Luis Fernando González-Beltrán
(Organizador)

Educação no Século XXI:

Perspectivas Contemporâneas sobre Ensino-Aprendizagem

VOL IV

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PRÓLOGO

La educación contemporánea, dentro de un contexto de cambios sociales y culturales, vertiginosos y contundentes, se caracteriza por una profunda transformación epistemológica, tecnológica y social. En las primeras décadas del siglo XXI, las instituciones educativas de distintos países han sido convocadas a repensar sus fundamentos, métodos y finalidades en un escenario marcado por la aceleración digital, la creciente diversidad de los contextos de aprendizaje y la necesidad urgente de promover competencias cognitivas, sociales y humanas que respondan a un mundo en constante cambio.

Esta obra, **Educação no século XXI: Perspectivas Contemporâneas sobre Ensino-Aprendizagem IV,** que reúne autores de múltiples países de América Latina, África y Europa, refleja precisamente esa pluralidad de miradas, experiencias y realidades. Las contribuciones aquí presentadas evidencian no solo la vitalidad de la investigación en educación, sino también la convergencia de esfuerzos internacionales en torno a la construcción de prácticas pedagógicas más inclusivas, innovadoras, contextualizadas y humanizadas.

La organización del libro en cuatro ejes temáticos ofrece una lectura articulada y coherente de los distintos enfoques.

El primer eje, dedicado a *la Enseñanza de la Matemática, el Pensamiento Crítico y la Inclusión Educativa*, aborda los desafíos formativos en el ámbito de la didáctica de la matemática en contextos diversos, y de la preparación docente. Inicia con el desarrollo, desde la primaria, del pensamiento crítico, tan relevante para la formación ciudadana. Continúa con la educación superior, se discuten experiencias en el contexto pospandémico, al combinar el enfoque tradicional con la metodología de Aprendizaje Basado en Equipo, que apuntan a reconstruir aprendizajes y fortalecer metodologías orientadas a una participación más activa y con equidad. Sigue con los retos de la formación inicial docente y la incorporación de enfoques inclusivos en la enseñanza, primero con respecto a la estadística, luego en términos generales de la matemática, y finalmente en la educación normalista.

El segundo eje, *Metodologías Activas, Tecnologías Educativas e Innovación Didáctica*, presenta reflexiones y experiencias que evidencian el impacto creciente de las tecnologías emergentes y de los modelos pedagógicos activos en los procesos de enseñanza-aprendizaje. Aquí se analizan el uso pedagógico de la realidad virtual y aumentada, que propicia un aprendizaje interactivo, con experiencias inmersivas para las prácticas que deben desarrollar los estudiantes. Asimismo, se revisa la aplicación de sistemas de inteligencia artificial para apoyar a docentes y estudiantes, donde se busca un uso ético que permita la autonomía y el pensamiento crítico. Se incorpora también la implementación del modelo *Flipped Teaching* en la formación en ingeniería, como estrategia didáctica innovadora para fortalecer competencias técnicas, bilingües y digitales. Además, se muestra la incorporación de dispositivos electrónicos de bajo costo en la experimentación científica y proyectos de investigación escolar sobre fenómenos naturales, que buscan vincular el aula con problemáticas locales y ambientales. Estas contribuciones muestran cómo la innovación tecnológica y metodológica puede ampliar horizontes didácticos, democratizar el acceso al conocimiento científico y promover aprendizajes activos y contextualizados.

El tercer eje, **Políticas Educativas, Gestión Universitaria y Reformas de la Educación Superior,** reúne estudios que examinan dimensiones institucionales, sociales y sistémicas de la educación. En este apartado se incorporan reflexiones sobre el currículo democrático y la educación para la protección civil, así como sobre los procesos socioeducativos vinculados a la sustentabilidad en contextos interculturales, que refuerzan el papel de la universidad en la transformación social y ambiental. Asimismo, se analiza la acción tutorial universitaria como un factor clave para la permanencia estudiantil, a pesar de sus limitaciones estructurales. Se abordan también la importancia de estructuras curriculares coherentes, con planes de supervisión adecuados, así como modelos integrados de gestión e innovación académico-administrativa que presentan posibilidades de transferencia a otros contextos universitarios. Finalmente, se examinan los desafíos que enfrentan los sistemas de educación superior en contextos marcados por tensiones sociopolíticas y económicas, ampliando el debate sobre la relación entre políticas públicas, gobernanza educativa y calidad de la formación.

Finalmente, el cuarto eje, **Formación Integral, Humanidades y Desarrollo Socioemocional**, se inicia con una reflexión contemporánea sobre las representaciones sociales de la automatización y la inteligencia artificial generativa en la formación universitaria, problematizando los vínculos entre saberes, ética y tecnologías emergentes.

Los capítulos abordan la creación de ambientes formativos seguros y libres de violencia, la vigencia del pensamiento pedagógico ilustrado en la defensa de una educación centrada en el sujeto, y la relevancia de las habilidades socioemocionales y de las denominadas *soft skills* en la formación profesional contemporánea. Se incorpora, además, un análisis sobre la supervisión pedagógica y la gestión estratégica como dimensiones fundamentales para garantizar la calidad de los procesos formativos, fortalecer la práctica docente y crear condiciones institucionales que posibiliten una educación integral, contextualizada y socialmente comprometida. En conjunto, estos textos reafirman la necesidad de una educación que considere al estudiante como una persona integral, capaz de actuar con autonomía, ética, sensibilidad y responsabilidad social.

Esta obra constituye, así, un mosaico amplio y multifacético de la educación en el siglo XXI. Al integrar perspectivas provenientes de diversas disciplinas, países y tradiciones académicas, el libro evidencia que los desafíos educativos actuales no pueden abordarse de manera aislada, sino que requieren diálogo, interdisciplinariedad y colaboración internacional.

Deseo que el lector tenga una lectura inspiradora y fructífera, que contribuya a ampliar debates, fortalecer prácticas e impulsar nuevas investigaciones en el vasto campo de la enseñanza-aprendizaje contemporánea.

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SUMÁRIO

CAPÍTULO 9

COLLECTION AND ANALYSIS OF MICROMETEORITES IN A MIDDLE/LOW SCHOOL EDUCATIONAL CONTEXT IN PORTUGAL

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ABSTRACT: Micrometeorites offer an accessible and scientifically valuable means of studying extra-terrestrial material reaching Earth. This study was conducted in a pilot class of Year 7 students (*n* = 16) and partially involved Year 5 pupils (*n* = 12) at a public school in Portugal. Its primary aims were to collect and identify potential micrometeorites and to measure their diameters through repeated observations. Using magnetic collection techniques, students gathered samples from schoolyard surfaces, which were then analysed under optical microscopes. Repeated diameter measurements were recorded for each particle suspected to be a micrometeorite to estimate its mean diameter. Statistical analysis of the collected sample of potential micrometeorites revealed a size distribution with abundance decreasing with size. These results demonstrate that meaningful and statistically valid scientific investigations can be conducted even within a classroom setting. In addition, the project introduced students to key scientific practices, including observation, measurement, data analysis, and critical thinking. The implementation of authentic scientific inquiry in the school environment supports both science education and early engagement with planetary science. These findings encourage the further development of interdisciplinary, hands-on approaches to STEM education and citizen science.

KEYWORDS: micrometeorites; science education; middle/low school; STEM activities; hands-on activities.

[1] Correspondent author.

RECOLHA E ANÁLISE DE MICROMETEORITOS EM CONTEXTO EDUCATIVO DE VÁRIOS NÍVEIS DO ENSINO BÁSICO EM PORTUGAL

RESUMO: Os micrometeoritos oferecem um meio acessível e cientificamente relevante para estudar material extraterrestre que chega à Terra. Este estudo foi realizado numa turma piloto de estudantes do 7.º ano (n = 16) e envolveu parcialmente estudantes do 5.º ano (n = 12) de uma escola pública portuguesa. Os seus principais objetivos foram recolher e identificar potenciais micrometeoritos e medir os seus diâmetros através de observações repetidas. Utilizando técnicas de recolha magnética, os estudantes recolheram amostras de superfícies do recinto escolar, que foram depois analisadas com microscópios óticos. Foram realizadas medições repetidas do diâmetro para cada partícula suspeita de ser um micrometeorito, a fim de estimar o diâmetro médio. A análise estatística da amostra recolhida de potenciais micrometeoritos revelou uma distribuição de tamanhos em que a abundância diminui com o tamanho. Estes resultados demonstram que investigações científicas significativas e estatisticamente válidas podem ser conduzidas mesmo em contexto de sala de aula. Além disso, o projeto introduziu os estudantes a práticas científicas essenciais, como a observação, a medição, a análise de dados e o pensamento crítico. A implementação de investigação científica autêntica no ambiente escolar apoia tanto a educação em ciências como o envolvimento precoce com as ciências planetárias. Estes resultados incentivam o desenvolvimento contínuo de abordagens interdisciplinares e práticas para a educação STEM e para a ciência cidadã.
PALAVRAS-CHAVE: micrometeoritos; educação em ciência; ensino básico; atividades STEM; aprendizagem prática.

1. INTRODUCTION

The study of micrometeorites provides a unique opportunity to bridge scientific research with educational engagement (Hecht et al., 2021). These celestial particles, which originate from cosmic bodies such as asteroids and comets, offer valuable insights into the history and evolution of the solar system (Genge et al., 2008).

This study presents a didactic activity designed to engage students from Year 7 to Year 10 in collecting, identifying, and measuring micrometeorites, within the scope of Physical Chemistry, Natural Sciences, Biology, and Geology. This initiative has been ongoing since 2016 as part of the Junior University programme at the University of Porto (UJ, 2016). Understanding micrometeorites is fundamental to contextualising this activity, as these extraterrestrial particles significantly contribute to various scientific disciplines and foster public engagement with science (Hecht et al., 2021).

Micrometeorites are extraterrestrial particles, typically less than one millimetre in diameter (Genge et al., 2008). They originate from larger celestial bodies such as comets and asteroids, undergoing various physical and chemical transformations during their passage through Earth's atmosphere (Genge et al., 2017). These transformations, including fusion processes caused by atmospheric friction, affect their morphology and aid in their identification (Taylor & Brownlee, 1991). However, the extent to which atmospheric entry alters their original chemical composition remains a subject of controversy. While some researchers suggest that a significant proportion of volatile compounds is lost (Greshake et al., 1998), others argue that the primary features are largely preserved (Brownlee et al., 2007).

Chemically, micrometeorites comprise silicates, metal oxides, and metallic elements, closely resembling carbonaceous chondrites. Their high iron content renders them magnetic, facilitating their extraction from collected samples using simple tools such as magnets (Taylor & Brownlee, 1991; Taylor et al., 2000a, 2000b; Genge et al., 2017). Once isolated, micrometeorites are classified according to their shape, size, and chemical composition (Genge et al., 2017). Nonetheless, debate persists regarding how terrestrial contamination influences these samples, with some studies indicating that urban pollution may alter their geochemical signatures (Suttle & Genge, 2017).

The significance of this study extends beyond scientific inquiry; it holds broader implications for both the scientific community and the general public (Genge et al., 2017). From a scientific perspective, micrometeorites provide valuable insights into the history of the Solar System (Heck et al., 2008). These particles preserve chemical and isotopic signatures of ancient astrophysical events, such as asteroid belt collisions, allowing researchers to infer episodes of orbital instability and structural changes in the Solar System (Taylor & Brownlee, 1991). Moreover, they indicate past chemical and climatic variations on Earth (Suttle & Genge, 2017; Rochette et al., 2008). The presence of organic compounds in micrometeorites further links their study to astrobiology, suggesting they may have contributed to prebiotic chemistry and the emergence of life on Earth (Galante & Horvath, 2016; Maurette et al., 2000). However, some researchers question whether these organic materials are truly extraterrestrial or if they result from terrestrial contamination (Sephton & Botta, 2005). Additionally, impact frequency analysis aids in understanding periods of heightened astrophysical activity (Kyte, 2002).

Beyond its scientific relevance, micrometeorite research carries significant societal and educational value. The study of these extraterrestrial bodies impacts fields such as technology, environmental science, space awareness, and, most notably, education (Russell et al., 2021). Providing students with opportunities to find extraterrestrial particles in their local environments, such as rooftops or gardens, fosters interest in physics and geology (Hecht et al., 2021). The interdisciplinary nature of micrometeorite studies facilitates engagement with multiple academic disciplines, creating synergies among different scientific domains (Gounelle, 2011).

Integrating micrometeorite research into school curricula aligns with the learning objectives outlined in the Portuguese educational standards. This approach enhances pupils' understanding of the Solar System while developing key scientific inquiry skills, including observation, investigation, and critical analysis. Specific educational outcomes encompass understanding the formation of asteroids, comets, and meteorites, along with the dynamic interactions that shape the Solar System (Jenniskens, 2006; Genge, 2017).

Citizen science initiatives focusing on micrometeorite collection from urban environments exemplify the integration of physics, chemistry, and geology in hands-on research. These projects cultivate essential 21st-century skills, such as critical thinking, teamwork, and problem-solving (Bonney et al., 2009). By engaging students in authentic scientific practices, this work bridges the gap between theoretical knowledge and practical exploration, promoting scientific literacy and inspiring future generations of researchers (Silvertown, 2009; Greshake et al., 2013a).

2. MATERIALS AND METHODS

2.1. METHODOLOGY FOR COLLECTING AND IDENTIFYING MICROMETEORITES

To ensure a systematic and replicable approach for the collection and identification of micrometeorites, the authors used a methodology that has been adapted from previous research on micrometeorite recovery from urban environments (Genge, 2017; Suttle & Genge, 2017) and is designed to be accessible for students from the fifth to twelfth years of schooling. It should always be noted that the collected particles are not guaranteed to be micrometeorites until chemical analyses are conducted. For this reason, these particles must be treated only as potential micrometeorites. To emphasise this point, the abbreviation PMM will be used when referring to them.

2.1.1. Materials and simple analysis

In conducting this work and considering its intended implementation in a school setting, the authors selected materials that are readily accessible and appropriate for the students' educational level. The methods and materials employed in this study are listed in Table 1 and include:

Collection: fine-mesh sieves to separate larger debris; brushes to collect accumulated dust from ceilings, rails or flat surfaces; magnets to attract ferromagnetic particles; sheets of paper; containers, and plastic bags for sample storage.

Preparation and examination: tweezers for handling particles; calibration rulers for distance measurements (example: particle diameter); affordable digital optical microscopes for observation of collected particles; computers for image visualisation and measurements, and data analysis.

Statistical analysis: simple statistical analysis, such as computation of the average diameter of each collected potential micrometeorite and corresponding standard deviation (STD). If the sample of potential micrometeorites is sufficiently large, students can also calculate the sample mean diameter, the sample standard deviation and the standard deviation of the mean.

Table 1. Methods and materials used for the collection and identification of PMMs.

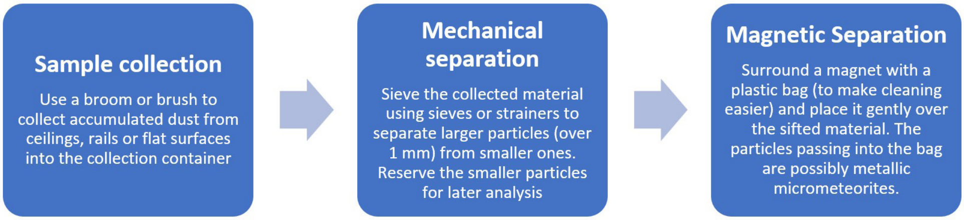
Collection	Preparation and examination	Statistical analysis
fine-mesh sieves	tweezers	particle mean diameter
brushes	calibration rulers	STD of particle mean diameter
magnets	digital optical microscopes	sample mean diameter
sheets of paper	computers	STD of sample diameters
containers, plastic bags		STD of sample mean diameter

2.1.2. Collection protocol

Site selection: When selecting locations for micrometeorite sampling, it is crucial to consider areas with minimal contamination from other types of particles, including sediments. Micrometeorite collection is often carried out in polar and desert regions due to the low levels of urban pollution in these environments. However, suitable collection sites in more accessible areas include urban rooftops, rainwater gutters, and open, flat surfaces where fine dust accumulates. These locations are optimal because they effectively trap atmospheric particulates, including micrometeorites (Genge et al., 2017). For this study, conducted with middle and lower secondary school students, flat building roofs, gutters, and other flat surfaces were successfully used and are recommended for others wishing to replicate the protocol. It is also advisable to choose sampling sites relatively distant from heavily trafficked or industrial areas to minimise contamination.

Sample collection: The collected dust and debris were sieved to remove larger contaminants, such as leaves and coarse particles. A magnet was used to separate ferromagnetic particles, as metallic micrometeorites typically contain high amounts of iron and nickel (Taylor & Brownlee, 1991; Taylor et al., 2000). The methodology used is depicted in Figure 1.

Figure 1. Different steps of the micrometeorite collection methodology.



Initial sorting: The magnetic particles fraction was then examined under a microscope to identify spherules and irregular particles with metallic luster or fusion crusts - features commonly associated with micrometeorites (Rochette et al., 2008).

2.1.3. Identification protocol

Morphological analysis: micrometeorites are categorized into three primary types:

Cosmic spherules: rounded, smooth particles formed by atmospheric entry melting.

Scoriaceous micrometeorites: porous, irregularly shaped fragments.

Unmelted micrometeorites: retaining their original mineralogical structure (Genge et al., 2008; Suttle & Genge, 2017).

Density and magnetism assessment: micrometeorites exhibit higher density than common terrestrial dust particles and exhibit strong attraction to magnets due to their high metallic content (Heck et al., 2008; Taylor et al., 2000a, 2000b).

Applying a weak acid helps distinguish micrometeorites from carbonate-containing terrestrial contaminants (Maurette et al., 2000). Additionally, energy-dispersive X-ray spectroscopy (EDS) can be used to confirm elemental compositions that match those of extraterrestrial materials (Greshake et al., 2013b). Due to the context setting and goals of this work, the authors did not use these last techniques.

This identification protocol provides an accessible and scientifically relevant method for collecting magnetic micrometeorites in an educational setting, aligning with citizen science initiatives and classroom engagement strategies (Bonney et al., 2009; Hecht et al., 2021).

3. RESULTS AND ANALYSIS

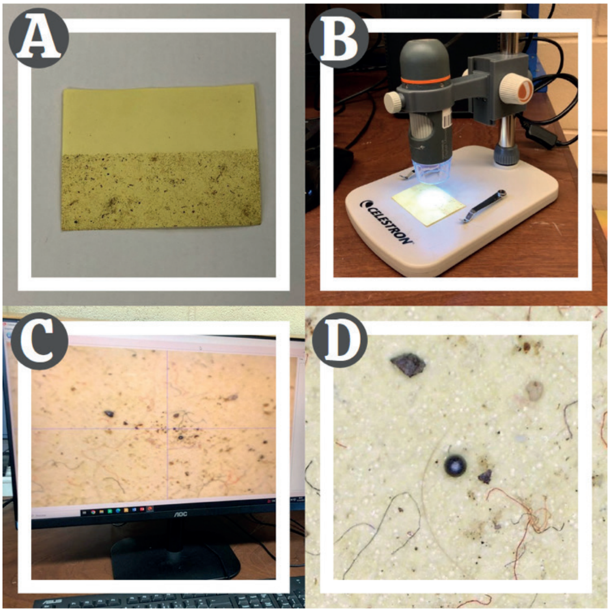
3.1. EXPERIMENTAL PROCEDURE

After collecting and separating the samples and identifying isolated potential micrometeorites (Figure 2), students were guided by the instructors or teachers through a basic statistical analysis, using selected measurements as data. It is important to note that, in this activity, students are expected to develop key skills such as autonomy and critical thinking. Therefore, identifying potential micrometeorites serves as a learning process, as students must be able to distinguish between actual celestial particles and urban waste. It is essential to understand that terrestrial particles - not considered micrometeorites - typically exhibit irregular shapes and rough textures.

To carry out the analysis, students executed the steps A to D, as described in Figure 2: A) spread the magnetic particles on a sheet of paper (Figure 2A), then B) used a digital microscope connected to a computer (a magnifying glass and a smartphone can be used as well) (Figure 2B) and then C) searched for particles with a spherical shape and metallic sheen (Figure 2C). Once potential micrometeorites were identified, they were photo-graphed and the images transferred to a computer (Figure 3D), where diameter measurements and descriptive statistical analysis could be carried out.

The results indicate that the abundance of the collected PMMs decreases with increasing particle size. Within the analysed sample, approximately 62% of the PMMs have diameters between 0.032 and 0.222 mm, while 29% fall within the 0.222 to 0.412 mm range, and only 10% measure between 0.602 and 0.792 mm.

Figure 2. Steps used to identify potential micrometeorites: (A) Dispersion of the sample on a sheet of paper; (B) Placement of the sample under a digital microscope/magnifying glass; (C) Observation of spherical particles with metallic sheen; (D) Potential micrometeorite identification image.



3.2. SIMPLE DESCRIPTIVE STATISTICAL ANALYSIS

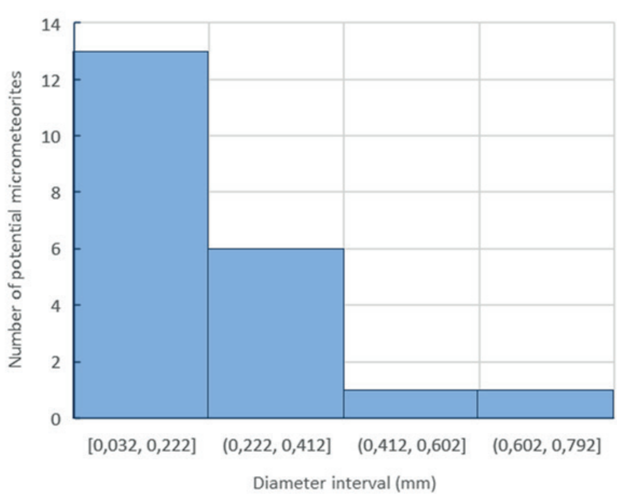
Students worked in an Excel spreadsheet tool to record 5 diameter measurements for each potential micrometeorite, as outlined in Table 2. The authors also suggest using Google Sheets or Python for this purpose. Then, for each PMM ($k=1,\cdots,p$), they computed the average diameter, $D_{avg}(k)$. Taking the whole sample of PMMs made available, students also calculated sample statistics: the sample mean diameter (D_{savg}), the sample standard deviation (D_{savg}), and the sample standard deviation of the mean diameter ($SSTD_{D_{savg}}$). Sample statistics are also included in Table 2. Details of how all these calculations can be performed in Excel and Python are presented in Appendix A.

Table 2. Outline of the statistical analysis of a sample of *p* micrometeorites (MM).

MM	D_1 (μm)	D_2 (μm)	D_3 (μm)	D_4 (μm)	D_5 (μm)	D_{avg} (μm)
1	$D_1(1)$	$D_2(1)$	$D_3(1)$	$D_4(1)$	$D_5(1)$	$D_{avg}(1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
p	$D_1(p)$	$D_2(p)$	$D_3(p)$	$D_4(p)$	$D_5(p)$	$D_{avg}(p)$
					Sample mean diameter (μm)	
					Sample diameter STD (μm)	
					Sample STD of mean diameter (μm)	

Conducting the proposed activity multiple times allows the formation of a growing sample of collected PMMs. Making it available to students allows for studying the size distribution of collected PMMs. Figure 3 shows a histogram of the size distribution of the authors' accumulated sample of potential micrometeorites.

Figure 3. Histogram of the size distribution of a sample of 21 collected PMMs.



The results indicate that the abundance of the collected PMMs decreases with increasing particle size. Within the analysed sample, approximately 62% of the PMMs have diameters between 0.032 and 0.222 mm, while 29% fall within the 0.222 to 0.412 mm range, and only 10% measure between 0.602 and 0.792 mm.

3.3. IMPLEMENTATION IN A SCHOOL CONTEXT

This study was conducted in a school setting with a 7th-grade pilot class consisting of 22 students from a Portuguese public school in the northern region. It was also partially implemented in other classes of the same school year, as well as in a 5th-grade class. To ensure compliance with the ethical standards required for educational research, informed consent and assent forms (Appendix B) were completed. The anonymity and voluntary participation of all individuals involved in this research project were fully safeguarded.

Thus, two 60-minute blocks were used to present the topic of micrometeorites, divided into two parts: a theoretical contextualization and the practical activity itself. Due to the number of students, the class was split into groups of four.

Accordingly, two 60-minute sessions were allocated to the presentation of the micrometeorite topic, structured in two components: a theoretical contextualization and the practical activity. Given the class size, students were organised into groups of four.

4. DISCUSSION

This study was implemented in a school setting in a 7th-grade pilot class composed of 16 students from a Portuguese public school in the North region, partially implemented in other classes of the same year and school, and in the 5th year of school (12 students). The primary goals of this work were to collect and identify potential micrometeorites and to repeatedly measure their diameters to explore scientific data statistical analysis practices in an educational context. The resulting measurement standard deviations can be used to infer the degree of internal consistency and support the validity of this methodology, even when applied in a classroom setting with limited technical resources.

From an educational perspective, this project provided a rare opportunity for middle school students to directly engage in authentic scientific inquiry. They were introduced to concepts in planetary science, microscopy, and statistics, while actively contributing to the identification and measurement of potential extraterrestrial materials.

4.1. FUTURE WORK

To build upon this initial work, the authors suggest future iterations of this study could consider the following enhancements:

1. **Expanded collection and geographic variation**

Gathering samples across different regions and environments could help explore the spatial variability in micrometeorite flux (Duprat et al., 2007).

2. **Data expansion**

Successive student cohorts can contribute to a growing PMM database, enhancing its scientific value while reinforcing continuity in STEM education.

3. **Automation and AI integration**

Image recognition software and AI-driven analysis could assist in both identification and measurement processes, making this project scalable and more consistent across classrooms (Dredge et al., 2021).

5. CONCLUSION

This pilot study achieved its dual objectives: (1) introducing students to scientific research through the collection and identification of potential micrometeorites, and (2) developing their skills in measurement, data handling, and interpretation. The findings confirm known characteristics of micrometeorites and validate the use of standard optical microscopy for basic dimensional analysis. This study demonstrates that with proper guidance and tools, students at the middle school level are capable of contributing meaningfully to scientific research. It offers a valuable interdisciplinary model that links space and planetary science, and statistical data literacy with active learning, thus aligning with broader educational goals in science and technology.

APPENDIX A

1. Details of the statistical calculations

- Consider a sample of p PMMs.
- For each PMM ($k=1,\cdots,p$), record 5 diameter measurements, $D_i\,(k)$ ($i = 1,\cdots,5$).
- For each PMM, compute the average diameter, $D_{\text{avg}}(k) = \frac{\sum_{i=1}^{5} D_i(k)}{5}$
- For the sample of PMMs, compute:
  - i. The sample mean diameter, $D_{\text{savg}} = \frac{\sum_{k=1}^{p} D_{\text{avg}}(k)}{p}$
  - ii. The sample diameter standard deviation, $SSTD_{\text{D}} = \sqrt{\frac{\sum_{k=1}^{p}\left(D_{\text{avg}}(k)-D_{\text{savg}}\right)^2}{p-1}}$
  - iii. The standard deviation of the sample mean diameter, $SSTD_{D_{\text{savg}}} = \frac{SSTD_{\text{D}}}{\sqrt{p}}$

2. Statistical calculations in Excel

- Create a table for 5 diameter measurements, D_1 to D_5; add a calculated column for D_{avg}, and calculated cells for D_{savg}, $SSTD_D$, $SSTD_{D_{savg}}$ (Table A1). Next, drag the formula for D_{avg} inserted in cell G2 down to cell G11.

Table A1. Example of an Excel worksheet for the statistical analysis of a sample of 10 potential micrometeorites.

	A	B	C	D	E	F	G
1	MM	D_1 (μm)	D_2 (μm)	D_3 (μm)	D_4 (μm)	D_5 (μm)	D_{avg} (μm)
2	1						=AVERAGE(B2:F2)
3							
4	3						
5	4						
6	5						
7	6						
8	7						
9	8						
10	9						
11	10						
12	Sample mean diameter (μm)						=AVERAGE(G2:G11)
13	Sample diameter STD (μm)						=STDEV.S (G2:G11)
14	Sample STD of mean diameter (μm)						=G13/SQRT(COUNT(G2:G11))

3. Statistical calculations in Python

- Create a Python code to compute D_{avg}, D_{savg}, $SSTD_D$, and $SSTD_{D_{savg}}$ (Figure A1).

Figure A1. Python code to implement the statistical calculations (top) and output results (bottom).

```
import numpy as np

# Example of 6 PMMs sample with 5 diameter measurements for each one:
diameters = np.array([[121, 119, 123, 122, 120],          # MM1
                      [111, 114, 113, 115, 112],          # MM2
                      [99, 101, 103, 102, 98],            # MM3
                      [85, 87, 88, 86, 84],               # MM4
                      [125, 128, 127, 124, 129],          # MM5
                      [133, 136, 135, 137, 138]])         # MM6

# Number of PMMs
p = len(diameters)

# Step 1: Compute the mean diameters of each PMM
mean_diameters = np.mean(diameters, axis=1)          # D_avg(k)

# Step 2: Compute sample statistics: mean, std, and std of the mean
sample_d_mean = np.mean(mean_diameters)             # D_savg
sample_d_std = np.std(mean_diameters)               # SSTD_D
sample_dmean_std = sample_d_std / np.sqrt(p)        # SSTD_D_savg

# Output results
print("Mean diameters of each PMM (μm): ", mean_diameters)
print(f"Sample mean diameter (μm): {sample_d_mean:.1f}")
print(f"Sample diameter std (μm): {sample_d_std:.1f}")
print(f"Sample std of mean diameter (μm): {sample_dmean_std:.1f}")
```

```
Mean diameters of each PMM (μm):  [121.  113.  100.6  86.  126.6  135.8]
Sample mean diameter (μm): 113.8
Sample diameter std (μm): 16.6
Sample std of mean diameter (μm): 6.8
```

APPENDIX B

Informed consent and assent forms in the original language (Portuguese):

Declaração de Consentimento Informado

(para alunos menores)

Título do projeto: Recolha e Identificação de Micrometeoritos

Nome do investigador principal: Ana Catarina Teixeira Rodrigues

Orientador/coorientador científico: Manuel António Salgueiro da Silva e Teresa Monteiro Seixas

Contactos do investigador principal (e.g., e-mail, telefone, etc): up201905317@edu.fc.up.pt

Eu, ____ (nome completo do encarregado de educação), encarregado de educação abaixo assinado, declaro que:

1. Autorizo a participação do meu educando ____ (nome completo do educando) no projeto acima referido.

2. Compreendi as informações contidas neste documento, bem como as eventuais informações verbais que me foram transmitidas pelo investigador acima referido, sobre o projeto supracitado.

3. Compreendi que a participação do meu educando no projeto mencionado incluirá a participação numa atividade experimental e no preenchimento de um questionário, conduzido pelo investigador principal.

4. Compreendi que a participação do meu educando é voluntária e que este poderá desistir a qualquer momento da sua participação neste projeto, sem indicar o motivo.

5. Percebi que os dados recolhidos serão tratados pelos investigadores, sendo garantido o anonimato para o exterior.

6. Entendi que os investigadores irão armazenar todas as informações e dados recolhidos de forma segura e confidencial, respeitando o Regulamento Geral de Proteção de Dados, e que os dados serão utilizados exclusivamente para fins do projeto em causa.

O encarregado de educação:

____

Data: __/ __/ ____

O investigador principal:

____

Data: __/ __/ ____

Declaração de Assentimento Informado

(de alunos menores)

Título do projeto: Recolha e Identificação de Micrometeoritos

Nome do investigador principal: Ana Catarina Teixeira Rodrigues

Orientador/coorientadores científicos: Manuel António Salgueiro da Silva e Teresa Monteiro Seixas

Contactos do investigador principal (e.g., e-mail, telefone, etc): up201905317@edu.fc.up.pt

Eu, ____ (nome completo do aluno) abaixo-assinado, aceito participar neste projeto, sabendo que é garantido o anonimato para o exterior, a confidencialidade no tratamento dos dados assim como a proteção e segurança dos dados dos intervenientes. Compreendo que a minha participação é voluntaria e anónima. Sei que posso desistir a qualquer momento da participação neste projeto, sem indicar o motivo.

O aluno:

____

Data: __/ __/ ____

O investigador principal:

____

Data: __/ __/ ____

FUNDING:

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INSTITUTIONAL REVIEW BOARD STATEMENT:

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Faculty of Sciences of the University of Porto (protocol code CE2025/p214, approved on 28 February 2025).

INFORMED CONSENT STATEMENT:

Informed consent was obtained from all subjects involved in the study.

DATA AVAILABILITY STATEMENT:

All data that support the findings of this study are included within the article (and any supplementary files).

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CONFLICTS OF INTEREST:

The authors declare no conflicts of interest.

ABBREVIATIONS

The following abbreviations are used in this manuscript:

PMM	Potential Micrometeorite
STD	Standard Deviation
SEM-EDS	Scanning Electron Microscopy with Energy Dispersive Spectrometry
STEM	Science, Technology, Engineering, and Mathematics

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ÍNDICE REMISSIVO

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EDITORA
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