks was estimated based on regular school procedures: daily for the kitchen and main rooms; once a week for the library and twice a week for the staff room.	Cleaning staff	• Weekly or daily data• Consumption per activity	All the water used for cleaning was assumed to be discharged into the toilets.The amounts of water used for cleaning each room were assumed to be constant. A single measurement was made in each room.
Irrigation	Water sourced from a 1000 L rainwater harvesting tank. A one-liter mark was added to the watering can to measure the volume of rainwater retrieved from the tank.	Each time a liter of water was used, a "X" was made on a tracking sheet in the two vegetable gardens of the school.	Students and teachers	• Weekly data• Use per garden	• Due to heavy rains, the tank was full at the beginning of the study and irrigation was discontinuous.• Crops were limited to educational purposes and little was growing at the time of the study.
Dishwashing	• Dish rinsing: the time required to rinse a single dish was measured, and a graduated container was used to determine the volume of water discharged during that time.• Dishwasher: the water consumption per wash cycle was obtained from the manufacturer's specifications. The Jemi-GS18 model consumes 23.3 liters daily (Jemi, 2025).	The number of dishes rinsed was tracked each day based on the total number of students and the frequency of dishwasher use throughout the day.	Kitchen staff	• Daily data• Use for entire school	• All dishes are assumed to be rinsed prior to dishwashing (3-second rinse per dish)

Table 2
Co-designed methodology for measuring food flows.

Activity	Data collection method		Participants in data collection	Data granularity	Assumptions and limitations
	Measurement of food inputs	Measurement of food waste flow			
Lunch	The trays for each meal were weighed before being served using a scale.	The trash bags were weighed at the end of each meal using a scale.	Kitchen staff	• Daily data • Aggregated for the whole school	Meal breakdown into individual ingredients was not possible because they are not prepared in the school.
Breakfast snack	Each student's breakfast snack was weighed once using a scale.	The amount thrown into the compost after a breakfast snack was weighed.	Students and teachers	• Monthly data • Aggregated data per age group (classroom)	• Difficulty due to the great diversity of food items brought from home. • Recorded weights aggregated to estimate total consumption.

self-sufficiency potential. To illustrate this process, three circular water management scenarios were modeled.

- Scenario 1 applies rainwater to irrigation, cleaning, and toilet flushing. This implies a more intensive use of the school's roof area to harvest rainwater as described in Supporting Information D.
- Scenario 2 replaces conventional toilets with urine-diverting models, which separate urine and feces while using different amounts of water for each function. These toilets use 2.5 L of water for urine rinsing and 4 L for feces flushing (see Supporting Information E). To model this scenario, the urination and/or defecation frequency is needed but was not included in the data collection for privacy reasons. The data collected suggest that each student uses the toilet once per day during school hours and, following existing literature (SEGHNP, 2017; Corazziari et al., 2005; Kajiwara et al., 2004; Mattsson et al., 2003), we assumed a 50% split between urination and defecation to account for student variability.
- Scenario 3 combines both interventions to evaluate their cumulative effects.

3. Results

3.1. Daily water and food consumption profiles

Tables 3 and 4 show the water and food consumption at Les Vinyes school on a daily, annual, and student basis. In the case of water, toilets represent the largest share at 57.5% of total consumption (129.9 m^3/year), followed by faucets (37.2 m^3/year), cleaning (36.3 m^3/year), kitchen activities (22.1 m^3/year), and irrigation (0.63 m^3/year). This translates into a daily use per person of about 6 L for toilets, 1 to 2 L for other uses, and a negligible 0.03 L for irrigation. The distinction between the different flows is crucial for identifying targeted interventions and designing effective circular strategies. Given the high share of toilet-related consumption, efforts to reduce water use should focus primarily on this area, without overlooking secondary uses that, while smaller, may also offer room for improvement.

The study also reveals that younger students consume more water than older students (see Supporting Information F and G). The 3- and 5-year-old groups registered a daily average of 13.0 and 18.4 L/student, respectively, whereas the oldest group (6th grade) consumed 4.2 L/day. Toilet demand was 5.8 times higher in the youngest class, which was combined with a more extensive use of threaded faucets, which are less water-use efficient. In general, older students reported during interviews that they are more likely to avoid using school restrooms, and that larger distances between their classroom and the restroom limited the data collection process. In contrast, younger children often go to the restroom in groups, making it easier for teachers to track and record usage.

Table 4
Food consumption profiles by activity on a daily, annual and per person basis. Values presented with standard deviations for data obtained within the 4-week monitoring period.

Activity	School consumption & waste		Consumption per person	
	kg/day	kg/year	kg/day	kg/year
Breakfast snack	2.3	407	0.024	4.19
Lunch meal	26.2 ± 4.2	4635 ± 56	0.270 ± 0.04	47.7 ± 0.6
Lunch waste	3.5 ± 1.3	626 ± 17.5	0.036 ± 0.01	6.45 ± 0.2
Compost	0.4	68	0.004	0.69

Regarding food, an average student consumes about 52 kg of food per year during school hours, combining breakfast and lunch meals. Of this amount, 7.14 kg are discarded and sent to either composting or landfilling. 90% of the waste is generated during lunch, totaling 625.7 kg/year, which likely reflects larger portion sizes and the communal nature of school lunches.

3.2. Water and food metabolism of the school

Our study suggests that there is great potential to rethink water and wastewater management in the school, whereas the food metabolism appears to be highly optimized (Fig. 2). The water metabolism shows a high dependency on potable water and end-of-pipe wastewater treatment. Potable water is the main water source in all end uses except for irrigation, which feeds from rainwater, whereas wastewater is managed at a conventional WWTP. A detailed analysis reveals that greywater discharged from faucets, dishwashers, and part of cleaning constitutes 33% of the water flowing to the WWTP together with blackwater from the toilets and part of the cleaning (66%). Additionally, the school is estimated to consume 0.6 m^3 of rainwater for irrigation if the climate conditions of the data collection period are maintained throughout the year. In this case, water demand lies below the capacity of the rainwater harvesting tank (i.e., 1 m^3), which in turn only collects rainwater from

Table 3
Water consumption profiles by end-use facility or activity on a daily, annual and per person basis. Values presented with standard deviations for data obtained within the 4-week monitoring period.

Water end-use facility or activity	School consumption		Consumption per person		Relative contribution
	L/day	m^3/year	L/day	L/year	
Faucets	209.1 ± 26.36	37.2 ± 0.35	1.7 ± 0.22	305 ± 2.9	16.4%
Toilet	734.1 ± 114.5	129.9 ± 1.52	6.0 ± 0.9	1073 ± 12.6	57.5%
Cleaning	205.2	36.3	1.7	300	16.1%
Irrigation	3.6 ± 4.91	0.63 ± 0.06	0.03 ± 0.04	5.27 ± 0.54	0.3%
Dishwashing	124.9 ± 28.9	22.1	1.0	182	9.8%
Total	**1277**	**226.1**	**10.5**	**1865**	**100%**

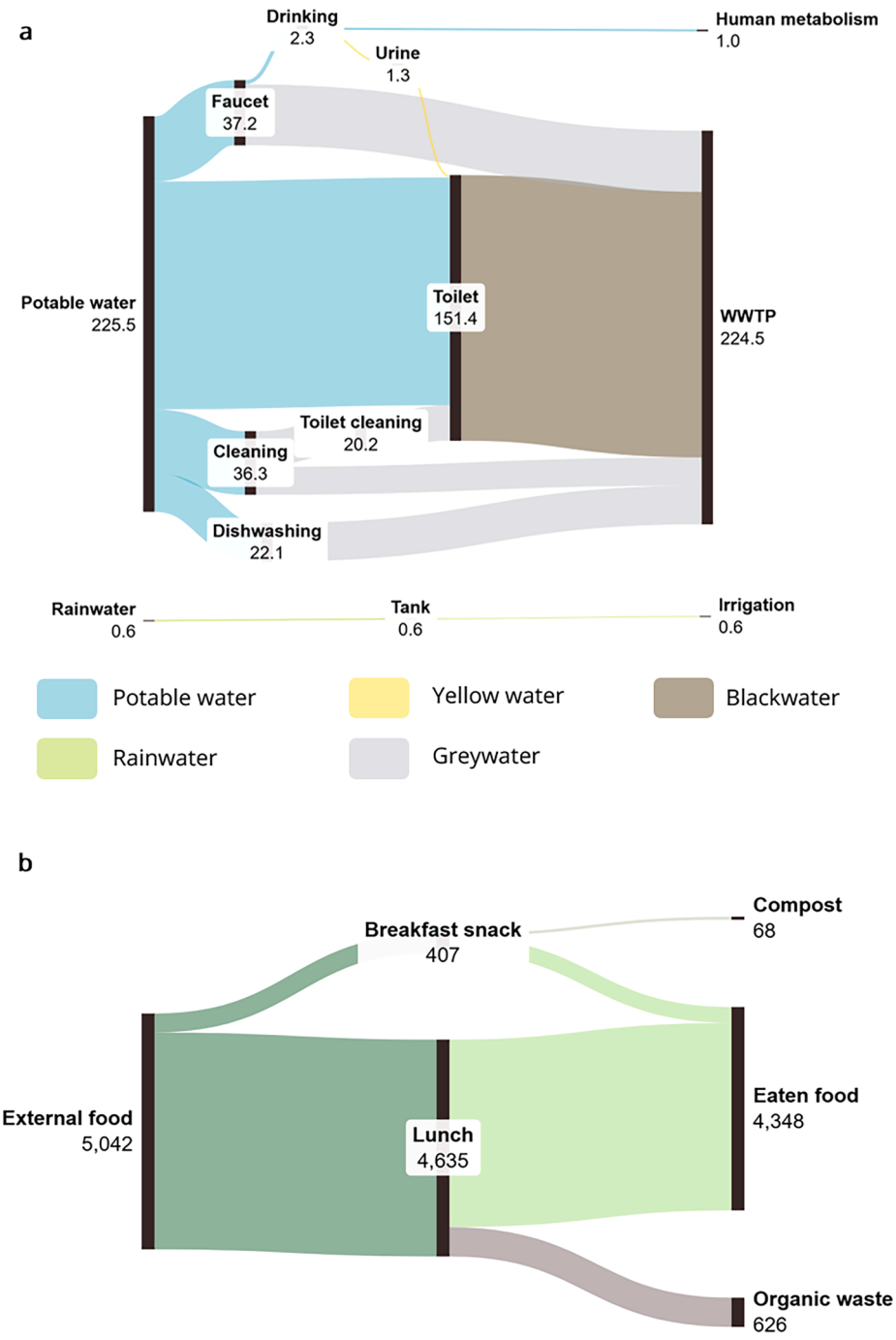


Fig. 2. Annual water (a) and food (b) metabolism of the school system, including sources, end uses, and end of life. Water values are expressed in m^3 and food values, in kg.

11% of the rooftop area for the school. Considering that toilets are the largest source of water consumption, our assessment shows that rainwater is particularly underutilized and has potential to be recirculated to reduce the dependency on potable water.

In the case of food, the existing system was already found to be relatively efficient for several reasons. First, the kitchen staff are highly aware of the importance of minimizing food waste and thus actively manage ingredients and portions to avoid overproduction. Second, the food entering the school is carefully accounted for and tailored to actual consumption patterns. For instance, students bring their snacks from home for morning recess, which are typically foods they enjoy, resulting in almost no waste. As for lunch, Catalonia's school meal policies ensure that portions are calculated to match nutritional needs and avoid excess, while this is not necessarily the case for other schools in other regions or countries. A potential improvement lies in diverting food scraps to composting, although the school's current infrastructure needs expansion, as existing bins cannot handle additional volumes.

3.3. *Circular water management scenarios*

Three alternative scenarios were developed to assess the potential for reducing water consumption and wastewater discharge following the baseline metabolism (Fig. 3). In scenario 1, the total roof area can potentially collect 313.7 m^3/year, which is 1.8 times higher than the

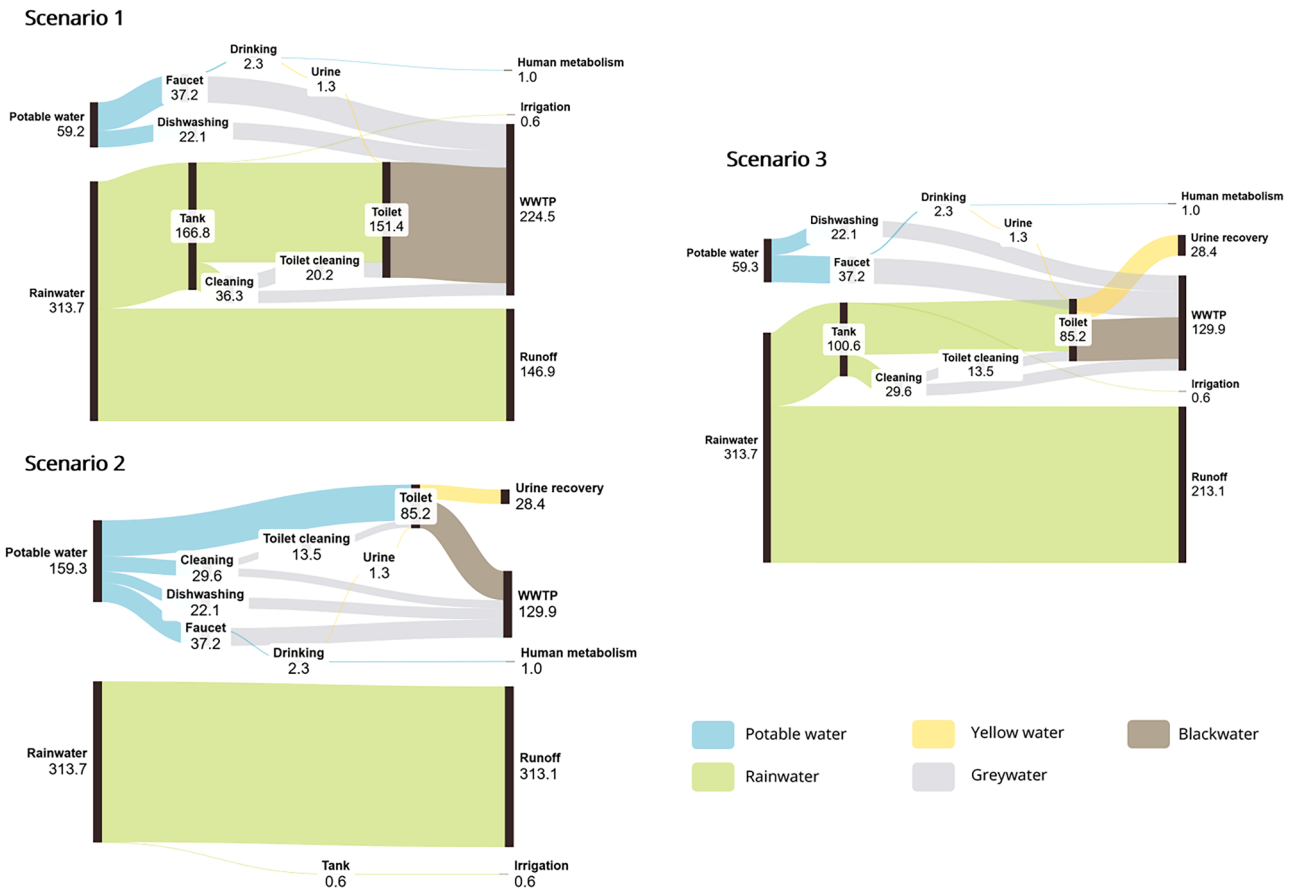


Fig. 3. Water metabolism of the school when applying the strategies defined in Scenarios 1, 2, and 3. Values expressed in m^3/year.

demand for cleaning, toilets and irrigation (166.2 m^3/year). Faucets and dishwashing rely on potable water (59.2 m^3/year), given the water quality standards needed for drinking water purposes and for items in close contact with food. This translates into a 74% potential reduction in potable water consumption. This estimate does not account for tank sizing limitations and yield after spillage but does provide a preliminary understanding of rainwater flows into the school system. Further research can delve into the specific technical requirements of a rainwater harvesting system and thus deliver a more nuanced accounting of rainwater availability.

Scenario 2 models the implementation of urine-diverting flush toilets. Based on the data collection process, we estimated 21,656 toilet flushes per year. With the current toilet designs, this results in a potable water demand of 129.9 m^3/year. Implementing urine-diverting flush toilets reduces water consumption by 45% (70.4 m^3/year). Cleaning-related flows also decrease, as current measurements include water used by cleaning staff for routine toilet cleaning. It is estimated that one full-volume flush per cleaning session is performed. As a result, potable water consumption for cleaning purposes decreases from 20.2 to 13.4 m^3/year. In total, scenario 2 could potentially yield 66 m^3/year of potable water savings. This strategy can also minimize the pressure on the municipal WWTP thanks to both the reduced water demand and urine diversion. As such, the wastewater flow to the WWTP is reduced by 42% and there could be 28.4 m^3/year of yellow water (i.e., urine + flush water) rich in nutrients ready for reuse. Research has shown that urine recovery is a viable strategy for producing fertilizers (Maiza et al., 2025) and thus this flow holds potential to be further explored in the future.

Finally, Scenario 3 combined both circular strategies. In this case, 100.6 m^3/year of rainwater are required for irrigation, urine-diverting toilets, and cleaning. While the potable water savings remain consistent with Scenario 1, the necessary rainwater volume is reduced by 40%. This implies that fewer storage tanks would be required, making the intervention more space- and cost-efficient.

3.4. Evaluating the citizen science approach

Applying the proposed framework in the testbed proved effective in involving both teachers and students in the analysis of food and water flows. The Green Squad actively contributed to measurement tasks, and teachers integrated the data collection into their lessons. The active participation of the school was essential for this research to take place and for the results to be as closely aligned with reality as possible. The relationship with the school and its various actors grew progressively stronger over time, as did their involvement and enthusiasm for participating in and contributing to the research process.

One of the most repeated comments was that students quickly adopted the habit of tracking their use of faucets and toilets. However, participants noted that the first week was the most challenging, and the pilot test was key in helping everyone adjust. Many students, understanding the goals of the study, were excited to contribute to knowledge production. At the beginning, however, the color coding of the faucets was conducive to a competition, as students wanted to have a track record for each color, which did not align with their regular water use. Teachers played a critical role in reminding students to record their usage when needed, especially in the lower grades, where changes in teachers and classroom routines made consistency more difficult. In contrast, older students, who tend to have more stable classroom settings, were more autonomous in completing the records. When students switched classrooms for specific subjects, data collection became more difficult, as the tracking tables were in their main classrooms. Some staff members proposed placing additional recording sheets in the bathrooms to ensure accurate tracking regardless of classroom location.

There was some confusion between the faucet and toilet recording sheets, particularly because they were placed close to each other. One teacher suggested separating them more clearly and adding distinctive visual cues to avoid mix-ups. Primary school teachers felt that the measurement process could have continued without much added effort, while kindergarten teachers found the process more chaotic, as they were the ones responsible for recording on behalf of the children. Despite this, teachers generally believed that the measurements done were a good representation of actual resource use. For the kitchen staff, weighing the food each day proved somewhat time-consuming, mainly due to the low quality of the scale, which slowed down the process.

Overall, no member of the school community felt that the research interfered with academic content or disrupted the daily rhythm of school life. On the contrary, it became an opportunity to integrate sustainability into the school's culture in a practical and engaging way.

4. Discussion

4.1. Contextualizing the results

Our proposed methodology yields water and food consumption that clearly aligns with existing literature. Les Vinyes' average daily water consumption per student was estimated at 10.5 L. This figure is consistent with school water consumption per student in Spain (7.34 L/day; Morote et al., 2020), Italy (18.7 L/day; Farina et al., 2013) and Brazil (13 L/day; Nunes et al., 2019). These comparisons support the validity of the data obtained in the testbed and suggest that Les Vinyes' consumption levels are plausible for a primary educational facility, especially given its rural context and infrastructure. However, our results remain illustrative of the case study and cannot be generalized. These estimates could not be verified with water bills, which were aggregated with other municipal utilities, thus reducing the capacity of the study to demonstrate its actual accuracy.

Our study found that toilets represented the largest share of daily consumption, averaging 6 L per student daily. While this may initially seem inconsistent with Mattsson et al. (2003), who estimate of 3–8 urinations per day for school-aged children, the discrepancy is clarified by context. Toilet flushing at the school uses approximately 6 L per flush, suggesting only one use per student daily. However, considering students spend only part of the day at school and some choose not to use restrooms during school hours, the recorded consumption aligns well with literature findings. An insightful comment from several students highlighted that personal comfort, privacy, and individual preferences also shape water use, with studies by Lundblad & Hellström (2005) and Shao et al. (2021) supporting these behavioral patterns and deterrents in school toilet usage.

When examining the food consumption data from Les Vinyes in comparison with existing studies, the results indicate a remarkably efficient system. According to Wilkie et al. (2015), plate waste in schools can vary widely, typically ranging from 20% to 50% of the food served. For instance, (Rodriguez Tadeo et al., 2014) estimated food waste in Spanish schools using visual methods, finding up to 26% of food left uneaten, while Byker et al. (2014) reported a waste rate of 45.3%. Other studies cited by Wilkie et al. (2015) indicate average daily waste quantities between 52 g and 227 g per student. In contrast, Les Vinyes shows a markedly lower waste generation of 36 g per day (13.7% of the total food served is wasted), which may be attributed to several factors. For instance, Kasavan et al. (2021) found that smaller schools tend to generate less food waste, a pattern consistent with the context of Les Vinyes. Furthermore, their study highlights that the highest levels of food waste typically occur during the pre-consumer stage, which is almost entirely absent at Les Vinyes, as no cooking takes place on-site. Additionally, research by Steen et al. (2018) concludes that canteens receiving externally prepared food generally experience higher waste due to limited cooling and storage. However, this is not the case at Les Vinyes, where adequate equipment and space allow proper meal storage and reheating. These findings suggest that institutional scale and infrastructure capacity play key roles in achieving efficient school food management.

It is important to highlight that Les Vinyes already fosters a strong culture of sustainability. The school community demonstrated high awareness and commitment to responsible resource use throughout the study, which makes the school an ideal setting for implementing new environmental initiatives. The applicability of the proposed methodology needs to be tested in larger schools under different sociocultural and geographical conditions, where involving the entire school community can be more complex.

4.2. School feedback and broader societal impact

While the school community was deeply involved in data collection, the research team developed the mass balances and proposed circular water scenarios. The results of the MFA were presented to the teaching staff during a wrap-up session, where the concept of mass balance was introduced to them for the first time. For this reason, our study relies on a single-period representation of the baseline MFA and the circular scenarios instead of more complex modeling approaches. Teachers were able to understand the composition of input and output flows and to easily detect the modifications in the system when rainwater harvesting and urine-diverting flush toilets were modeled. They also highlighted the usefulness of the Sankey diagrams for communicating the results to the older students, and didactical materials are under development. To date, the impact of these mass balances has transpired the boundaries of the school, as they were presented to all public-school principals in the county. Experimental activities for elementary schools are also being developed using the results of this study.

The wrap-up workshop also served to discuss the school's opinion about the proposed circular strategies. Implementing these changes would likely require structural modifications, such as installing additional rainwater storage tanks, connecting toilets to the rainwater harvesting system, or replacing existing toilets. Expanding the rainwater harvesting system was well received, whereas replacing toilets was deemed more complicated. Concerns revolved around water regulations and economic costs of a larger intervention, which must be covered by the municipal administration. The legal framework that affects this specific school allows and encourages the recovery of rainwater for toilet flushing and irrigation. According to the Spanish Royal Decree 1290/2012 and the Technical Building Code (TBC) (Agencia Estatal Boletín Oficial del Estado, 2026; Ministerio de Agricultura, 2012), rainwater harvesting is allowed for non-consumptive uses such as irrigation and toilet flushing without any additional administrative concession. These are the conditions envisioned in the modeled scenarios. Since 2025, a legal framework also dictates the mandatory reuse of greywater from showers and sinks for toilet flushing in new building constructions (Barcelona Cicle de l'Aigua et al., 2025). However, the use of yellow water is not considered and therefore handled as a residue to be treated in the public wastewater treatment network. Still, the TBC allows building owners to develop alternative solutions for water management if hygiene, security and environmental protection are ensured (Ministerio de Vivienda, 2006). Therefore, while these circular solutions might not require additional regulations, the use of yellow water as a nutrient source would need to be properly justified and monitored if this strategy were prioritized in the future.

5. Conclusions

Our study proposes a methodology for mapping and quantifying water and food flows in schools from a citizen science perspective. Its application was tested in a selected rural Catalan school with an already existing interest in the implementation of sustainability projects, especially regarding food waste. The results indicate that the method aligns with literature relying on utility bills and purchase orders. The

participatory methodology not only enabled a detailed quantification but also fostered active engagement and environmental awareness. A key strength was the co-creation of data collection methods with students and teachers, facilitating data gathering, despite the lack of reliable water meters and accurate bills, as well as ownership of sustainability challenges. The citizen science approach proved effective in overcoming common research limitations in school settings, such as data accessibility and feasibility of daily monitoring.

By focusing on disaggregated flows and community participation, this study provides new insights into the field of sustainable and circular educational infrastructure. Findings underscore schools' potential as resource consumers and as spaces for practicing and modeling sustainability. However, limitations were noted, including varying precision in tracking and weighing procedures, which need to be considered before generalizing the application of our method in other schools.

The case study confirms that schools are key sites for promoting sustainable practices, both through behavioral change and infrastructural improvements. It offers actionable strategies, such as enhancing signage for tracking systems, expanding the use of harvested rainwater beyond irrigation, and improving food waste separation and composting. These recommendations are based on the school's own metabolism and are therefore realistic, scalable, and potentially transferable to other educational institutions with similar characteristics.

Beyond technical outcomes, the participatory approach leaves a transformative legacy. By involving the school community in every stage of the data collection process, the research strengthens local ownership of sustainability practices and equips participants with tools and knowledge to continue monitoring and improving their resource management independently. Future research should aim to refine data collection methodologies to reduce uncertainty and better capture flows in complex or variable school contexts. Academic and educational communities are encouraged to further test this methodology in other settings.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Gemini AI and Chat GPT for text condensation and grammar revision. After using these tools, the authors conducted an exhaustive review of the content that resulted in an extensively edited text. The authors take full responsibility for the content of the published article.

CRediT authorship contribution statement

Tomás Ezequiel Teicher: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Petit-Boix:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Verónica Arcas-Pilz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2026.200399.

Data availability

All data are provided in the Supporting Information

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