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Developing a Model of Bacteria: A Journey Through the Understanding of Prospective Early Childhood Teachers

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Abstract

This work aims to identify the development of the model of bacteria described by 369 prospective teachers of early childhood education, collected over eight academic years. The objective is to determine their pre-existing ideas about bacteria and the evolution after completing a sequence involving work on scientific skills. Before and after the sequence the participants are asked 'What is a bacterium?' The participants' responses are subjected to content analysis. Initial results show a simplified model of bacteria. In their final models, they are able to add new characteristics such as type of cell or reproduction. There is also an increase in the number of students who mention the beneficial activities of bacteria. Regarding location, they acknowledge that bacteria are ubiquitous. Therefore, we identify an evolution of their model of bacteria towards one that is closer to the scientific reference model, although it is still incomplete.

Keywords Bacteria · Early childhood education · Health education · Models · Teachers in training

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Introduction

Educational research advocates contact with science from an early age as a method to develop scientific thinking and create a positive attitude towards science (Zamalloa et al., 2025). Science education proposes that early childhood education should support children in beginning to construct their initial models of scientific phenomena and the surrounding world. These initial models would then be gradually refined and expanded as they progress through the educational system, eventually aligning more closely with the models utilised within scientific disciplines (Ravanis & Boleivin, 2022).

From this perspective, the teacher's role is to support and guide students to facilitate the process of constructing and evaluating these models. This task is particularly crucial during the early childhood education stage, as teachers play an essential role in bringing scientific knowledge into the classroom (Jones & Rua, 2006; Zamalloa et al., 2025). Therefore, they must possess sufficient scientific knowledge to design learning scientific situations though scientific practices (Mazas & Bravo, 2018). However, the lack of knowledge is one of the causes of teachers being a source of alternative ideas that can be transmitted to students (Marcos-Merino et al., 2019). So, one of the key needs within the framework of initial training should be to provide early childhood educators with opportunities to acquire both disciplinary and pedagogical knowledge in a way that enables them to become aware of their own scientific models (Lippard et al., 2018).

In their classrooms, early childhood educators should assume the great responsibility of caring for pupils' well-being (Orden ECD/853/2022). This pedagogical goal requires that teachers support students in developing a scientifically grounded understanding of three key concepts: (a) that invisible microorganisms, in particular bacteria, are ubiquitous, existing both throughout the environment and within the human body; (b) that bacteria can enter the body through various pathways—such as the mouth, nose, or other bodily openings; and (c) that bacteria can exert both beneficial and harmful effects on humans. On the one hand, they play a crucial role in processes that lead to the production of foods such as yogurt. On the other, certain species are pathogenic and can cause infectious diseases in humans. Promoting such conceptual understanding is essential for enabling students to connect abstract microbiological knowledge with everyday practices. Through this connection, learners can appreciate the scientific rationale underpinning hygiene-related behaviours—such as handwashing, covering the mouth and nose when sneezing, and maintaining clean surfaces—as strategies to prevent the spread of infectious agents. Consequently, instruction that integrates these ideas contributes not only to students' scientific literacy but also to their capacity to make informed health-related decisions (Ortuzar-Iragorri et al., 2024). To do so, a basic knowledge about microorganisms, particularly bacteria, is needed (Castellar-Cárdenas et al., 2023). However, as Marcos-Merino and Esteban (2017) have shown they usually hold alternative conceptions about them. Therefore, training student teachers of early childhood education on bacteria, is deemed important and it should focus on acquiring adequate knowledge about these organisms. This is the reason why this study aims to assess the knowledge of prospective early childhood education teachers about bacteria, specifically about their characteristics, functions (defined as their role in the environment and in relation to humans) and locations. Identifying the initial conceptions of the prospective teachers participating in the study enabled the design of a teaching sequence aimed not only at enhancing their mental model of bacteria but also at providing functional knowledge regarding their characteristics, functions, and localizations. Comparing these initial conceptions with those collected at the end of the intervention will make it possible to examine the development of their models, highlighting both the improvements achieved and the limitations that may still remain. The data is collected at the beginning and at the end of the teaching sequence. Prospective teachers were asked to submit a one-minute paper to identify how their bacterial models develop, due to this technique helps to ascertain the initial and final ideas of the teachers and to establish their progression (Ghosh et al., 2025).

The research questions are:

- What ideas do future teachers of early childhood education have about bacteria?
- How do these ideas about bacteria change when they work on a learning sequence that addresses their characteristics, functions and locations?

Microorganisms

Authors such as Ruiz-Gallardo and Paños (2018) and Biyikoglu et al. (2025) propose addressing microorganisms from the earliest educational stages, based on the students' ideas are easier to shape and transform in the early stages of education. In the same vein, Cavicchioli et al. (2019) suggest encouraging proper scientific understanding, as this would help students to appreciate the importance of bacteria for human beings and life on Earth. According to Simard (2023) this implies that students need to be aware of the characteristics that differentiate bacteria from other organisms, such as their reproduction methods.

Nevertheless, learning about microorganisms poses challenges for students. The analysis of students' ideas about microorganisms and their role in the environment began in the 1950 s with Nagy (1953), who revealed that primary education students viewed microorganisms as harmful, often depicting them with characteristics akin to animals or humans. Then, Byrne et al. (2009) also recognised these ideas in the students and identified that pupils only considered bacteria's harmful effects, although bacteria are essential for the functioning of the planet. For instance, bacteria's role in the food chain and biogeochemical cycles is indispensable for the existence of the trophic levels (Cavicchioli et al., 2019). Besides, bacteria are also involved in economic and industrial processes, such as the manufacture of biological fertilizers and pesticides (Jones & Rua, 2006). Related to bacteria's location, students link them with dirty places or the human beings (Marcos-Merino et al., 2019), they do not recognise the ubiquity of bacteria. These students' ideas persist, despite current social challenges like the overuse of antibiotics and the emergence of resistant strains (Castellar-Cárdenas et al., 2023; Simard, 2023).

Ballesteros et al. (2018) and Ampatzidis and Tsevreni (2026) show that these misrepresentations are also found in textbooks and teachers' ideas. Regarding textbooks, authors such as Mafra et al. (2015) and Špernjak et al. (2023) find that textbooks portray microorganisms—and bacteria in particular—solely as pathogens, neglecting other functions. They also note that microorganisms are usually represented based on anthropomorphism. With respect to teachers, Marcos-Merino et al. (2019) show that they also limit their microbial knowledge to diseases, which could favour their classes focusing on the harmful role of bacteria and not delving into their benefits.

Most of the studies in the literature concerning ideas about microorganisms, particularly bacteria, were conducted with students at different educational stages (Ballesteros et al., 2018; Byrne, 2011; Špernjak et al., 2023). Among them, some are geared towards working on content about bacteria with activities relating to food safety (Faccio et al., 2013), hygiene practices (Castellar-Cárdenas et al., 2023) or the role of bacteria in our lives (Mafra et al., 2015). These activities have been mainly aimed at students of early childhood and primary education. In secondary education, studies such as the one conducted by Robredo and Torres (2021) show that approaching the topic of bacteria using practical activities improves student knowledge about these organisms. In all the examples proposed, the activities were always designed by experts on the subject, such as Biologists, rather than the teachers themselves.

Works that address the ideas held by teachers of early childhood education are scarce (Ampatzzidis & Tsevreni, 2024; Ortuzar-Iragorri et al., 2024). Moreover, in the few studies involving practical activities with trainee teachers, the activities were also proposed by external individuals (Biyikoglu et al., 2025; Faccio et al., 2013). This aspect should be considered, as it is the teacher who decides what and how to teach (Constantinou et al., 2018). If teachers lack the necessary knowledge, their capacity to conduct such activities in their classrooms is hampered, be it due to insufficient knowledge about the subject or the activity itself. Furthermore, according to Schori and Gal (2024), when teachers possess sufficient knowledge about their teaching content, their ability to implement this knowledge is substantially enhanced. This underscores the need for effective teacher training (Ruiz-Gallardo & Paños, 2018). For this reason, this study focuses on trainee teachers of early childhood education as there are hardly any studies that describe their ideas about bacteria. Understanding their ideas and models regarding what a bacterium is, as well as its functions and locations, is fundamental for designing effective training interventions that enable them to progress towards models that are more aligned with the scientific community and to identify and rectify the alternative ideas they may have (Marcos-Merino et al., 2019). Concurrently, it is crucial for these trainee teachers to acquire strategies that will assist early childhood students in constructing their initial models of bacteria, steering them away from misleading representations that may be found in textbooks and other sources.

Construction and Use of Models in Science Teaching

It is difficult to consider science without models (Couso, 2020). In this sense, Gilbert and Justi (2016) indicated that the process of modelling consists of creating a specific, simplified representation of complex systems, objects or phenomena of study. Models are especially necessary when direct observation of the object of study is not possible (Megalakaki & Tiberghien, 2011), since they make it possible to visualize and understand its behaviour, which is an approach to science learning.

The use of models in science teaching facilitates the use of prior knowledge and reveals alternative ideas, thus favouring conceptual change and the acquisition of new knowledge (Megalakaki & Tiberghien, 2011). It also encourages the development of skills such as description or argumentation (Couso, 2020).

In the specific case of biology, models are present daily in classroom due to the level of abstraction of many of the concepts addressed: from models that represent micro-level structures, such as the cell or the DNA double helix, to those that represent macro-level phenomena, such as ecosystems (Metzger & Yowler, 2019). Bacteria, as microorganisms, cannot be directly observed with the naked eye. Consequently, different methods of representation and modelling are required in most classrooms. Therefore, teachers need to acquire an appropriate model of bacteria to handle concepts that provide them with a foundation for designing learning situations.

In order to characterize the model of bacteria that prospective teachers of early childhood education should have and the domains that it should be integrated are defined based on: 1) the studies such as Castellar-Cárdenas et al. (2023) who identify preschool students (4–5 years)' conceptions of bacteria through the analysis of their oral answers and drawings and 2) topics relating to bacteria in the Spanish curriculum contained in the law applicable to their entire schooling (Ley Orgánica para la Mejora de la Calidad Educativa [LOMCE], 2013) and in textbooks. Regarding the latter, textbooks were included because the curriculum scarcely mentions specific concepts about bacteria, but rather addresses them broadly; for instance, the classification of kingdoms or health emerges when discussing infections produced by microorganisms. So, to provide a more comprehensive overview of bacteria-related topics covered throughout the entire pre-university schooling period, Fig. 1 presents the list of topics studied, using some of the most used textbooks in Spain from the fifth year of primary education to the second year of post-compulsory secondary education. Given the aims of this study, the educational curriculum established during the secondary school stage exerts a clear influence, as it represents the students' initial academic background and serves as the primary source for constructing their initial mental model. Specifically, the knowledge outlined in these curricula should provide a foundational image of what students are expected to know concerning bacteria before starting their university education. Consequently, this curriculum overview can be viewed as a conceptual map, indicating the elements we might anticipate the perspective teachers would mention in their responses and thus forming their initial mental model.

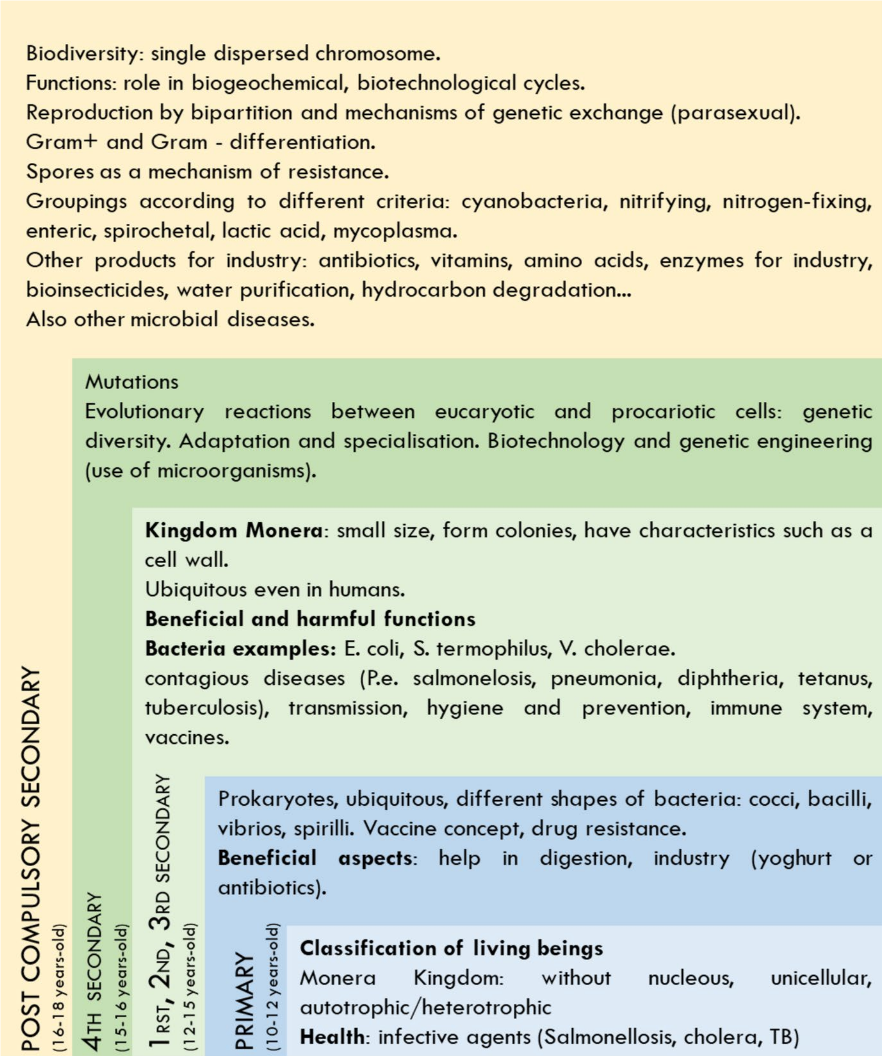


Fig. 1 List of topics on bacteria throughout three different educational stages under the LOMCE (2013)

Considering the knowledge envisaged for the different courses (Fig. 1), we believe that to work adequately with students, prospective teachers should build a model of bacteria that considers them as:

Prokaryotic, unicellular microorganism belonging to the Kingdom Monera, with a ubiquitous presence in all environments, which, depending on its genus and species, presents different characteristics such as cilia, flagella…and different bacterial shapes (cocci, bacilli, vibrios, spiral…). They reproduce asexually by binary fission, although they can incorporate external genetic material by various means (transformation, conjugation, transduction), which provides them with new characteristics, *both beneficial and harmful. Some bacteria contribute to the pharmaceutical and food industries, for instance there are bacterial strains that are used as probiotics or participate in the production of yogurt, while others are beneficial to humans because they are an essential part of the intestinal microbiota. Nevertheless, certain bacteria harm other living beings and cause disease. Some examples of bacterial diseases are dental caries (Streptococcus mutans), salmonellosis (Salmonella spp.) or foodborne illness (Escherichia coli.). Given the prevalence of these illnesses in early childhood, understanding their transmission—*via *saliva, contaminated food and water, person to person contact, or feces—is essential to promote hygiene practices, such as handwashing and toothbrushing, to prevent them.*

Bacterial diseases can be controlled with vaccines, which protect the organism by preventing the appearance of infection, or with antibiotics, once infection has occurred.

Currently, due to the great number of bacterial mutations and the rapid transmission of diseases, resistance to antibiotics is a major problem, so we should use them responsibly so that they do not stop working completely.

To ascertain the model of bacteria held by the participating teachers, they need to express their mental model, which is why this work expressly prompts them to consider and express it. Accordingly, they were asked to respond to an open-ended question, allowing them to articulate their own ideas by constructing their responses using the elements and concepts they associate with the notion of bacteria, thus revealing the actual model they have in mind. Conducting this process both at the beginning and at the end helps the teachers to evaluate their own models and to acknowledge their evolution (Couso, 2020). Thus, within the context of modelling, the process of evaluating constructed models is as relevant as the process of constructing them, as it is through this practice that the teachers become aware of their progress (Mendonça & Justi, 2011), a perspective embraced in this research.

Methodology

The findings of this study are grounded in a qualitative research methodology aimed at generating knowledge from human experience (Sandelowski, 2004). Such experiences are diverse, and participants may articulate their perspectives orally—through interviews or video recordings—or in written form, such as essays or drawings, which can subsequently be subjected to content analysis. In this study, we draw on prospective teachers' written responses.

To identify the ideas about bacteria that constitute their models, we analyzed the content of these responses by examining the various fragments that compose them. These fragments, or units of analysis, were classified into previously established dimensions. A unit of analysis refers to any segment of text that provides evidence relevant to one or more of the dimensions under study (Gee, 2005). To determine the dimension(s) addressed in each response, a recursive content analysis was conducted (Krippendorff, 1990).

Content analysis uses reading as a tool to collect information, with the researcher making judgements about the coding, theming, decontextualizing and recontextualizing of the data (Ruiz, 2007) in a systematic, objective, reproducible and valid manner (Nowell et al., 2017). To validate the tool, several cycles of analysis can be carried out independently by the researchers. After each cycle, the results are grouped together to identify discrepancies and jointly review the categories and their characterisation. This iterative process allows the coding system to be refined and the reliability of the analysis to be strengthened (Bardin, 1991; Miles & Huberman, 1994).

Context

At the University of Zaragoza (Spain), the first science subject on the early childhood education degree course is 'Childhood, health and nutrition'. It covers knowledge related to health and illness during the early childhood educational stage, including the organisms that cause diseases such as bacteria, their characteristics, locations and functions, their transmission vectors, and the ideas that young learners may have about these concepts. It also explores various practical proposals that future educators can implement both to strengthen their own understanding and to effectively transfer this knowledge to their classrooms. In this way, the teachers will also be able to recognize infectious and chronic illnesses in order to manage certain situations that may arise in the classroom.

Participants

The study involved 369 future teachers in their second year of the early childhood education degree who had taken this subject in eight academic years (Table 1). Most of the students in the Degree programme are females (only 3,8% of males), and the mean age is 19.86 (SD 3.2). Hereinafter, each academic year is referred to by the first year of the two, e.g.: year 2016 refers to 2016/17 and so on.

The overall profile of the participants regarding their scientific knowledge is mostly low. In general, they have not studied either the scientific-technological or the health sciences specialization in post-compulsory secondary education, which means that their last contact with scientific content was between the third and fourth years of compulsory secondary education and that is at least five years earlier.

Development of Activities

The sequence involves four activities (A, B, C, D) relating to bacteria (Fig. 2). The objective is for the prospective teachers to develop a model of bacteria that helps them handle basic concepts about them so that they feel competent enough, from the

Table 1 No. of participants in the study by academic years

	2016	2017	2018	2019	2020	2021	2022	2023
Pre-test	49	54	36	49	43	43	40	44
Post-test	51	41	44	45	30	38	40	45

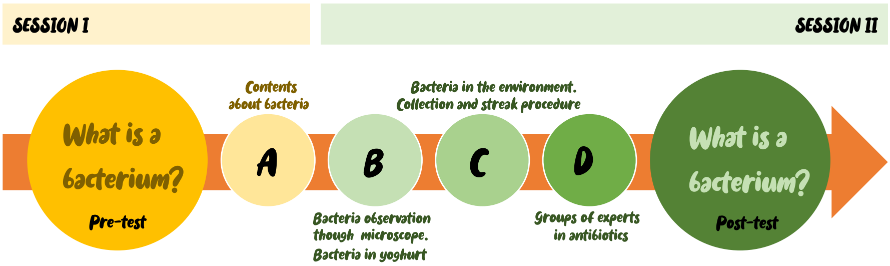


Fig. 2 Sequence of activities on bacteria in two sessions

earliest stages of schooling, to address topics related to microorganisms and Monera in particular.

To this end, before the first activity, the participants are asked the question 'What is a bacterium?' (pre-test), which they will answer individually in approximately one minute before the activity A starts. Once the intervention is over, they will be asked the same question again (post-test). This will help us to analyse and characterise the model of bacteria to know the evolution of the model that they have before and after the sequence, as well as any changes that have occurred (Ghosh et al., 2025). The intervention is the same in the eight academic years covered by the study and the topics are included in Table 2.

Session 1

Once the question described in the previous paragraph has been posed and answered, the responses are collected and then the professor presents topics such as the main characteristics of bacteria, depending on their classification, their morphology (prokaryotic microorganisms, lack of nucleus, parts of a bacterium and components), and their utility in industry. Their ubiquity, oxygen tolerance and type of reproduction (asexual and sexual) are also mentioned. Lastly, the focus turns to resistance to antibiotics. After all this information, the teacher lists illnesses such as dental caries or acute otitis media.

Table 2 Summary of topics about bacteria in the proposed sequence, grouped by domains

Domains	Contents
Characteristics	Main characteristics of bacteria, depending on their classification (Kingdom Monera), their morphology, prokaryotic microorganisms, unicellular, lack of nucleus, oxygen tolerance, types of reproduction
Function	Beneficial functions: Utility in industry (manufacture of antibiotics, yoghurt, cheeses…)
	Harmful functions: Frequent childhood illnesses: dental caries or acute otitis media
Location	Ubiquity, food, human body
Others	Resistance to antibiotics
	Examples of bacteria

Session 2

Following authors such as Gail-Jones et al. (2013) and Robredo and Torres (2021), whose results indicate the necessity of working with bacteria through the lens of practical work, the second session takes place in the laboratory. This is a practical activity, divided into several parts:

(1) This session begins with a preparation to observe the bacteria in yoghurt using an optical microscope. The objective is for the prospective teachers to be aware of the size and different shapes of bacteria, to realize that these microorganisms can be found in foodstuffs such as yoghurt and to link their presence to their role in the fermentation of this product (utility). The teachers also practice the necessary procedure to see bacteria thereby developing scientific skills such as sample preparation, identification of observable characteristics or use of the optical microscope (Reiser, 2013).

(2) Following this, they take a sample from a place they believe may contain bacteria. Once the sample has been collected (the most frequent places are usually bathrooms, door handles, mobile phone screens or one's own mouth), they are told how they should streak the Petri dishes, which contain nutrient agar (Mueller–Hinton). Once streaking is completed, they add three antibiotic discs (amoxicillin, ampicillin and cefotaxime) and a common natural product with antibacterial properties (garlic) to conduct an antibiogram and thus establish whether a certain antibiotic is effective against the present bacteria. In this second part, the prospective teachers should identify whether there is bacterial growth (to assess ubiquity), recognize different types of colonies in their dishes and observe how antibiotics affect their growth (Fig. 3).

(3) Finally, they are asked to form four groups of experts to work on the official website for antibiotic resistance https://www.resistenciaantibioticos.es/es The groups of experts are as follows: a) Experts on antibiotic resistance in Spain and

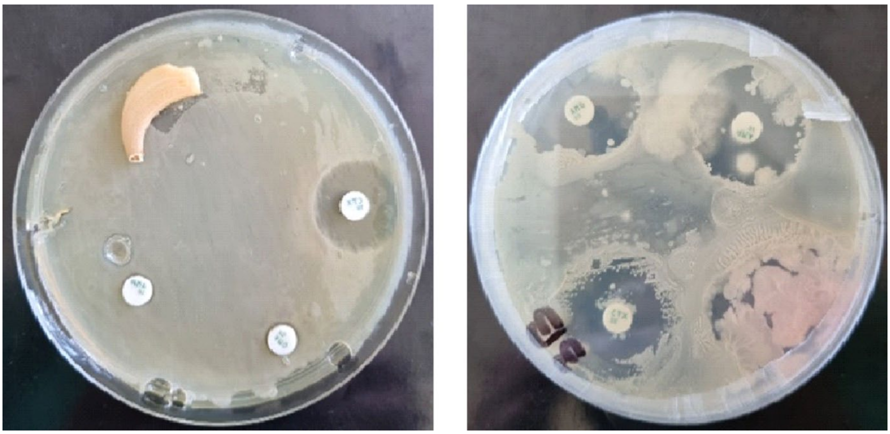


Fig. 3 Examples of antibiograms produced by the students

worldwide; b) Experts on situations where antibiotics are inactive against bacteria; c) Experts on different antibiotics; and d) Experts on situations of antibiotic inactivity against viruses.

Each group of experts must identify the relevant information to be able to answer one of the following four questions:

- What problems are there involving antibiotic resistance?
- What would happen if antibiotics did not work against bacteria?
- What difference is there between antibiotics in eliminating the different bacteria?
- Why are we not able to eliminate viruses, such as coronavirus, with antibiotics?

Once each group has reflected on the assigned subject, the experts re-join their original groups to share and explain the information covered with the expert groups (Pujolás, 2003). In this process each person gains a comprehensive understanding of antibiotic resistance.

The objective is to raise awareness about the use of antibiotics and the resistance associated with improper use. Likewise, this increases knowledge on how to treat and prevent bacterial illnesses by addressing aspects related to antibiotic resistance using the data from the provided website.

Data Registration and Analysis

During the eight years of the study, the protocol remained unchanged, i.e., traditional pen-and-paper methods were used, the instructor was the same teacher, and the intervention was consistent. The students wrote their answers on a blank piece of paper in approximately one minute, using the one-minute paper technique (Gray et al., 2005).

The participants' responses about their model of bacteria were collected at the beginning and at the end of the sequence to have information about their ideas and compare both models. With the results of both questions, a content analysis of each prospective teacher's answers was carried out (Ruiz, 2007). According to Yin (2018), the unit of analysis of a study must be selected on the basis of the analysis conducted. Thus, in this study, the selected analysis unit was the fragment of text, i.e., a word or set of words containing an idea or concept related to bacteria and that can be associated with a domain.

In order to identify the different units of analysis in each participants' answers, they were fragmented and each unit was assigned to the defined domain. Considering this, the analysis of the prospective teachers' responses follows the subsequent procedure:

(1) Defining the three main domains of the reference model of bacteria: characteristics, location and function, and the categories that are part of each of them.
(2) Fragmenting the responses of the prospective teachers in their unit of analysis based on the domain to which they refer. These domains were compared to the

responses finding that within each of these domains, preservice teachers refer to specific aspects of bacteria such as the size, the number of cells, reproduction, etc., so different categories of analysis were established within each domain according to the specific aspect of bacteria that they were referred to. After the analysis, an emerging domain, ‘others’, is included to add those fragments that do not fit into any defined category.

This example shows how the different fragments can be associated with characteristics (in blue), location (in green), function (in yellow) and others (in orange).

> ‘*It is a microorganism, present everywhere in our surroundings, and there are several types. Some are good and are needed to make yoghurt or cheeses, and, in contrast, others are bad, they give us diseases and we need antibiotics to kill them*’.

(3) Assigning the fragments according to the established domains based on the aspect of bacteria it deals with (Table 3), reviewing them to check their consistency and homogeneity. To do so, firstly the answer is fragmented by identifying the domain to which they refer, and then each fragment is assigned to the specific category. The total number of fragments was greater than the number of students’ responses, as individual students often incorporated multiple fragments within a single answer.

(4) A final analytical framework was established through a subsequent cycle of analysis. Each student response was re-examined, segmented into discrete units, and assigned to the appropriate category. Two researchers conducted this process independently, and coding outcomes were compared. Discrepancies were discussed until consensus was reached, accounting for less than 10% of the fragments and indicating high intercoder reliability.

Results and Discussion

Analysis By Domains

Characteristics

In the category ‘characteristics’, the number of references to the size of bacteria decreases from the pre-test to the post-test in all the years (Fig. 4). It seems clear that participants preferred to emphasise other characteristics learnt during the sequence, such as structure, type of reproduction, or cell type—recognising bacteria as prokaryotic cells.

These results support the conclusions proposed by Simard (2023), who suggests that explicitly addressing the characteristics that differentiate bacteria from other

Table 3 Examples of categorization of the pre-test responses

		Examples
CHARACTERISTICS	Size	Microorganisms, very small, observable with a microscope, element, small thing, microscopic body/thing, particle
	Shape or structure	Purple, circles, various shapes and sizes
	No. of cells	Unicellular, uni/multi/group of cells
	Reproduction	Rapid reproduction, 'They reproduce'
	Prokaryotic cell	Prokaryotic cell
	Kingdom Monera	Insects, parasites, one of five kingdoms
LOCATION	Everywhere	In all types of environments, 'Bus, objects, surfaces, street', [air, land and water]
	Atmosphere	Air, environment, nature
	Living beings	Animals, organisms, living beings
	Our organism	Hands, intestine, human body
	Food	Yoghurt, beer
FUNCTION	Beneficial and harmful	Benign and malignant, good and bad, negative, good and bad, necessary and detrimental
	Beneficial	They protect the organism; they create nutrients such as vitamins (B12), bacterial flora, aids digestion
	Harmful	They produce infections, contaminate food, diseases, health problems, discomfort
OTHERS	They adapt to the medium and/or mutate	They seek to create the living conditions that are most favourable for them
	Antibiotics/soap eliminate them	Hand-washing, they can be killed with antibiotics Antibiotics are an effective treatment for us
	Specific examples	Staphylococci, E. coli

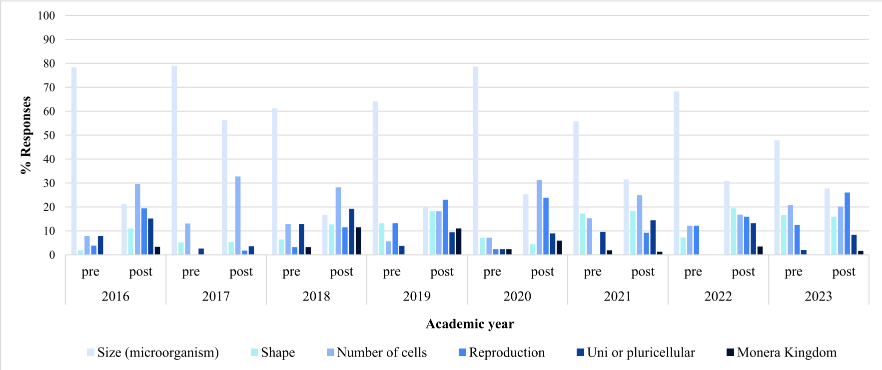


Fig. 4 Percentage of responses that refer to the characteristics of bacteria (pre and postest)

organisms would enhance the understanding of this scientific topic and also try to reverse some alternative ideas that were reinforced by the recent pandemic. Some of those alternative ideas related to characteristics expressed by the participants are:

- Classifying bacteria in kingdoms such as Animal or Protozoa, for example, A1: 'Bacteria are insects that live on different objects'; A2: 'Unicellular living being, belonging to the Kingdom Protozoa…'; A3: '(…) it is the smallest organism in the Animal Kingdom'; A4: 'It is like a type of virus (…)'.
- Confusing the way they reproduce, A5: '(…) Their reproduction is very fast, and they are hermaphrodites'.
- Comparing bacteria and a type of biomolecule, not considering them as living beings, A10: 'A bacterium is a glaucid.

Regarding the characteristics related with the kingdoms and the number of cells, while the confusion about kingdoms or the way bacteria reproduce has disappeared in the post-test, the number of participants who believe that bacteria are multicellular organisms increases (three students in the pre-test and eight in the post-test), for example A12 said: 'They are multicellular microorganisms (…)'. With the idea that colonies are the macroscopic manifestation of bacterial growth, perhaps they were left with the idea that each colony was a bacterium and associated this with the fact that they could have several cells (Marcos-Merino & Esteban, 2017). Or perhaps they did not understand what they were being asked. In the light of this result, it is essential to review the intervention to identify which activity may have contributed to the acquisition of this incorrect concept.

Location

While the categorisation was divided into five sections according to their more literal responses, it is possible to interpret that when they say that bacteria are 'in the atmosphere', they may imply that they are 'everywhere' or, for example, that 'in

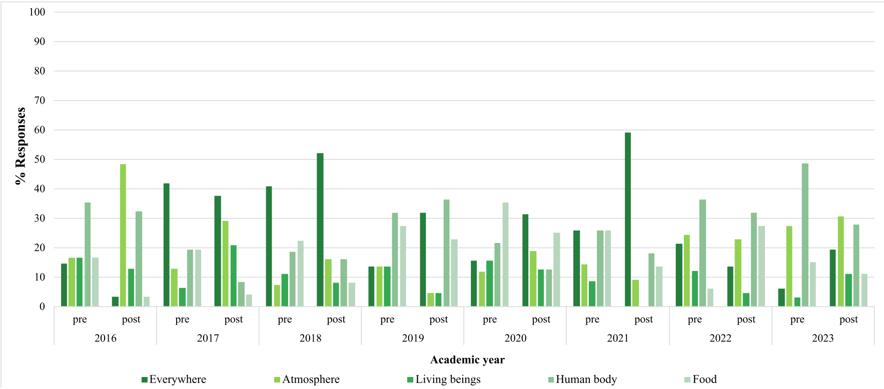


Fig. 5 Percentage of fragments of responses regarding location in the pre-test and post-test

the human body' (hands, intestine) might also fall under the category 'in all living beings'. However, they display a clear inclination to identify location based on more familiar topics studied in the practical activity involving bacteria in yoghurt (activity b) as they indicate that bacteria are present in foodstuffs such as yoghurt. Most student teachers consider that bacteria are 'everywhere', making it the most frequent option in the post-test for the years 2017, 2018, 2020, 2021, or 'in the atmosphere' (2016, 2023). However, the most frequent response for location in 2019 and 2022 is still 'in the human body' (Fig. 5).

Some of alternative ideas in identifying the typical bacterial habitats are detected in pre-test, for example, when they think that bacteria can be dissolved as if they were a soluble substance, confusing dissolution with fermentation: A9: '…they are usually dissolved with other elements, for example, we can find bacteria in yoghurt'. Those ideas weren't identified in the post-test.

This domain is linked to how prospective teachers perceive the actions that bacteria can undertake concerning humans. If they view bacteria only as harmful, they associate these microorganisms with illnesses and pathologies; in the case they consider the benefits of bacteria, they only associate them with the utility they may have for human beings, for example, in food preparation, production of antibiotics or decomposition of organic material (bacterial flora), A7: 'They are living beings… there are bacteria in foodstuffs that help to transform them, such as yoghurt or kefir', without taking into account their role in the ecosystem. For instance, A13 mentioned: 'It is a microorganism, present everywhere in our surroundings, and there are several types. Some are good and are needed to make yoghurt or cheeses; others, in contrast, are bad, they cause illnesses, and we need antibiotics to kill them'; showing limitations in distinguishing between the types of diseases caused by these organisms, A8: 'A bacterium (…) can lead to infectious and non-infectious diseases'. Other alternative ideas, we can observe that bacterial functions for other organisms such as fungi, A6: '(…) they are usually harmful to health. However, I think that there are also good bacteria in food such as brewer's yeast.

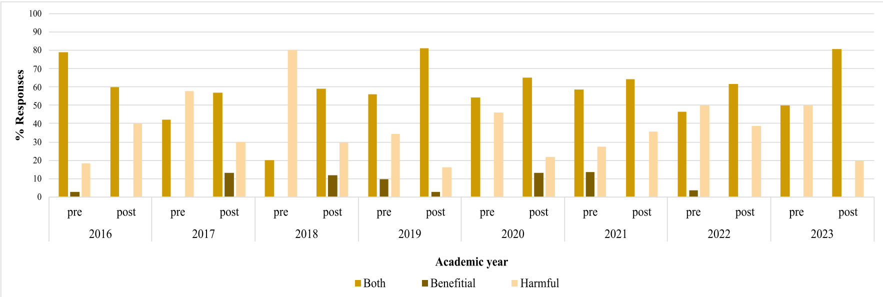


Fig. 6 Regarding function in the pre-test and post-test percentage fragment of responses

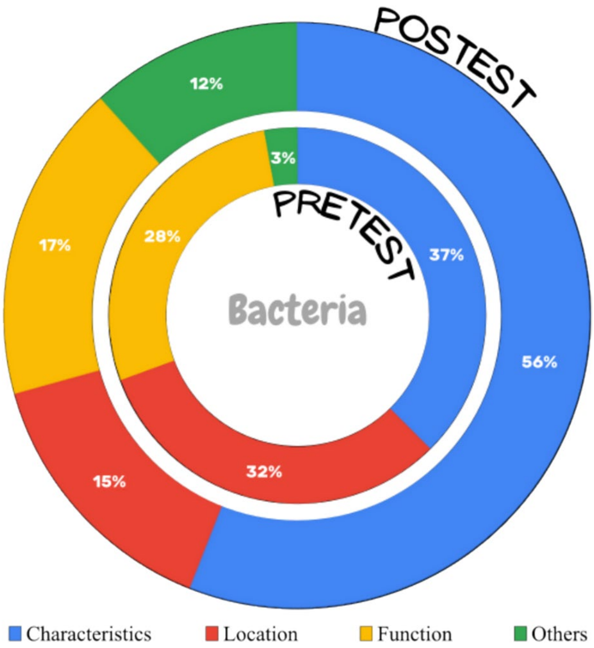
While in the pre-test, there is a major number of future teachers that only recognise the harmful functions of bacteria, in the post-test this tendency changes, increasing the number of participants that consider both harmful and benefit effects, especially in seven out of the eight years of the study (2017–2023), although the benefit functions are still only related with human beings. In 2020, not a single participant out of 43 participants referred to the beneficial function of bacteria, whereas after learning the bacteria unit, approximately 10% of the participants referred to this characteristic. In 2021, approximately another 10% referred to the beneficial characteristic of bacteria in the pre-test stage, but in the post stage, none of the participants referred to this characteristic, precisely after learning about bacteria in yogurt and cheese. In several years (2016, 2021, 2022, 2023) persists the idea that bacteria only have harmful effects in the post-test (Fig. 6) such as A14: 'A bacterium is an organism that (…) can cause infectious diseases'. This persistent emphasis on harmful bacterial functions as opposed to others is not surprising, given its recurrence in different years, as indicated by Robredo and Torres (2021).

Others

This dimension includes the ideas that do not fit into the other categories. For example, there are references to the ways to eliminate bacteria, including the role of antibiotics, particularly prominent in the post-test. There are also alternative ideas related to the meaning of 'to become resistant', for instance A16: 'You become immune if you take them frequently or when you are not supposed to', suggesting a belief in acquired immunity by the organism. Another common response involves the notion that organisms perceived as 'inferior' can spontaneously create themselves, as seen in response A17: 'For me bacteria are living organisms that can create themselves voluntarily through reactions, or involuntarily, and can appear in food (…)'. Both ideas need explicit attention in teacher training, given that if they persist, they could be transmitted to teachers' future pupils, and to citizens in general (Špernjak et al., 2023).

Lastly, the post-test presents a greater variety of specific examples of bacteria, especially those covered in the sequence (Streptococcus, Lactobacillus, E. coli or

Fig. 7 Initial and final characterisation of what prospective teachers consider bacteria to be



Staphylococcus), and illnesses, such as dental caries, scarlet fever, otitis, and other sporadic ones such as tuberculosis. This suggests that this aspect was easily learned by the teachers.

Initial and Final Characterisation of What a Bacterium Is: Evolution

In Fig. 7 it is shown the visual difference between pre and post-test in terms of percentage of characteristics, location, function and other aspects that the preservice teacher could refer to when we ask what a bacterium is. Therefore, it is represented proportionally by colours and percentages, based on the overall responses throughout the years of the study.

As shown in Fig. 7, an initial model of bacteria (pre-test) can be defined using the responses to the question 'What is a bacterium?' Considering the three dimensions that integrate the bacteria model, prospective teachers in their initial model mainly refer to the general characteristic of bacteria (37%), then to their location (32%) and finally to their function (28%). There are only a few of them who consider other ideas (3%) such as the use of antibiotics to eliminate bacteria.

Considering the results and their relationship with the model of bacteria of the theoretical section, prospective teachers show a limited model of bacteria. Although all of them have studied bacteria at some point in primary and secondary education, concepts such as classifying bacteria as members of the Kingdom Monera or their asexual reproduction are absent from their ideas. Other characteristics, such as classification based on the type of Gram stain barely appear. This reality can be related to the fact that these topics are addressed in fourth year of compulsory secondary education and post-compulsory secondary education (Fig. 1) and many of the participants have not received that training, despite of the importance of having of basic and functional knowledge of microorganisms in general, and bacteria, in particular.

From the perspective of educating scientifically literate citizens, working on these topics would help them to understand certain aspects, such as the identification of bacteria as living beings, recognizing that they are part of one of the big life kingdoms on the planet. Or, for example, understanding how bacteria are transmitted and how they multiply in our bodies would also help prospective teachers to start up preventive measures, including the use of antibiotics. This means that we can work on hygiene with more sense, for example washing hands, teeth, etc., and medication with caution.

In this respect, alternative ideas, especially those relating to the identification of bacteria as viruses or fungi and the difficulty determining their functions beyond causing illnesses to have also been found among school-age children (Simard, 2023) and adults (Špernjak et al., 2023). In the specific case of pre-service early childhood teachers, similar findings have been reported by both Ampatzidis and Tsevreni (2026) and Ortuzar-Iragorri et al. (2024). Regarding this issue, we share the concern initially expressed by Byrne and Grace (2010), who highlighted students' lack of knowledge about the beneficial aspects of microorganism activity. They argued that understanding these positive roles could serve as a crucial foundation for comprehending more complex applications of microorganisms later in the curriculum, particularly in fields like technology and biotechnology.

The deficiencies or limitations found in the students' initial mental model could be a reflection of the shortcomings in the teaching of this topic in the previous educational stages of the Spanish system. Although it is evident that this work is highly influenced by the specific profile of students pursuing early childhood teacher training, the predominant profile consists of students who ceased taking science subjects at the age of 15 or 16. However, even for this cohort, the national curriculum indicates that they should possess certain knowledge about bacteria, which is not consistently detected in their initial models, as was also reported by Ortuzar-Iragorri et al. (2024).

After implementing the sequence and collecting the teachers' responses, the analysis shifts to understanding how the prospective teachers have characterized bacteria and how their ideas have evolved after the teaching sequence (Fig. 7). Considering the three dimensions that integrate the bacteria model, prospective teachers in their final model mainly refer to the general characteristic of bacteria (56%), to their location (15%), to their function (17%), and other ideas (12%).

The bacteria model developed by the prospective teachers after the sequence shows clear differences with respect to their initial model (Fig. 7). They have increased their knowledge in all their domains generating a model of bacteria that is closer to the reference model suggested in this work. Regarding characteristics, although there is still a predominance of considering bacteria as a microorganism, the prospective teachers incorporate a greater number of characteristics such as their recognition as a unicellular organism, the identification of their asexual reproduction, or the inclusion of the bacteria in Monera Kingdom. In particular, the identification of bacteria as a unicellular organism predominates in the post-test in every single year if we compare it to the pre-test. In 2019 the type of reproduction prevails over other characteristics, indicating that they reproduce asexually. In the final model, the inclusion of the bacteria in the Monera Kingdom is at least pointed out one time in all the years except 2017, in which none of the students mention this idea. Moreover, none of the teachers consider bacteria in other kingdoms such as animals or plants. This integration of ideas could demonstrate the effectiveness of the sequence in addressing these aspects, although there is still work to do as there are ideas such as bacteria are cells without nucleus or have a specific morphology (cocci, bacilli, spiral…) that do not appear in prospective teachers' answers.

Regarding location, part of the teachers has managed to move beyond the ideas identified in the literature, such as locating bacteria exclusively in human beings (Marcos-Merino et al., 2019) to recognise that bacteria can be found everywhere. However, some teachers still continue to hold the same alternative ideas regarding the localization that they expressed in their original model. It can therefore be inferred that these beliefs endure and remain prevalent throughout preschool, primary and even secondary education, influencing prospective teachers, despite having worked with them through an educational sequence focused on this topic. This situation underscores the need for a more thorough and systematic approach to the localisation of bacteria, suggesting the incorporation of activities that facilitate a clearer connection between the functions of these microorganisms and their location.

Regarding the functions of bacteria, while the proportion of fragments referencing these functions declined (19%) relative to the initial model (28%), recognition of their roles increased. More teachers were observed acknowledging both the beneficial and harmful functions of bacteria; however, in most cases, benefits were associated exclusively with humans. These findings emphasise the importance of incorporating instructional activities that address the role of bacteria beyond the human context. For example, such activities could explore their involvement in the decomposition of materials, such as plastics, and examine potential applications, thereby broadening teachers' and students' understanding of their ecological and technological significance.

Finally, with respect to other aspects not covered in previous sections, it is of note that the bactericidal action of antibiotics is mentioned in all the years, thus acknowledging their role in health. This result is important due to understanding illness, its causes and treatments is crucial in students' development as capable citizens (Martin & Luth, 2000) as in the future they should take decisions such as when they should use antibiotics to avoid their overuse.

Limitations and Conclusions

The study presented is not without limitations. Firstly, regarding the development of the study, other aspects must be considered as limitations to the work carried out. There is some variability in the size and profile of participants across the different course groups. This variability is inherent to the use of convenience samples, as the study worked with students enrolled in a specific university module. Following the same logic, there is a threat of sample attrition during the study's development. Since data collection processes were carried out during class sessions, there may be variations between the participants completing the initial task and those completing the final task due to factors such as attendance. Furthermore, a decision was made to collect data anonymously to encourage participants to respond to the questions as naturally as possible, revealing their 'actual' mental models instead of attempting to provide responses they believed the instructor expected. These factors have the indirect consequence that it is not possible to link the response of an individual participant in the initial task with the response provided in the final task. This prevents a comparison of the evolution of each individual and entails that the analysis focuses solely on the evolution at the group level, which is how the results are analysed in the present work.

Finally, based on the analysis of the results described in this work, we detected an additional limitation regarding the procedure's capacity to delve deeply into the mental model. In future research, it would be necessary to further investigate the change in the model and determine which activities within the sequence are most effective in promoting this change. This might involve including intermediate questions after each activity in the sequence, such as: "What have you learned about bacteria during the activity?" "How have your ideas about bacteria changed after completing the activity?" and "How did the work during the activity contribute to these changes?" Incorporating this type of question would allow researchers to record the specific changes in the mental model of bacteria prompted by each activity and, simultaneously, identify which sequence activities are more effective. Furthermore, it would enable students to become more conscious of what they have learned and how they have learned it, fostering their metacognitive skills and promoting a more reflective teaching profile aware of how science learning occurs. By being more conscious of their own learning and disciplinary knowledge, they would be better prepared to design the learning process for their future students.

According to the results obtained, the answers for the research questions outlined would be:

The initial model of bacteria described by the students portrays them as microscopic beings with both beneficial and harmful functions, present in the human body and susceptible to elimination by antibiotics. Alternative ideas include classification of bacteria in other kingdoms such as fungi, misconceptions about reproduction or the attribution of functions performed by other microorganisms.

After the teaching sequence, as the results show prospective teachers expand their model of bacteria, adding more characteristics such as the identification of bacteria as unicellular prokaryotic microorganisms with asexual reproduction. Future teachers also start considering them as part of the Monera kingdom. The ideas related with bacteria's functions remain both beneficial and harmful, but there is a decrease in the cases that solely indicate harmful function. Prospective teachers also note that bacteria are present everywhere, instead of only in human beings, as there is an increase in the number of post-test responses in which future teachers consider that bacteria are ubiquitous. With respect to notions like eliminating bacteria with antibiotics reappear, along with new concepts such as antibiotic resistance.

Therefore, based on these results, we conclude that prospective teachers improve their model of bacteria after carrying out the activities that addressed topics referring to characteristics, actions performed in the environment and on living beings, location and global issues like antibiotic resistance. This improvement will help them to address issues such as the symptomatology of bacterial illnesses in children or hygiene practices (hygiene after using the toilet, food hygiene, hygiene after playing in the playground, etc.) as the participants will acknowledge the ubiquity of bacteria and their relationship with disease. They will also be able to address the beneficial functions of bacteria regarding foodstuffs, as they will understand how some of them are made (yoghurt).

However, some ideas, such as bacteria being nucleusless cells with a specific morphology, do not appear in the prospective teachers' responses. Based on that it is still very important to distinguish between bacteria and other pathogens such as viruses, which are so present in early childhood education schools. In the future, activities related to viruses could be included, to distinguish the pathogens that cause the most frequent diseases in early childhood education. As for the functions of bacteria, we must insist on the idea of the role of bacteria in ecosystems or their industrial applications beyond food production, including in the sequence some activities involving bacteria in the production of antibiotics, in the cycles of nitrogen, carbon, phosphorus… considering, for example, the role of bacteria in the decomposition of corpses.

In a nutshell, these results indicate that the designed sequence is effective in advancing the bacteria' mental model of pre-service early childhood teachers. In this sense, their final models reflect greater disciplinary knowledge, and simultaneously, throughout the development of the sequence, they have been able to become aware of how they learned, and how a sequence based on scientific practices yields better results than other "classic" strategies. The latter, which still dominate secondary education, clearly result in learning that is superficial and easily forgotten, as evidenced by the pre-test results.

These findings are consistent with the trends and antecedents described in the literature presented in the theoretical framework, and once again highlight the benefits of introducing the topic from a practical standpoint, perhaps not only in initial teacher training. This highlights the importance of continuing to implement, evaluate, and improve the sequence to address these aspects, but also of continuing research into the mental models held by prospective teachers, their alternative ideas, and how to support the evolution of these ideas towards those that align more closely with scientific models. Moreover, these results could also potentially be relevant for secondary education teachers, who could test the sequence with their own students.

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

References

Ampatzidis, G., & Tsevreni, I. (2026). Investigating early childhood education students' ideas about microorganisms. *International Journal of Science Education, 4(1)*, 142–154. https://doi.org/10.1080/09500693.2024.2400316

Ballesteros, M. I., Paños, E., & Ruiz-Gallardo, R. J. (2018). Microorganisms in primary education. Conceptions in children from 8 to 11 years old and influence of the textbooks. *Enseñanza De Las Ciencias, 36*(1), 79–98. https://doi.org/10.5565/rev/ensciencias.2274

Bardin, L. (1991). *El análisis del contenido* [Content analysis]. Akal

Biyikoglu, I., Bora, N., Ozsavran, M., & Kuzlu, T. (2025). Impact of personal hygiene education based on social learning theory on preschool children. *Early Childhood Education Journal, 53*, 539–550. https://doi.org/10.1007/s10643-023-01603-7

Byrne, B., Grace, M., & Hanley, P. (2009). Children's anthropomorphic and anthropocentric ideas about microorganisms. *Journal of Biological Education, 44*(1), 37–43. https://doi.org/10.1080/00219266.2009.9656190

Byrne, J. (2011). Models of micro-organisms: Children's knowledge and understanding of micro-organisms from 7 to 14 years old. *International Journal of Science Education, 33*, 1927–1961. https://doi.org/10.1080/09500693.2010.536999

Byrne, J., & Grace, M. (2010). Using a concept mapping tool with a photograph association technique (CoMPAT) to elicit children's ideas about microbial activity. *International Journal of Science Education, 32*(4), 479–500. https://doi.org/10.1080/09500690802688071

Castellar-Cárdenas, M., Romero López, M. C., & Jiménez Tejada, M. P. (2023). What do clean and dirty hands of primary school pupils look like? *Journal of Biological Education, 58*(5), 1168–1185. https://doi.org/10.1080/00219266.2023.2174159

Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., Behrenfeld, M. J., Boetius, A., Boyd, P. W., Classen, A. T., Crowther, T. W., Danovaro, R., Foreman, C. M., Huisman, J., Hutchins, D. A., Jansson, J. K., Karl, D. M., Koskella, B., Mark Welch, D. B., & Webster, N. S. (2019). Scientists' warning to humanity: Microorganisms and climate change. *Nature Reviews Microbiology, 17*(9), 569–586. https://doi.org/10.1038/s41579-019-0222-5

Constantinou, C. P., Tsivitanidou, O. E., & Rybska, E. (2018). What is inquiry-based science teaching and learning? In O. E. Tsivitanidou, P. Gray, E. Rybska, L. Louca, & C. P. Constantinou (Eds.), *Professional development for inquiry-based science teaching and learning* (pp. 1–23). Springer International Publishing. https://doi.org/10.1007/978-3-319-91406-0_1

Couso, D. (2020). Aprender ciencia escolar implica construir modelos cada vez más sofisticados de los fenómenos del mundo [Learning school science involves building increasingly sophisticated models of world phenomena]. In D. Couso, M. R. Jiménez-Liso, C. Refojo, & J. A. Sacristán (Eds.), *Enseñando Ciencia con Ciencia* (pp. 63–74). Penguin Random House.

Faccio, E., Costa, N., Losasso, C., Cappa, V., Mantovani, C., Cibin, V., Andrighetto, I., & Ricci, A. (2013). What programs work to promote health for children? Exploring beliefs on microorganisms and on food safety control behavior in primary schools. *Food Control, 33*(2), 320–329. https://doi.org/10.1016/j.foodcont.2013.03.005

Gail-Jones, G. E., Gardner, T. L., Poland, G., & Robert, S. (2013). The impact of microbiology instruction on students' perceptions of risks related to microbial illness. *International Journal of Science Education, Part b: Communication and Public Engagement, 3*(3), 199–213. https://doi.org/10.1080/21548455.2012.684434

Gee, J. P. (2005). *An introduction to discourse analysis. Theory and method* (2nd ed.). Routledge.

Ghosh, R., Singha, J., & Gardia, A. (2025). Formative assessment strategies in social science education: A conceptual framework for achieving the goals of national education policy 2020. *Asian Journal of Education and Social Studies, 51*(5), 395–407. https://doi.org/10.9734/ajess/2025/v51i51927

Gilbert, J., & Justi, R. (2016). *Modelling-based teaching in science education*. Springer.

Gray, F. E., Emerson, L., & MacKay, B. (2005). Meeting the demands of the workplace: Science students and written skills. *Journal of Science Education and Technology, 14*(4), 425–435. https://doi.org/10.1007/s10956-005-8087-y

Jones, G., & Rua, M. J. (2006). Conceptions of germs: Expert to novice understandings of microorganisms. *Electronic Journal of Science Education, 10*(3), 1–40.

Krippendorff, K. (1990). *Metodología del análisis del contenido. Teoría y Práctica* [Methodology for analyzing content. Theory and practice]. Paídos Ibérica, S. A.

Ley Orgánica para la Mejora de la Calidad Educativa [LOMCE]. (2013). Ley Orgánica 8/2013, de 9 de diciembre, para la mejora de la calidad educativa [Organic Law 8/2013, of December 9, 2013, for the improvement of educational quality]. Retrieved from https://www.boe.es/eli/es/lo/2013/12/09/8/con

Lippard, C. N., Tank, K., Walter, M. C., Krogh, J., & Colbert, K. (2018). Preparing early childhood preservice teachers for science teaching: Aligning across a teacher preparation program. *Journal of Early Childhood Teacher Education, 39*(3), 193–212.

Mafra, P., Lima, N., & Carvalho, G. S. (2015). Experimental activities in primary school to learn about microbes in an oral health education context. *Journal of Biological Education, 49*(2), 190–203. https://doi.org/10.1080/00219266.2014.923485

Marcos-Merino, J. M., & Esteban, R. (2017). Concepciones alternativas sobre biología celular y microbiología de los maestros en formación: Implicaciones de su presencia [Alternative conceptions of cell biology and microbiology among pre-service teachers: Implications of their presence]. *Campo Abierto, 36*(2), 167–179.

Marcos-Merino, J. M., Esteban, R., & Gómez, J. (2019). Formando a futuros maestros para abordar los microorganismos mediante actividades prácticas. Papel de las emociones y valoraciones de los estudiantes [Training future Primary teachers to approach microorganisms through practical activities. Role of students´ emotions and values]. *Revista Eureka Sobre Enseñanza y Divulgación De Las Ciencias, 16*(1), Article 1602. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2019.v16.i1.1602

Martin, D. M., & Luth, F. W. (2000). Where are the men? The scarcity of males in early childhood classrooms. *Journal of Early Childhood Teacher Education, 21*(3), 321–330. https://doi.org/10.1080/0163638000210303

Mazas., B., & Bravo, B. (2018). Actitudes hacia la ciencia del profesorado en formación de Educación Infantil y Educación Primaria [Attitudes towards science among pre-service teachers in early childhood and primary education]. *Profesorado: Revista De Currículum y Formación De Profesorado, 22*(2), 329–348. https://doi.org/10.30827/profesorado.v22i2.7726

Megalakaki, O., & Tiberghien, A. (2011). A qualitative approach of modelling activities for the notion of energy. *Electronic Journal of Research in Educational Psychology, 9*(1), 157–182. https://doi.org/10.25115/ejrep.v9i23.1432

Mendonça, P., & Justi, R. (2011). Contribution of the 'model of modelling' diagram to the learning of ionic bonding: Analysis of a case study. *Research in Science Education, 41*(4), 479–503. https://doi.org/10.1007/s11165-010-9176-3

Metzger, K. J., & Yowler, J. Y. (2019). Which way is better? Comparison of two interactive modeling approaches for teaching meiosis in an introductory undergraduate biology course. *The American Biology Teacher, 81*(2), 98–109. https://doi.org/10.1525/abt.2019.81.2.98

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded source book* (2nd ed). Sage.
Nagy, M. (1953). The representation of 'germs' by children. *The Pedagogical Seminary and Journal of Genetic Psychology, 83*(2), 227–240. https://doi.org/10.1080/08856559.1953.10534089
Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic analysis. *International Journal of Qualitative Methods, 16*(1), 1–13. https://doi.org/10.1177/1609406917733847
Ortuzar-Iragorri, A., Uskola, A., & Zamalloa, T. (2024). Early childhood preservice teachers' knowledge of micro-organisms and cystitis. *Journal of Turkish Science Education, 21*(1), 1–21. https://doi.org/10.36681/tused.2024.001
Pujolás, P. (2003). *El aprendizaje cooperativo: algunas ideas prácticas* [Cooperative learning: Some practical ideas]. Universidad de Vic.
Ravanis, K., & Boilevin, J.M. (2022). What use is a precursor model in early science teaching and learning? Didactic perspectives. In J.-M. Boilevin, A. Delserieys, & K. Ravanis (Eds.), *Precursor models for teaching and learning science during early childhood* (pp. 33–49). Springer International Publishing. https://doi.org/10.1007/978-3-031-08158-3
Reiser, B. J. (2013). *What professional development strategies are needed for successful implementation of the next generation science standards*. Paper presented at the Invitational Research Symposium on Science Assessment, Washington, DC. Retrieved from https://ride.ri.gov/sites/g/files/xkgbur806/files/eeie/Resources/articles/What_Professional_Devel_Strategies.pdf
Robredo, B., & Torres, C. (2021). ¿Es consciente el alumnado de secundaria de la patogenicidad de los microorganismos y de la problemática sobre la resistencia a los antibióticos? [Are secondary school students aware of the pathogenicity of microorganisms and the problem of antibiotic resistance]. *Revista Eureka Sobre Enseñanza y Divulgación De Las Ciencias, 18*(3), Article 3301. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2021.v18.i3.3301
Ruiz-Gallardo, J. R., & Paños, E. (2018). Primary school students' conceptions about microorganisms. Influence of theoretical and practical methodologies on learning. *Research in Science & Technological Education, 36*(2), 165–184. https://doi.org/10.1080/02635143.2017.1386646
Ruiz, J. (2007). *Metodología de la investigación cualitativa* [Qualitative research methodology]. Universidad de Deusto.
Sandelowski, M. (2004). Using qualitative research. *Qualitative Health Research, 14*, 1366–1386. https://doi.org/10.1177/1049732304269672
Schori, H., & Gal, A. (2024). Perception and self-efficacy to teach science in kindergarten: Undergraduate students' and teachers' point of view. *Early Childhood Education Journal, 52*, 1779–1787. https://doi.org/10.1007/s10643-023-01516-5
Simard, C. (2023). Microorganism education: Misconceptions and obstacles. *Journal of Biological Education, 57*(2), 308–316. https://doi.org/10.1080/00219266.2021.1909636
Špernjak, A., Puhmeister, J. A., & Šorgo, A. (2023). Public opinions and knowledge about microorganisms. *Research in Science & Technological Education, 41*(2), 800–818. https://doi.org/10.1080/02635143.2021.1952407
Zamalloa, T., Salgado, M., & Berciano, A. (2025). How to promote scientific practices in early childhood education: The teachers' role. *International Journal of Science and Mathematics Education, 23*(7), 2975–2995. https://doi.org/10.1007/s10763-025-10557-8