Introducing Chaos Theory: A Life Sciences Students' Perspective

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This article details a concise in-class workshop to introduce life science students to basic chaos theory concepts, which is a modern subject and has high potential for applications in life sciences and other fields, justifying its knowledge. The teaching approach is based on a pragmatic strategy that uses only the essential mathematical and computing concepts required to reach the learning outcome, which this article explains step-by-step and, therefore, at least in expectation, even students or professors with no previous software knowledge could understand them. The proposed educational approach uses a meaningful learning approach with population growth models as educational anchors, which is a common subject for life science students and is intuitive for students from other areas. Feedback from 70 students surveyed after the workshop yielded positive results, and 72.9% of the students expressed confidence in explaining basic chaos theory concepts following the session, and 94.7% indicated they would recommend it to their peers, which underscores the present proposal feasibility.

Keywords: Chaos theory, population growth, science teaching, Chaos theory teaching, butterfly effect, quality education

INTRODUCTION

In the basic sense, the term *chaos* represents a state of disorder, unpredictability and confusion. However, *chaos theory* is a broader scientific concept that focuses on the study of natural systems that exhibit seemingly random behavior, but in reality, they are governed by fixed principles. Therefore, if we know these fixed principles, then we can predict how the system will behave over time. A classic example of a chaotic system is the population growth model called *logistic map*, which was presented by Robert May in 1976 and became popular due to its markedly chaotic behavior and, in addition, is interesting for educational approaches because of its mathematical simplicity.

It is important to emphasize that not all random phenomena have behavior that can be mathematically fixed, but, in any case, it composes a fascinating branch of scientific research with applications in several areas. For example, Akmeşe (2022) demonstrated the chaos theory relevance through a bibliometric analysis that registered publishing 3068 journal articles and 2020 conference papers centered on chaos theory, between 1987 and 2021, which included publications in 659 journals. Among these countries, China was the top one with 27.8% of publications, USA had 16.7%, and India, Japan and United Kingdom contributed about 5.5%.

A formal definition of chaos theory requires a deep analysis of several scientific concepts, but a simple and conceptual definition for teaching proposes can focus on the fact this theory deals with the called *chaotic systems* and all these phenomena present two fundamental characteristics, which are:

1. *Deterministic behavior*: It means that, despite the random appearance of their behavior, they are not random and therefore it is possible to predict their behavior. Although the mathematical representation of a chaotic system is possible, it can be a complex work. In fact, it may seem strange or contradictory to label a predictable phenomenon as chaotic, but it is important to highlight in the classroom that the disorder of these chaotic systems is, in fact, only apparent.
2. *Sensitivity to the initial conditions*: It means that even a tiny variation in a specific variable value can lead to significant alterations in the system's behavior over time. Therefore, the relation between the input variation (variable value) and the output outcomes (system behavior) can be highly disproportionate. This idea gave rise to the term butterfly effect in 1972 that arose from an imaginary question: "Does the flap of a butterfly's wing in Brazil set off a tornado in Texas?". It is a symbolic question but serves as a powerful analogy to highlight that minor events can sometimes have major consequences (Lorenz, 2000; Oestreicher, 2007). Although the butterfly effect only symbolically represents the sensitivity to the initial conditions, this term has practically become a synonym for chaos theory for the lay public.

Despite the scientific complexity, this subject became popular through the term *butterfly effect*, which is a way to express the sensitivity to the initial conditions and, indirectly, the chaos theory itself. This term is enigmatic and has captivated the minds of many people among the lay public, inspiring several books, websites, films and publications dedicated to exploring this subject for non-scientific audiences.

The scientist Edward Lorenz detailed the chaos theory principles in the early 1960s when studied meteorological systems (Oestreicher, 2007; Krishnamurthy, 2015; McWilliams 2019) and, currently, it is

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widely used across various disciplines like physics, meteorology, biology, social sciences, and mathematics (Skiadas & Skiadas, 2017; Su, 2021; Grassi, 2021). Besides, it has a significant potential for applications in life sciences (Azizi et al., 2021; Letellier, 2019; Mashuri et al., 2024), which is detailed in several studies focused on specific applications such as population growth models (Khater, 2022; May, 1976), astrobiology (Zaraoulia, 2011), systemic blood pressure oscillations (Moreno, 2022), molecular biology (Kyriazis, 1991; Walker, 2022), arrhythmia detection (Gupta et al., 2020), and genetic systems (Wu, 2021). Among the various areas of application, there may be areas such as:

1. Meteorology: Meteorology is an area with applications in several other fields, including fields of life sciences such as ecology and agriculture, and besides, historically, meteorological studies led to the chaos theory emergence in the 1960s, when Edward Lorenz studied the behavior of heat transmission phenomena in the atmosphere to help weather forecast. Depending on the temperature difference between a lower warm region and a higher colder region, the heat transmission mode, until that time, was represented only by very complex equations. However, Lorenz achieved to simplify this mathematical representation with only three equations, and besides, observed that these equations exhibit high sensitivity to initial conditions under certain circumstances, which led to the chaos theory emergence (Lorenz, 1963; Li et al, 2024). Currently, meteorological simulations with slightly varying initial conditions help to understand better the weather dynamics, which improves predicting severe events such as storms, hurricanes, and tornadoes, and besides, it also helps meteorologists to study long-term climate variability (Mihailović at al., 2014), which can improve the advance preparation of actions against the effects of extreme weather events. Shu et al. (2021) observed 32 rainfall stations in UK, during a 30 years period, and stated the existence of chaos in these data can be clearly identified, which is important because the rainfall dynamics quantification can be associated with existing rainfall models to enhancing its overall accuracy and reliability, and could also provide additional insights for modification of regional models.
2. Population growth: The chaos theory impact on population growth prediction is very relevant, allowing us to predict, for example, oscillation, stabilization of growth or even the extinction of species (Figueroa et al., 2020) and, besides, it can associate with subjects such as biodiversity maintenance, ecosystem stability, conservation strategies, evolutionary processes, and response to climate changes. Rogers at al. (2022) presented a work where they analyzed 175 population time series and found evidence for chaos in more than 30%, which isn't easy to verify because common mathematical models usually mischaracterize dynamics and treat complexity as simple noise. Therefore, they used special algorithms for chaos detection and verified evidences of chaotic behavior in 81% of the phytoplankton data series, 43% for insects, and 16% for mammals. Besides, the prevalence of chaos decreased in species with longer generation times, many short-lived species tend to have chaotic population. they suggest a reflection on the fact that evidence for chaos population growth reflects methodological and data limitations, rather than rarity. It proves the chaos theory applied in population growth is more common than we usually assume.
3. Pandemic dynamics: In the case of diseases caused by microorganisms, there are aspects of birth, growth, death, diffusion, etc., that involve the microorganisms and the infected humans. It creates a complex scenario and, in the case of the COVID-19 spreading, it showed strong dependence on initial conditions associated with factors such as biological characteristics of the virus, human behavior, social distancing measures, environment, and socioeconomic conditions (Mishra et al., 2023). In his context, the work of Calistri (2024) achieved to determine the growth rate of three coronavirus variants, which is impactful because it is a fundamental variable for determining a chaotic behavior and its fixation is not simple for a dynamic system. In the same context, Sivakumar and Deepthi (2022) used the concepts of chaos theory to examine the temporal dynamic complexity of COVID-19 in 40 countries/regions around the world and presented results that have important impact for modeling and prediction of the COVID-19 dynamics and other infectious diseases.

Although chaos theory has a high potential for applicability, it also has limitations that are inherent to any theory. It suggests that seemingly random behavior may exhibit underlying patterns, but identifying and interpreting these patterns can be challenging. Its effectiveness may vary depending on the specific system characteristics under study, limiting its generalization. Furthermore, practical interventions in a system may have unpredictable results (Boeing, 2016) and even works that discuss pandemic dynamics, such as Sivakumar and Deepthi (2022), Mishra et al. (2023), and Calistri (2024), don't present chaos theory as a magic solution for the pandemic spreading analysis. Another example, in the field of geosciences, is the analysis of chaotic earthquake behavior, which has many favorable arguments, but which has been a challenge because of the short observation time available (Gualandi et al., 2020).

When we study chaos theory, it often appears in a broader terminology that includes terms such as systems and complexity (Kesić, 2024; Lartey, 2020; Reigeluth, 2023; Turner & Baker, 2019), which deserves special attention from the teacher because these terms may come up in the classroom.

A system is a collection of components (parts) that interact locally with each other (Turner & Baker, 2019) to achieve a common function, and these components can be physical (such as parts of a machine or climatic factors), conceptual (such as social issues and ideas) or biological (such as ecosystems). In this context, a system is called dynamic when its behavior changes over time based on a rule that defines the present states in terms of the past, from an initial condition, which fits with the concept of a chaotic system. However, chaotic systems are always dynamic, but not all dynamic systems are chaotic. A complex system is a system composed of many components that can interact with each other. The actions of one component can influence the other components, creating an interdependence between its elements, and can produce outputs (results) that are unpredictable. Complex systems can evolve and adapt over time in response to changes in their environment or internal dynamics. Conversely, a non-complex system can be fully understood through the study of its individual units, such as a car engine where the parts interact locally with each other to achieve a common function, which is the rotation of the engine, but in this case, all the parts function in the same way over time.

Chaos and complexity theory share common characteristics, such as the analysis of the essential unpredictability of nonlinear dynamical systems and establish a sense of order. However, they are different concepts, and chaotic systems are not necessarily complex, and complex systems are not necessarily chaotic. Chaos Theory allows the analysis of the behavior of an apparently random system based on the iteration of a simple rule, while complexity theory is a broader concept based on a dynamic but collective behavior based on the interactions of its parts, and besides, it incorporates several theories and topics, such as chaos theory itself, fractal geometry, nonlinearity, catastrophe theory, mathematical logic, etc.

The chaos theory potential for applications in different areas is great, but its teaching isn't a simple question because it requires special strategies based on students' level, mathematical background, and field of study. In this intricate context, most works on teaching chaos theory prioritize the direct presentation of tools, software, and experiments, while lacking pedagogical considerations. For example, Perea Martins (2023) presented an interesting educations strategy where the chaos theory is presented through the simple logistic map equation, whose variation over time is shown simultaneously by graph and sounds, creating a ludic way of analysis. Another traditional device widely used in teaching to demonstrate chaos theory is the pendulum, which exhibit a wide range of interesting behaviors, from simple harmonic motion in the single pendulum to chaotic dynamics in multi-arm pendulums, as shows in works as Skordoulis et al. (2014) and Kaheman (2023) and Parlati et al. (2024).

With another emphasis, there are works that focus on educational strategies to teach chaos theory. For example, Meszéna (2017) presented a facultative program for 17-year-old students with a sum of 12 teaching hours, which was based on the use of a free mathematical software named Dynamics Solver that was suitable for classroom use at secondary level and allowed the chaos theory introduction and its examination with computers. Fülöp (2020) presents a teaching topics sequence and proposes an interesting question to challenge students to find teachers or scientists who work with Chaos Theory in their country. These works, among other as Seoane et al. (2008), Tél (2021), Moysis et al. (2022), also use physical resources such as computers and apparatus, but they seek to approach the in a more pedagogical way than simple laboratory experiments. However, they are limited to propose a of a sequence to present mandatory topics to introduce and describe this theory, as the central ideas in chaos theory, chaotic phenomena observation and butterfly effect. They present coherent and interesting teaching sequence, but they don't present realistic in-depth details on how to implement it, nor results in the students' learning or perception. Therefore, this work seeks to overcome this problem because, in addition to presenting a logical teaching sequence and the use of technological resources, it also presents an assessment of students' learning and perception.

The paragraph above focuses on exemplification of ways to teach chaos theory, but there are works, such as Akmansoy and Kartal (2014), Odrowaz-Coates (2020) and Kırlar-Can at al. (2024), that focus on a reverse direction, exploring how chaos theory could be applied on education, which can use this theory, for example, to analyze how small differences and variations in the student's background, or student-teacher interactions, or long-term outcomes predication could influence the educational approach. This focus is outside of the present work scope, but, at least, it is interesting to mention that it is another chaos theory application.

Therefore, this work established a hypothesis that it would be possible to design an efficient class to introduce this theory, selecting only the strictly necessary mathematical concepts and presenting this theory in association with a context usually familiar to the students. It proposes a class design structured according to the pedagogical approach *meaningful learning* that proposes the acquisition of new knowledge linked to a previously acquired concept, which are symbolically called *anchor* (Hong et al., 2020; Polman et al., 2021; Mollo-Flores & Deroncele-Acosta, 2021; Rolando et al., 2021).

As explained earlier, this work emphasizes that it was designed to serve undergraduate and graduate students from life sciences and other different areas without previous knowledge of mathematics or software, since all these concepts are detailed in this article. This work adaptation for students with more advanced levels of mathematics and software would be simple and could include in-depth analysis of the presented topics. Despite the objectivity and conceptual simplicity of this proposal, we believe that secondary school students could also use it, but a detailed analysis of this group is outside this article scope.

Figure 1 shows the class design structure in the meaningful learning context, where this work also used the *authentic learning* principle that focuses on engaging students in real-world problems (Howland et al. 2013), and the *active learning* principle that proposes the integration of practical activities into the teaching process (Bonwell and Eison 1991).

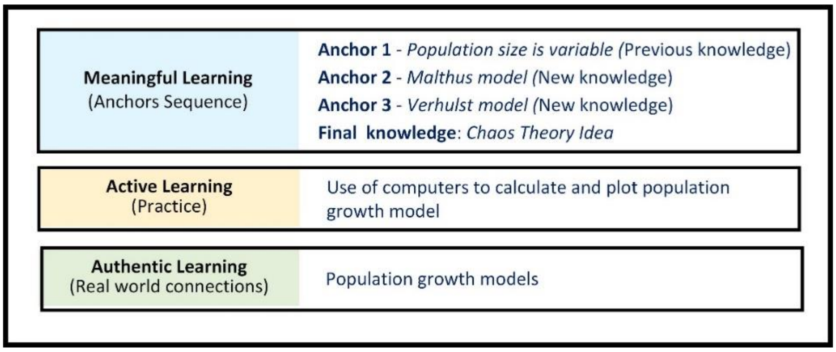

Figure 1. Proposed teaching design

This work focused on the chaos theory teaching for life science students, and selected the population growth subject as an educational anchor. Although the original proposal of this work is focused on life sciences students, it can be applied to students from different areas, as the idea of population growth is almost intuitive for most people. The main original contribution of this article is:

1. The proposal of an objective methodology for chaos theory teaching, based on the educational approach meaningful learning.
2. The prove that live sciences students can use and change a software code for exercises related to chaos theory, which also has the potential to motivate them in the area of software development.
3. The presentation of quantitative outcomes about chaos theory teaching for life sciences students, discussing the students' perception in relation to this class

The next sections will present the class design details and its results. The methods section includes details of the lesson plan and practical activities, and the results section shows this work evaluation based on feedback from 70 students, and the discussions section analyses the students' perception and emphasize that 71.9% of the students stated that they had confidence to explain this after the class, which this work considers quite satisfactory.

METHOD

The present teaching proposal is based on a short-term training with a multidisciplinary approach and a duration of four hours, whose primary structure is based on three stages that are introduction, procedures and final conclusions. Nurtanto et al. (2021) and Jourbet et al. (2021) emphasize lesson plans should be a dynamical proposal to allow their adjustments according to each local reality of teaching and learning, including time, resources available, students' background, instructors' training, motivational accepts, educational strategies, and use of technologies. These reflections stimulated the present work to propose a flexible lesson plan that meets these premises, which is shown in figure 2.

Lesson Plan: Introducing Chaos Theory

Duration: 4 hours

Learning Goals (After-class skills):

1. Explain the fundamental ideas about the chaos theory
2. Explain the logistic Map equation
3. Plot an equation curve with Octave or Matlab

Previous knowledge: No previous knowledge is required.

Initial questions:

1. What is chaos theory?
2. What is a mathematical population growth model?
3. What is the relation between chaos theory and population growth?

Learning analysis: Through a survey

Class materials: Computers with Octave or Matlab software, and a propjector

Teaching and learning activities

Stage 1: Introduction (Duration: 50 minutes)
It presents the basic conceptual chaos theory ideas, as the predictability and strong dependence on a variable (initial conditions)

Stage 2: Pratical Activities (Duration: 2h45m)
A) A summarized presentation of the Matllab or Octave mathematical processing software
B) Presentation of the population growth models proposed by Malthus and Verhulst
C) Presentation of the logistic map model of population growth

Stage 3: Final conclusions (Duration: 25 minutes)
it summarizes the theoretical class content, emphasizing the chaos theory potential for applications in different areas and motivating the use of computers

Figure 2. Basic design of a lesson plan.

The lesson plan activities of teaching and learning composes the lesson core, which this work divides into three stages that are detailed below.

The stage 1: Introduction

The introduction explains conceptually the chaos theory idea, starting with a pivotal question: What is chaos theory? The answer explains the characteristics of a deterministic behavior and the sensitivity to the initial conditions, as outlined above.

Note the idea of predictability becomes the introduction core, as the idea of being able to predict how a given system will behave in the future justifies and motivates the chaos theory study. The introduction also clarifies other subjects and it should include the following topics:

1. Deterministic behavior and predictability.
2. Sensitivity to the initial conditions.

3. Chaos theory history. The work of Oestreicher (2007), among others, is a great reference for teachers to prepare this item.
4. The butterfly effect idea;
5. Chaos theory applications.

This work considers the introduction as the ideal moment to motivate students to think about applications of this theory in their respective areas, which also favors improving these students' critical sense and proactivity.

Stage 2: Practical Activities

Basically, the practical activities stages include:

1. An initial practical analysis of mathematical software to compute and plot the curves of mathematical expressions. As most students had no experience in direct manipulation of software codes or in using mathematical software, this part was proportionally the most difficult, as the students had to overcome an initial barrier to using a new tool. Despite the existence of these difficulties, they could be easily overcome because the approach adopted was simple and extremely practical, which was a strong motivational factor for students to strive to understand the topic.
2. The analysis and use of software codes to process and plot graphs of the population growth models:
   2.1. Model of Malthus.
   2.2. Model of Verhulst.
   2.3. Logistic map model that has a chaotic behavior and can induce to interesting discussions about chaos theory principles.

This work breaks down the study of each population growth model into three distinct pats, which are:

1. A preliminary inquiry: What is the shape of the curve associated with the population growth model under study?
2. The model details: Understand the mathematical population growth model equation and its variables.
3. A challenge: Use a set of computer commands to compute and plot the model curve, which also includes an experiment to change the values of each model equation to verify the resulting curve variation.

Each growth model presentation has a well-defined beginning and end, since it started with the introductory question and culminating in a challenge, which serves to explain the objectives and sequence of each presentation.

The experiments with computers require a mathematical processing software, and this work chose the software named Octave, which is a free and similar to another popular tool similar mathematical processing software named Matlab. Therefore, the software procedures shown in this work are compatible with both platforms.

The first practical task involves exploring the user-friendly Octave work environment. Figure 3 shows the intuitive Octave software screen, and emphasizes its main panel, which is called "command window" and acts as an interface where the user can type commands and visualize the results.

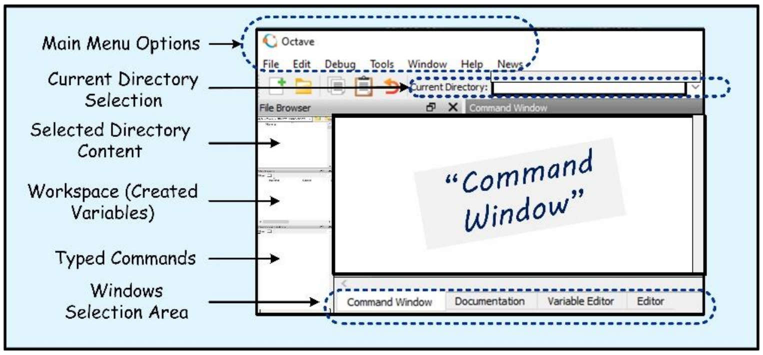

Figure 3. The Octave software screen.

The users must write a program, also refereed as a *script* in this environment, using the text editor of the Octave environment or even the traditional windows notepad. The script is structured as a text, but it must be saved with an extension ".m", like for example "script_name.m". Later, to run the script, the users must first click on the box "current directory" and set the directory where the script was saved. Next, they must just type the script name in the Octave Command Window and press the enter key, thus it will open the script file and execute all its commands, line by line.

This work assumes that not all instructors may have advanced knowledge of software, and therefore the forthcoming sections will explain each presented script in details, step-by-step. Therefore, at least theoretically, any enthusiastic instructor could teach the fundamental concepts presented in this work by following the proposed steps, even if the instructor has no prior knowledge. This work proposal is that computational requirements do not become a barrier.

The Malthus model of population growth

Figure 4 curves shows Thomas Malthus' theory curves, which was presented in 1798. It stated the population's growth was exponential (red line), while the food supply growth was linear (blue line) and therefore it would cannot meet human needs, causing hunger, poverty and death. In fact, the exponential human population growth curve isn't realistic because it doesn't consider other complex and dynamic factors behind a population growth that could affect the exponential curve trend. However, he has the merit of being a pioneer and drawing attention to this subject in the 18th century.

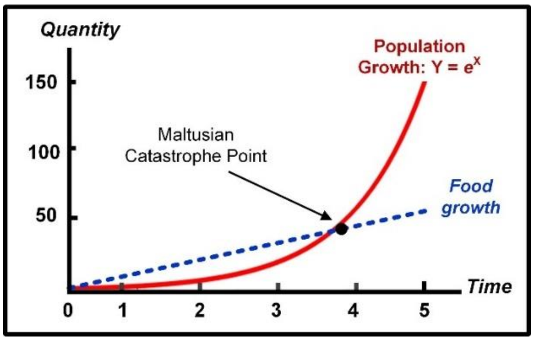

Figure 4. The exponential Malthus' model curve.

Mathematically, the exponential curve model is expressed as:

$$N(t) = No\ e \qquad (1)$$

Where No is the initial population, *r* is the population growth rate, and *t* is the time.

Equation 1 is simple, but in the present context, a question immediately arises: how to calculate it and plot its graph with a computer? It depends on software, and figure 5 shows an Octave script to compute and plot the equation 1. The scrip is in the blue box, but the figure includes additional comments in the white blocks on the right to allow an easier understanding of each command line.

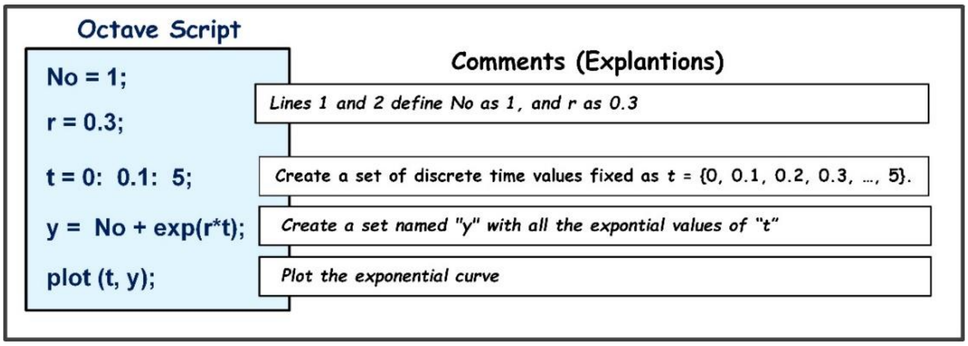

Figure 5. The commands to plot an exponential curve.

Note that just a five-line script is enough to carry out this experiment. It is also interesting that instructors ask students to change the values of *No*, *r* and *t*, to verify their influence on the curve behavior, which is also a way for students to become more familiar with this software environment.

The Verhulst model of population growth

The mathematician Pierre Verhulst proposed in 1838 a population growth model where the curve depends on the existing population and the available resources quantity, which is more coherent than the older exponential model, and is known as Verhulst model or logistic model. Figure 6 shows its typical curve that follows a mathematical pattern called sigmoid curve, and where the population reaches a natural stabilization after a period of growth.

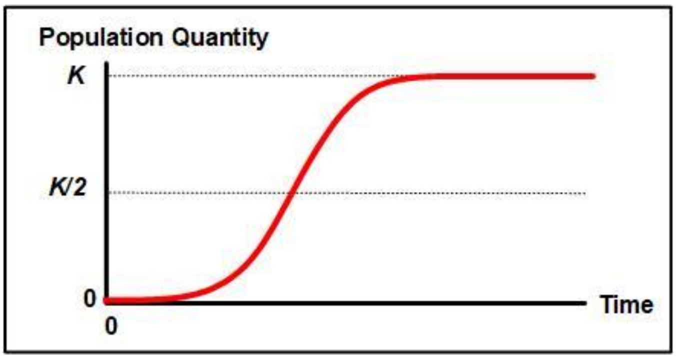

Figure 6. A typical Verhulst model curve.

The figure 6 curve is mathematically expressed as:

$$N(t) = \frac{k}{+\left(\frac{k}{\;}\;\;1\right)e^{-rt}} \qquad (2)$$

Where: *N(t)* is the number of individuals at the instant *t*.

No is the initial number of individuals.

r is the growth rate

k is the carrying capacity, or the maximum number of individuals that the environment supports.

Figure 7 shows a scrip to compute and plot the Verhuls model curve according to equation 2, which includes software commands and simple text comments that are written after the % symbol. Comments are not mandatory, but they are a great practice. Formally, comments are short and free-form text annotations that software designers write into their code to make it easier to understand. In Octave, comments can be written on the same command line with the symbol % at their beginning, which separates commands and comments. Comments are only for human understanding and all text written after the symbol % is ignored in the processing, and therefore don't affect the processing performance.

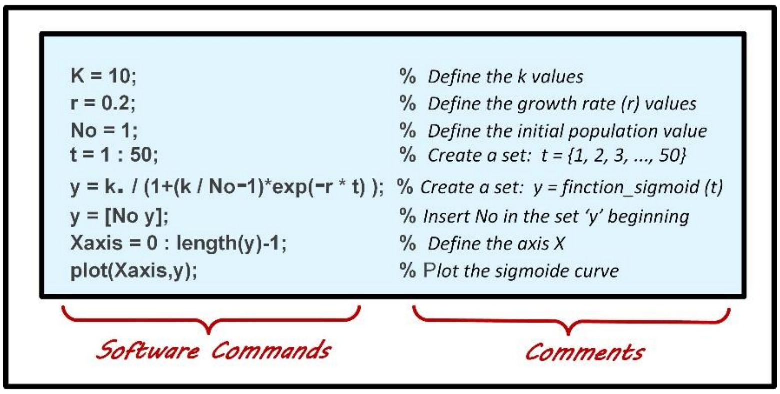

Figure 7. Script to plot the Verhulst model curve.

The fifth line in figure 8 is the equation 2 written in only one line because it is the standard of programming languages, and the students should be careful when typing it to avoid typos. Bellow, equation 3 is the equation 2 written in one line.

$$(1 \quad (k \qquad 1) \quad exp(- \quad t)) \tag{3}$$

The Logistic Map model of population growth

The logistic map is a population growth model presented by Robert May in 1976 (May, 1976), and it is a spotlight subject in the proposed class because it has a chaotic behavior. In the proposed class, the models of Malthus and Vershulst serve only as a preliminary sequence to introduce the logistic map, which consequently serves as a practical introduction to the chaos theory.

Equation 4 shows the logistic map expression, which is very simple and therefore becomes ideal for teaching approaches. If the model growth rate (*r*) varies slightly, the model curve varies markedly over time., which is a chaotic behavior.

$$\frac{Nt\,(k \quad Nt)}{} \tag{4}$$

Where *Nt* is the number of individuals at the time instant *t*.

If the carrying capacity (k) is assumed as a maximum referential value fixed at 1, then equation 4 is rewritten as:

$$Nt_{+1} = r\,N_t\,(1-N_t) \tag{5}$$

Equations 4 and 5 calculate the population (*Nt*) at any instant (*t*), but it is inserting to emphasize in the classroom they present a mathematical particularity. Not, to calculate the population at a specific instant *t*, it is mandatory to know the population at the previous instant *t-1*. Mathematically, it is a case of deterministic *sequence*, where the calculation of any element value in the sequence can occur only if the previous value is known. For example, to compute the population at the instant *t5*, it is necessary to know the population at the instant t4, and so on. For practical purposes, we assume that the initial population *No*, at instant *t0*, is known and then calculate the population in the following instants up to a desired instant. Figure 8 shows an example of the manual logistic map values calculations up to the instant 3, with an initial population (No) fixed at 0.5 and a growth rate (r) at 3.7.

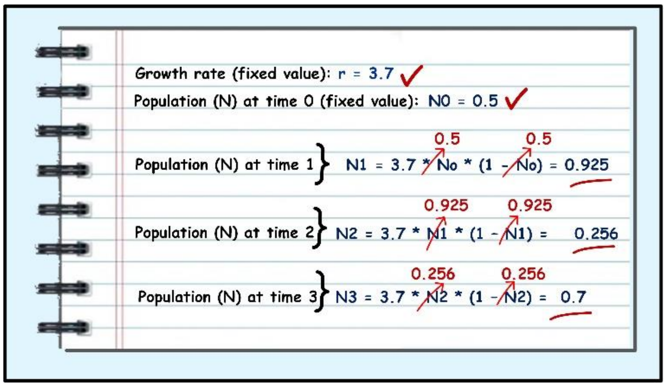

Figure 8. Logistic map computation

Figure 10 shows the Octave script to compute and plot the equation 4 curve. The variable *r* determines the sensitivity to the initial conditions, and therefore its initial valor changes significantly the curve behavior over time.

```
r = 3.6;                                          % Growth rate (r) value
tmax = 50;                                        % Higer time value
k = 1;                                            % Carrying cpacity
pop=[ ];                                          % Vector to store pop the poulation values
pop(1) = 0.1;                                     % Initial population at time 1
for t  = 2: 1: tmax                               % Loop: t varies from 2 to tmax
    pop(t) = ( r * pop(t-1) * (k - pop(t-1)) ) / k;  % Computes population at time 't'
end
plot (pop);                                       % Graph plot
```

Figure 10. The Octave script to compute and plot the logistic map.

Figure 11 shows curves representing the population growth variation computed according to equation 4 and using the figure 10 script. It shows two superimposed curves computed with *r*=3.7 (blue curve) and *r*=3.7001 (red curve), whose absolute difference is only 0.0001. Despite the insignificant difference, the curves show a significant difference over time and, in this specific case, both curves have coincidentally the same behavior until the instant *t* equals 22, but from that moment on, the behaviors become absolutely different.

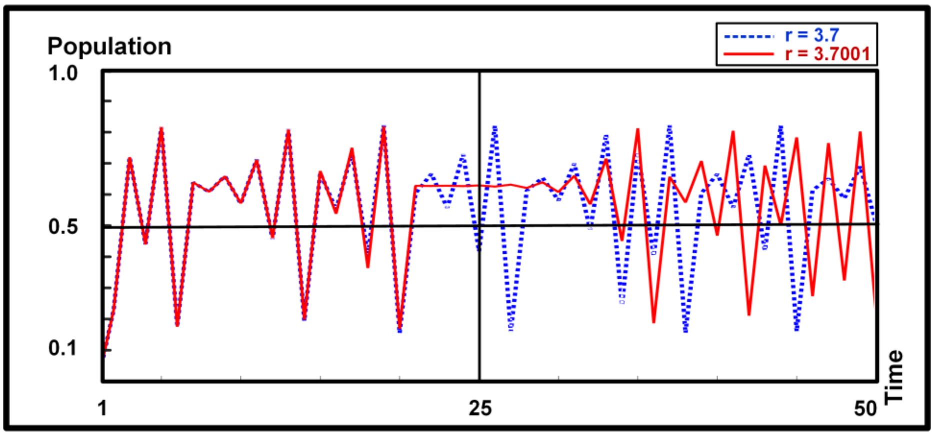

Figure 11. Two logistic map curves with tiny growth rate (r) difference.

Figure 11 shows a classic example of chaotic system behavior, and if students repeat this experiment with another *r* value, the result vary. This model is mathematically simple, but as explained by Robert May (1976), it has a very complicated dynamics, where the dynamic describes how the system responds to a stimulus over time, which, in this case, is the growth rate variation.

Stage 3: Final Conclusions and Survey

The final conclusions stage presents a general summary of everything that was taught, and it is also interesting to encourage the students to improve their critical sense about scientific applications of chaos theory, and about the use of computers as a fundamental tool for scientific research.

After the workshop session, students were requested to take part in a survey to assess their perception of their learning progress and motivation. We evaluated the students' perceptions without employing formal tests to gauge quantitatively the level of gained knowledge. A quantitative approach could provide a more precise evaluation of absorbed knowledge, but the primary goal of this workshop was to teach fundamental concepts about chaos theory rather than aiming to make students experts in this subject, which would require an extensive time investment and advanced mathematical proficiency. Therefore, in this context, surveys are an effective tool for evaluating the teaching proposal efficacy.

Students took part in the survey by answering questions directly on Google Forms, which provides integrated analytics and visualizations, helping the results and trends analysis. In this case, assuming that the focus of the statistical analysis was a percentage classification of students' perception, Google Forms sufficed to provide this analysis, with no more advanced statistical data processing tools. Google Forms was chosen because it is an efficient tool for courses evaluation, it is easy to use, ensures student anonymity in relation to peers, allows real-time data collection, students can access the form from different devices such as computers or smartphones, and provides a basic integrated data analysis. Using this tool to collect data for course evaluation has already been used successfully in several educational works, as shown in works such as Selvaraj et al. (2021), Zain-Alabdeen (2023), Zaidaan et al. (2024), Agtarap (2024).

The present survey was applied to two similar groups in different periods of time and had very similar results, which indicates its reliability. We consider it was also validated because it allows the analysis of the students' perception regarding their learning and also because the different questions were directly planned in order to allow a complementary analysis.

RESULT and DISCUSSION

This work evaluation was based on feedback from students who took part in this practicum, including 70 students, with 38 undergraduate students of veterinary in Chile and 32 graduated students of agronomy in Brazil. Both courses are in life science area, but with distinct focus, goals and curricular structure, and besides, with students from two countries that don't border, don't speak the same language and have specific characteristics in the educational suture before university. The students were selected because they were part of the same class, as this ensures a more homogeneous group in all aspects and allows for a more consistent analysis of results, and, in both cases, this course was taught in a computer lab where theoretical concepts were presented and practical software experiments were carried out. The workshop was taught separately at different times for each of the two groups, but, despite their differences, the results were quite similar. This similarity can be justified by the fact that the chaos theory is a concept little explored in undergraduate and graduate courses in the area of life sciences, and, in addition, the workshop was designed to meet different groups of students.

Figure 12 shows the survey was divided into four key parts. The initial part focused on profiling the students to gauge their prior knowledge of population growth, chaos theory, and software design. The second section aimed to evaluate the students' understanding of chaos theory. The third part delved into assessing student motivation, and in the fourth part, the students evaluated the workshop. As previously mentioned, this work considers surveys as an adequate tool for evaluating the effectiveness of educational proposals centered on conceptual ideas.

Survey

Part 1 - Previous Knowledge

1.1) What was your previous knowledge about population growth?
1.2) What was your previous knowledge about Chaos Theory?
1.3) Did you already have specific knowledge of Octave or Matlab?
1.4) What was your knowledge of algorithms or computer programming languages?
1.5) What was your knowledge about the use of application software for mathematical or graphic data processing?

Part 2 - Knowledge acquired

2.1) Can you explain the idea of chaos theory?
2.2) Can you explain the relationship between the terms "chaos theory" and "butterfly effect"?
2.3) Can you explain the relationship between population growth and chaos theory?

Part 3 - Motivation

3.1) Do you think this type of class with technology applied to a topic in your area is more motivational?
3.2) Do you feel motivated to think more frequently about technologies can be applied in your area?
3.3) Do you feel motivation to take a more proactive stance in relation to your own future learning on applied technology?
3.4) Would you like to take other courses that involve the use of technology/computer science in your area?
3.5) What degree of difficulty do you think students in your area would have in learning more (going deeper) about applied computing technologies?

Part 4 - Class evaluation

4.1) Did the class provide an appropriate balance between theory and practice?
4.2) Did the class present the concepts clearly and in a coherent sequence?
4.3) Regarding learning: how do you rate the efficiency of a workshop integrating technological and scientific concepts?
4.4) Would you recommend this class to your colleagues (students or professionals) in your area?

Figure 12. The survey to verify the student's perception.

Figure 13 summarizes the general students' perception about the workshop and their leaning. Almost all students stated that had little or no prior knowledge about chaos theory before the workshop, but 72.9% of them felt safe to explain the chaos theory after it. This work considers this result quite significant, and it and other issues will be detailed in the next section.

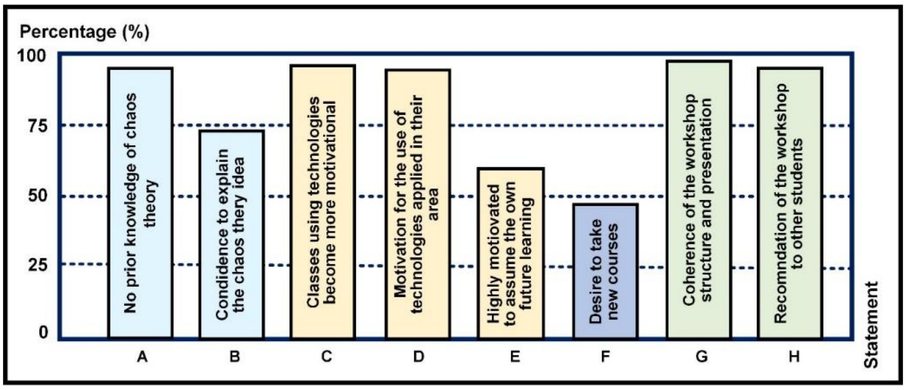

Figure 13. General students' perception.

Discussion

Figure 13 shown the general students' perceptions, which this section details and also discuss their relevance according to the literature and author opinions. To ensure a more objective discussion, focused on the main points, this article divides it into three parts that are: the students' profile, the main learning, and the students' motivation and engagement.

The students' profile

The first survey part analyzed the students' profile. Only 10% of the students claimed to have studied population growth in depth, but the other 90% were familiar with the topic. Concerning chaos theory, 94.3% admitted to having little to no prior knowledge about it and only 25.7% of students had knowledge of algorithms or programming languages. In short, the first survey part showed these students were familiar with the population growth models, but weren't familiar with either computing or chaos theory.

These percentages were already expected because there are works that analysis specifically the mathematics and computation in life science courses (Zuckerman at al., 2024; Zuckerman & Juavinett, 2024) and, despite the increasing use of these fields in the area of life sciences, many students still have a fear of studying then and arrive at university without prior knowledge of this subject, which also limits their level of motivation in the undergraduate courses. However, this problem attenuation is not an impossible task and, on the contrary, it becomes challenging in the sense that teachers seek appropriate teaching methodologies for this issue (Mariano et al., 2019; McDonald et al., 2022). Besides, this work assumed that many of these students may present a lack of self-confidence in relation to mathematics and, in some extreme cases, some students may present a severe apprehension and negative emotional response when confronted with mathematical subjects, a widespread issue referred to as mathematics anxiety (Lee & Clinedinst, 2020; Khasawneh et al., 2021; Tanujaya & Jeinne, 2022; Horne et al., 2022). In these extreme cases, the teacher must identify these students and try alternatives to motivate them to face this problem.

This analysis concludes these life science students, with no prior knowledge of chaos theory and computing, compose the ideal audience for this work because they allow to check the present proposal efficiency., verifying what extent it is possible to introduce chaos theory to students with this profile.

The main learning acquired

In this work, the main learning is the chaos theory idea, where students should be able to explain this theory principles, the butterfly effect and a specific use of computer associated with this subject. Therefore, this work initially asked if the students could explain the relationship between population growth and chaos theory. It is a strategic question because the population growth was an anchor to introduce chaos theory, and therefore students able to explain chaos theory should also be able to explain this relationship. Fortunately, the response percentages were the same as the previous question and it represents a satisfactory level of the students' responses coherence, which suggests that the group was reliable.

When the students were asked if they felt safe to explain the chaos theory idea, 72.9% answered yes, which this work considers a satisfactory result. However, and 77.1% felt safe to explain the butterfly effect after the workshop. Assuming the butterfly effect is only an informal and playful idea to represent the chaos theory principle, and both concepts are in the same context, it induces to a question: Why do 4.2% of students claim to know how to explain the butterfly effect but do not feel confident explaining the concept of Chaos Theory? It deserves special reflections to identify probable reasons. Maybe, in fact these students didn't understand effectively these concepts, but the problem may be more critical, and it is plausible to consider a hypothesis that some students may be afraid of being forced to give a more in-depth explanation about a more complex topic when they assume a more emphatic position of self-confidence. This is a problem that can affect the student's entire academic performance and also their future professional life.

These 4.2% of students seem to grasp the concept but are hesitant to assume a more challenging position, which may occur because of a fear of failure. If some of these students usually present this behavior, it may be a case of *atyquiphobia* that leads to an exaggerated fear of failure. Consequently, they present pervasive doubts about their abilities and it can influence negatively their academic performance (Junuthula, 2022; Karim et al.; 2022). Besides, it may be a case associated with the *impostor syndrome* (IS) where some individuals present an extreme lack of self-confidence that generates a persistent fear that their achievements will end up exposing them as a fraud, because they attribute their accomplishment to another factors, such as simple causality or luck (Chakraverty; 2022; Shreffler et al., 2023). The students' psychopedagogical analysis is outside of its article scope, but it suggests that instructors reflect on this issue and learn to identify students who perhaps fit this profile.

The students' motivation and engagement

The survey also allowed the analyzed the students' motivation about applied technology, and 95.7% considered interesting classes using technologies as a way to become they more motivational, and 94.3% felt at least reasonably motivated to think more frequently about the use of technologies applied in their area. In both questions, there is a small percentage of students that presented a certain resistance to technology, which was expected because the acceptance of new technologies may suffer from the influence of factors such as job insecurity, fear of the unknown or person's inadequacy.

Despite the high degree of motivation, a more objective and concrete analysis about the students' encouragement to think more deeply about the use applied computing and take responsibility for your own future learning on this topic, only 57.1% were highly motivated, 40% answered maybe.

Note the positive statement decreased from 95.7% to 57.1%, which, even with the drop, remains a satisfactory result. This decreasing occurs because motivation and enthusiasm are different concepts (Jungert et al. 2020, Palmer 2020). Enthusiasm represents a passive state of excitement, while motivation involves consequences and engagement in particular activities. Therefore, to better clarify this issue with a very pragmatic approach, this work asked students if they effectively would like to attend other specific courses of applied computing in their area, and 47.2% answered yes, 42.8% said they might, and 10% answered emphatically they would not like. Note positive positioning decreased from 57.1% to 47.2%, and therefore, as the required degree of objectivity and concreteness increases, the interest decreases. In any way, 47.2% of life science students with interest to attend other specific courses of applied computing in their area, is a result that may be satisfactory.

Perhaps these students who do not want to take courses weren't able to measure the effective impact that technology can have in their daily lives as future professionals, and therefore, they must be aware and motivated to face this challenge. Currently, the applied computing potential in life sciences is so great that has motivated new specific fields of studies, such as "computational life sciences" (Dörpinghaus et al., 2023), "environmental computing" (Heikkurine et al., 2015), and "Bioinformatics" (Ramsden, 2023). These fields incorporate hardware and software aspects, including physical phenomena monitoring, environmental protection systems, sensors, telemetry, remote sensing, data loggers, artificial intelligence, embedded systems, simulation, data mining, etc. The benefits of the applied technology in the different life sciences branches are unquestionable and promising, which deserve special attention.

Based on this survey part, it is possible to conclude that the workshop enthused almost all the students who participated, and it effectively motivated about half of the students to take a proactive stance in relation to their training and knowledge of applied computing, which this work considers satisfactory result for a short teaching action.

Students' opinions about the workshop

The fourth part of the survey analyzed students' opinions regarding the workshop and 97.1% stated the workshop provided an appropriate balance between theory and practice, and 94.3% considered the concepts presentation was based on a coherent sequence. The efficiency of workshops designed with the integration of technological and scientific aspects was recognized by 95.7% of the students, and 94.7% of them would recommend the workshop to other students. Therefore, this survey part showed the workshop had a great approval.

Limitations and findings value

This study was conducted with 38 undergraduate veterinary students in Chile and 32 graduate agronomy students in Brazil. Although the results were satisfactory and both groups were in the life sciences, in the future, the study could be expanded to include items such as

1. Analysis of other groups within life sciences fields, such as biology, ecology, or zoology students.
2. The number of students could be increased in order to discover possible variations.
3. The group could be again analyzed some semesters later, to see what the long-term results were.
4. Analysis of this teaching process in more countries

These limitations do not invalidate the results presented and their solution could be easily solved by replicating this experiment. Despite the limitations inherent in any work, it is interesting to emphasize that among this work findings, two deserve emphasis, which are:

1. The feasibility of teaching the basic chaos theory concepts in a short time activity.
2. The motivational factor caused by the use of computers to make easier the understanding of abstract concepts, based on software code graphical data analysis, such as a chaotic function behavior. In

addition, the use of graphs and code design contributes to developing of analytical skills and facilitating data comparison ability.

Teaching advanced science concepts in just a few hours can be challenging, but a right approach makes it possible. It is essential to clearly establish the concepts that need to be understood and present them in a clear and objective way, associating the concepts with simple ideas, used as anchors, which makes the learning less abstract. It is also important to periodically reinforce key points to merge learning, and finally, the use of computer creates a more challenging and dynamic environment.

This work finding about the viability to teach scientific concepts with short-term courses, was also analyzed in other works (Mena-Guacas et al., 2023). For example, Pasáčková (2023) didn't find any great difference between the scores of quizzes of the long-term and short-term courses of mathematics, which include advanced topics as complex numbers and combinatorics, and whose analysis was based on 69 students in the longer course and 63 in the short-term course. Another finding that meets the present work was discussed by Florence et al. (2021) that proved the major students' expectation in short term courses was to learn about real-life applications and to learn new concepts to increase their scientific knowledge.

These findings can be transformed into effectively practical actions. The feasibility of teaching advanced scientific concepts in short activities with computational resources represents an experience that is not limited to the teaching of chaos theory and could be applied to teaching the basics of other scientific subjects, such as fractal geometry, automation engineering, or simulation. These lessons also suggest that advanced topics, with short-term teaching with practical computational support, could be an interesting option for the insertion of special topics in the curriculum of different disciplines.

Assuming this work was applied with success to students of two different life science courses in two different countries, it is possible to assume that it could apply to a wider population or different groups of students. In any case, it is interesting to present some recommendations, such as the software that should be done calmly, in order to ensure that students effectively understand what they are doing without creating a false sense of knowledge, which may require a variable amount of time depending on the characteristics of each group. This concern may be less when we approach the subject for students who usually study software development in their normal curriculum, which can happen in physics, mathematics or engineering courses. However, when we deal with the area of biological sciences or human sciences, this analysis regarding the teaching time of software becomes more critical.

Another possible limitation is related to the teachers' lack of training and time, which do not depend on this paper itself, but deserve comment. Perea Martins (2024) discuss the teachers' lack of technological training may be a serious problem, and besides, there is a usual problem of teachers' lack of time to update themselves in the use of technologies and to prepare classes with this content. Beardsley (2021) shows that the teacher confidence in preparing classes with the use of technology has increased, but despite this increasing, Kearney et al., (2022) shows it is still a critical problem. Therefore, as explicated earlier, in order to get around these problems and make this proposal feasible, this work selected only the simplest and essential technological resources necessary.

CONCLUSIONS

This work presented the proposal and analysis of a teaching strategy to introduce basic conceptual ideas of chaos theory to life science students, and it proved that it is possible with a four-hours workshop designed with the meaningful learning strategy. It used computers as a motivational tool and population growth models as educational anchors to teach the proposed concepts associated with real-world problems. This study contributed to the teaching of chaos theory by proving that its teaching in a short period is viable, even for students who are not from the exact sciences such as mathematics or physics and it also proved that simple software procedures, encoded in Ocatave or Matlab, can provide all the computational resources required for the practical activities and, at least in expectation, even students or professors with no previous software knowledge could understand them. The proposed methodology for teaching chaos theory can be directly used to teach students of different disciplines with no changes. It is based on very simple concepts of mathematics and software, and the anchor theme, which is population growth, is a common theme for the general population. This makes the use of this work quite flexible. The results were based on the perception reported by 70 life science students, where 72.9% presented self-confidence to explain chaos theory idea after the workshop, which this work considers satisfactory for a short time workshop. The results also indicated an interesting question, as 94.3% of the students felt at least reasonably motivated to think more frequently about the use of technologies applied in their area, but only 47.2% effectively would like to attend other courses of applied computing, which deserves special attention from professors in the life sciences area in order to make their students aware of their technological training importance. Regarding workshop acceptance, 94.7% of the students would recommend it to other students. This work considers satisfactory the presented workshop outcomes and emphasizes the significant percentage of students self-confident to explain chaos theory idea after it, which suggests the present proposal has potential to be reproduced by other instructors.

Declarations

Conflict of Interest

No potential conflicts of interest were disclosed by the author(s) with respect to the research, authorship, or publication of this article.

Ethics Approval

This study is based on data colleting and is not among the studies requiring ethics committee permission by the local instiruituons.

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Research and Publication Ethics Statement

This study was conducted with local institutions guidance and authors state:

- This material is the authors' own original work, which has not been previously published elsewhere.
- The paper reflects the authors' own research and analysis in a truthful and complete manner.
- The results are appropriately placed in the context of prior and existing research.
- All sources used are properly disclosed.

Contribution Rates of Authors to the Article

All the authors contributed equally to this work.

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