Addressing Teleological and Essentialist Reasoning in Evolution Education: Effects of a Multi-Strategy Instructional Intervention on Conceptual Understanding and Critical Thinking Among Junior College Students

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Abstract

Evolution remains one of the most challenging topics in biology, with students often relying on teleological and essentialist reasoning that differs from scientific explanations. This mixed-methods quasi-experimental study examined the impact of a multi-strategy instructional intervention on junior college students' conceptual understanding of evolution and critical thinking. The study involved 172 students from two junior colleges in Mumbai, India, with an experimental group (N = 91) and a control group (N = 81). Pre-intervention interviews with 25 students revealed teleological and essentialist reasoning, misconceptions about common ancestry, and a distinction between microevolution and macroevolution. Quantitative findings showed that students who participated in the intervention achieved significantly higher post-test scores in conceptual understanding (U = 657.5, p < .001, r = .71) and critical thinking (U = 612.5, p < .001, r = .72). The findings suggest that multi-strategy instructional approaches can promote conceptual change and improve evolution learning.

Keywords: *Evolution education, conceptual change, conceptual understanding, critical thinking, teleological reasoning*

1. Introduction

Evolution is widely recognised as the unifying framework of modern biology, explaining the diversity, adaptation, and interconnectedness of living organisms through time. It provides a coherent account of phenomena ranging from genetic variation and adaptation to speciation and biodiversity, making it fundamental to biological literacy and biology education (Dobzhansky, 1973; Wei et al., 2012). Evolutionary thinking also contributes to understanding contemporary scientific and societal issues (Jørgensen et al., 2019; Matthews et al., 2020).

Despite its central role in biology, evolution remains conceptually challenging for learners. Students frequently struggle with natural selection, adaptation, variation, and evolutionary change, often relying on intuitive or alternative conceptions that differ from scientific explanations (Bishop & Anderson, 1990; Demastes et al., 1995). The complexity of evolutionary processes and learners' prior conceptions contribute to these difficulties (Bishop & Anderson, 1990; Dunk et al., 2019).

Evolution education research has identified teleological and essentialist reasoning as two important cognitive barriers to understanding evolution (Coley & Tanner, 2012). Teleological reasoning

involves explaining biological structures or evolutionary changes in terms of purpose, need, or intention, such as assuming that organisms develop traits because they require them for survival. Essentialist reasoning, in contrast, reflects the belief that species possess fixed and immutable characteristics, making it difficult for learners to understand variation within populations and evolutionary change across generations. These intuitive reasoning patterns can lead students to construct explanations that conflict with scientific accounts of evolution based on variation, inheritance, and natural selection (Hanisch & Eirdosh, 2020). Recent studies have further demonstrated that teleological explanations continue to influence students' interpretations of evolutionary phenomena (González Galli et al., 2020) and may hinder the transfer of evolutionary reasoning across biological contexts (de Lima & Long, 2023).

Addressing such reasoning patterns requires instructional approaches that promote conceptual change and evidence-based reasoning. Conceptual change perspectives suggest that meaningful learning occurs when learners examine existing conceptions and reconstruct their understanding in response to scientific evidence and alternative explanations (Czinczel et al., 2025; Demastes et al., 1995). Active-learning approaches, including inquiry-based activities, simulations, concept mapping, collaborative discussions, and model-based learning, can improve conceptual understanding of evolution and support scientific reasoning (Balgopal et al., 2025; Czinczel et al., 2025; Frasier & Roderick, 2011; Freeman et al., 2014; Peel et al., 2019).

Research examining evolution education in the Indian context remains relatively limited, particularly regarding how multi-strategy interventions can address teleological and essentialist reasoning among junior college students (Bast & Tahilramani, 2018). Further investigation is also needed into whether such interventions can enhance both conceptual understanding and critical thinking about evolution. Therefore, the present study examined the impact of a multi-strategy instructional intervention designed to promote conceptual understanding, evidence-based reasoning, and critical thinking.

Research Objectives

The objectives of the study were as follows:

1. To identify forms of teleological and essentialist reasoning exhibited by junior college students prior to evolution instruction.
2. To examine the impact of a multi-strategy instructional intervention on conceptual understanding of evolution.
3. To examine the impact of a multi-strategy instructional intervention on critical thinking about evolution.

Null Hypotheses

H_{01}: There is no significant difference in conceptual understanding of evolution between students who participated in the multi-strategy instructional intervention and those who received conventional instruction.

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H_{02}: There is no significant difference in critical thinking about evolution between students who participated in the multi-strategy instructional intervention and those who received conventional instruction.

Research Questions

The study was guided by the following research questions:

RQ1. What forms of teleological and essentialist reasoning do junior college students exhibit prior to instruction on evolution?

RQ2. What is the impact of a multi-strategy instructional intervention on students' conceptual understanding of evolution?

RQ3. What is the impact of a multi-strategy instructional intervention on students' critical thinking about evolution?

2. Methodology

Research Design

The study employed a mixed-methods quasi-experimental design to examine the impact of a multi-strategy instructional intervention on junior college students' conceptual understanding of evolution and critical thinking. Qualitative data from pre-intervention interviews explored students' existing reasoning patterns and conceptual difficulties, while quantitative data evaluated the intervention's impact on conceptual understanding and critical thinking (Creswell & Plano Clark, 2018).

Participants

The study involved 172 junior college students from two educational institutions in Mumbai, India. Twenty-five students participated in the pre-intervention interviews used for qualitative analysis. The experimental group comprised 91 students who received the instructional intervention, while the control group comprised 81 students who received conventional instruction. Intact classroom groups were used to preserve existing instructional arrangements, resulting in a quasi-experimental design.

Instructional Intervention

The instructional intervention was designed to promote conceptual understanding of evolution and address common reasoning patterns that hinder evolution learning. The intervention incorporated multiple active-learning strategies, including flipped classroom activities, educational videos, simulations, concept mapping, collaborative discussions, evidence-based learning tasks, and experiential learning activities.

The intervention was developed using the ADDIE framework. PowerPoint presentations, animated videos, worksheets, concept maps, simulations, SmartArt flowcharts, and socioscientific issue (SSI)-based scenarios were prepared through session-wise lesson plans and storyboards. The

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instructional materials and modules were reviewed by four experts in biology education, pedagogy, and educational research for content accuracy, curriculum alignment, pedagogical appropriateness, clarity, instructional design, and feasibility. The intervention was pilot-tested during April–May 2025 with Grade XII students comparable to the target population but not included in the main study. Revisions were made based on expert feedback, pilot findings, and researcher observations.

Pre-intervention interviews were subsequently conducted from 21–25 June 2025 to explore students' prior understandings, misconceptions, acceptance positions, and reasoning patterns. These interviews were not used to develop the assessment instruments or the original intervention design; where necessary, interview findings were considered for targeted refinement of instructional materials and delivery before final implementation. Where interview findings indicated specific conceptual difficulties, subsequent instructional refinements emphasised variation and natural selection to challenge need-based explanations, fossil and molecular evidence and concept mapping to strengthen understanding of common ancestry, and simulations, speciation activities, and evidence-based discussions to connect microevolutionary change with macroevolutionary outcomes.

The final intervention was implemented from 27 June to 1 August 2025 across 10 modules and 20 sessions. Students engaged in activities such as pre-class videos and live polls, group presentations and concept mapping, evolutionary scenarios and inquiry tasks, simulations of natural selection and genetic drift, comparative fossil analysis, evidence-based discussions, and bioinformatics-based comparison of proteins during human evolution. These activities required students to interpret evidence, examine alternative explanations, discuss perspectives, and justify conclusions. The strategies provided complementary opportunities for conceptual change and scientific reasoning: simulations and visualisations made evolutionary processes more observable, concept mapping organised relationships among variation, natural selection, adaptation, and common ancestry, while inquiry, collaborative discussion, and evidence-based tasks encouraged students to evaluate alternative explanations and justify claims using evidence.

Data Collection

Qualitative data were obtained through semi-structured pre-intervention interviews designed to explore students' reasoning about evolutionary phenomena and their understanding of concepts such as adaptation, common ancestry, speciation, and evolutionary change. The interview guide was developed independently of the emergent themes as an original set of 32 open-ended questions, informed by previous research and reviewed by two biology educators for conceptual relevance, clarity, and appropriateness. Quantitative data were collected using a Conceptual Understanding of Theory of Evolution Test (CUoT) and a Critical Thinking Test (CT) designed to assess students' ability to analyse evidence, evaluate alternative explanations, and apply scientific reasoning to evolution-related situations. Tools were administered to both groups after their respective instructional periods.

Data Analysis

Qualitative interview data were analysed thematically following Braun and Clarke (2006). Interview transcripts were read repeatedly to achieve familiarity with the data, followed by initial

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coding and grouping of related codes into broader themes. The analysis focused on students' prior conceptual understanding of evolution, misconceptions and reasoning patterns, acceptance of evolutionary explanations, and influences on their reasoning. Three recurring patterns were identified: teleological and Lamarckian reasoning, essentialist reasoning and common-ancestry misconceptions, and the micro–macro evolution distinction. Frequencies represent the number of participants whose responses reflected each pattern, with participants potentially contributing to more than one theme. The qualitative findings provided contextual explanation for the quantitative findings. Quantitative data were analysed using descriptive statistics and Mann–Whitney *U* tests to compare post-test conceptual understanding and critical thinking between the experimental and control groups. Effect sizes were calculated to determine the magnitude of observed differences.

3. Results and Discussion

RQ1: Pre-Instruction Reasoning Patterns

Analysis of the pre-intervention interviews revealed several reasoning patterns that have the potential to hinder students' understanding of evolutionary processes. Three major themes emerged from the data that reflected students' intuitive explanations of evolutionary processes: teleological and Lamarckian reasoning, essentialist reasoning and common ancestry misconceptions, and micro–macro evolution distinction.

Theme	**Description**	**Frequency (n = 25)**
Teleological and Lamarckian Reasoning	Evolution explained as need-based, purposeful, or goal-directed change	7
Essentialist Reasoning and Common-Ancestry Misconceptions	Essentialist interpretations of species as distinct or fixed categories, including linear interpretations of human evolution and misunderstanding of common ancestry and evolutionary relationships	6
Micro–Macro Evolution Distinction	Acceptance of small-scale changes but difficulty accepting speciation and large-scale evolutionary change	10

Table 1: Major Pre-Instruction Reasoning Patterns Identified in Student Interviews

Note. Frequencies represent the number of participants whose responses reflected each reasoning pattern. Individual participants could contribute to more than one theme

Teleological and Lamarckian reasoning was evident in the responses of seven participants and appeared in several forms. Some students explained evolutionary change as arising from the needs or requirements of organisms; for example, one stated, '*Duck evolved webbed feet because they need to swim*'. Other responses reflected use-and-disuse reasoning, in which structures were expected to disappear when no longer needed, and some students interpreted '*survival of the fittest*'

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in terms of physical strength rather than reproductive success. These explanations indicate a tendency to view evolutionary change as purposeful or directly induced by environmental demands rather than as a population-level process involving heritable variation and natural selection.

Essentialist reasoning and common-ancestry misconceptions were observed in six participants. Some responses reflected essentialist thinking, in which species were treated as distinct and fundamentally different categories, while others showed linear or transformation-based interpretations of human evolution, such as '*Humans evolved from monkey*'. Students also demonstrated difficulties understanding branching evolutionary relationships and shared ancestry, with some rejecting common ancestry or reasoning that ancestral species should no longer exist if humans had evolved from them. These responses indicate difficulty understanding evolutionary relationships as branching patterns of descent rather than a sequence in which one existing species transforms directly into another.

A third recurring pattern, identified in the responses of ten participants, was the distinction students made between microevolution and macroevolution. While many participants accepted observable small-scale changes within species, they expressed scepticism regarding speciation and large-scale evolutionary change. Statements such as '*Small changes can take place but I don't believe in speciation*' illustrate this selective acceptance of evolutionary processes. These findings suggest that students often relied on direct observability as a criterion for accepting scientific explanations and struggled to connect small-scale changes with long-term evolutionary outcomes. Similar difficulties in applying evolutionary reasoning consistently across biological contexts have been reported by de Lima and Long (2023).

Students also expressed varied views regarding the acceptance and learning of evolutionary theory. Some participants accepted evolution on the basis of scientific evidence, whereas others indicated that their acceptance depended on convincing evidence or was influenced by religious beliefs. Some attempted to reconcile scientific and religious explanations, while others expressed conflict between evolutionary explanations and their religious beliefs. Students also expressed a preference for clear explanations, visual and multimedia resources, real-world examples, scientific evidence, discussion, and interactive learning opportunities. They emphasised that classroom discussion could improve understanding while also expecting scientific teaching to be conducted respectfully and sensitively in relation to differing beliefs.

Taken together, these findings suggest that students entered the intervention with fragmented conceptual frameworks and intuitive explanations that differed from scientific accounts of evolution.

RQ2: Conceptual Understanding of Evolution

Experimental Median	**Control Median**	***U***	***Z***	***p***	***r***
30	13	657.5	−9.29	< .001	.71

Table 2: Mann–Whitney U Test Results for Conceptual Understanding of Evolution

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Objective 2 sought to examine the impact of the multi-strategy instructional intervention on students' conceptual understanding of evolution. To address RQ2 and test Null Hypothesis H_{01}, a Mann–Whitney *U* test was conducted to compare post-test conceptual understanding scores between students in the experimental and control groups. As shown in Table 2, the experimental group obtained a higher median score (Median = 30) than the control group (Median = 13). The analysis revealed a statistically significant difference between the two groups ($U = 657.5$, $Z = -9.29$, $p < .001$), leading to the rejection of Null Hypothesis H_{01}. The effect size was large ($r = .71$), indicating that the multi-strategy instructional intervention had a positive impact on students' conceptual understanding of evolution.

RQ3: Critical Thinking About Evolution

Experimental Median	Control Median	*U*	*Z*	*p*	*r*
32	16	612.5	−9.43	< .001	.72

Table 3: Mann–Whitney U Test Results for Critical Thinking

Objective 3 sought to examine the impact of the multi-strategy instructional intervention on students' critical thinking about evolution. To address RQ3 and test Null Hypothesis H_{02}, a Mann–Whitney *U* test was conducted to compare post-test critical thinking scores between students in the experimental and control groups. As shown in Table 3, the experimental group obtained a higher median score (Median = 32) than the control group (Median = 16). The analysis revealed a statistically significant difference between the two groups ($U = 612.5$, $Z = -9.43$, $p < .001$), leading to the rejection of Null Hypothesis H_{02}. The effect size was large ($r = .72$), indicating that the multi-strategy instructional intervention had a meaningful impact on students' critical thinking about evolution.

Discussion

With respect to RQ1, the pre-intervention interviews revealed that many students entered the study with teleological and essentialist forms of reasoning that influenced their understanding of evolution. Students frequently explained evolutionary changes in terms of need, purpose, or intention and demonstrated misconceptions related to common ancestry and speciation. These findings suggest that students' interpretations of evolutionary explanations may be influenced by pre-existing conceptions and intuitive reasoning patterns that affect how evolutionary concepts are understood and applied (Dunk et al., 2019). These findings are consistent with previous research identifying teleological and essentialist reasoning as major barriers to understanding evolution (Coley & Tanner, 2012; González Galli et al., 2020; Hanisch & Eirdosh, 2020). Such intuitive explanations can hinder students' ability to understand evolution as a population-level process driven by variation, inheritance, and natural selection (Bishop & Anderson, 1990; González Galli et al., 2020). Students were generally more willing to accept observable changes within species than large-scale evolutionary change and frequently explained adaptations in terms of what organisms required for survival. These patterns indicate that students entered the intervention with coherent yet scientifically inaccurate explanatory frameworks that shaped how evolutionary concepts were interpreted and evaluated.

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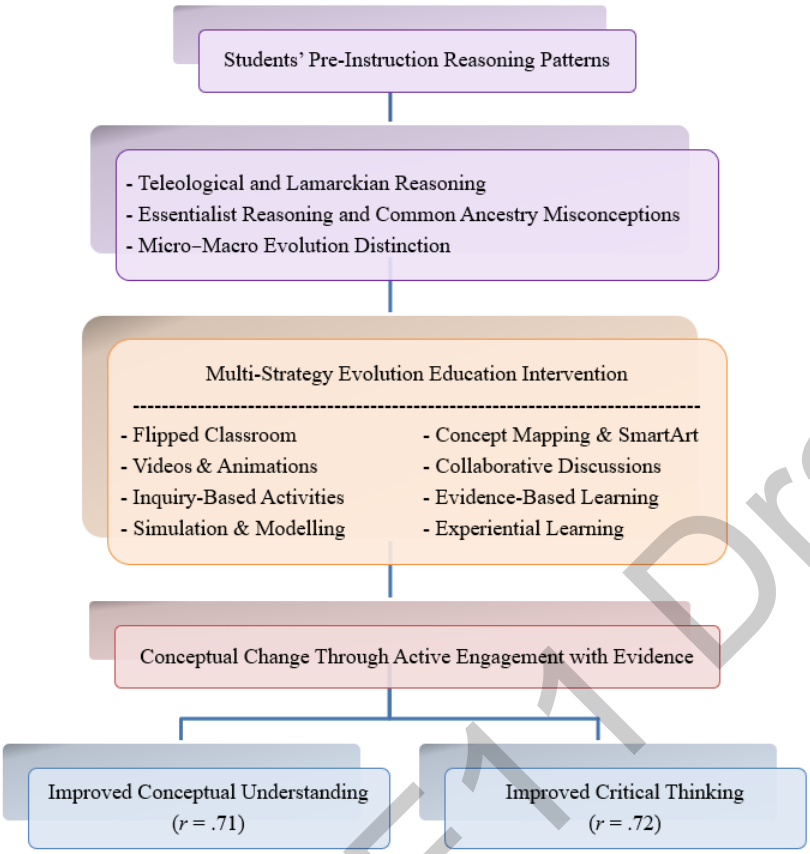

Figure 1: Conceptual Framework Linking Pre-Instruction Reasoning Patterns, Instructional Intervention, Conceptual Change, and Learning Outcomes

The identification of these reasoning patterns was particularly important because they informed targeted refinement of the instructional materials and delivery. Activities such as simulations, concept mapping, collaborative discussions, and evidence-based learning tasks were intentionally selected to challenge need-based explanations, highlight variation within populations, and encourage students to evaluate evolutionary claims using scientific evidence. This alignment between identified reasoning patterns and instructional design reflects a conceptual change approach in which teaching strategies are intentionally selected to challenge existing conceptions and support scientifically accurate explanations. The qualitative findings therefore provided an important foundation for interpreting the quantitative outcomes observed following the intervention.

Regarding RQ2, the substantial improvement in conceptual understanding observed among students in the experimental group suggests that the multi-strategy instructional intervention was effective in addressing these reasoning patterns. The large effect size ($r = .71$) indicates that the intervention produced meaningful educational gains. This finding is consistent with broader evidence indicating that active-learning approaches produce significant improvements in student achievement across STEM disciplines (Balgopal et al., 2025; Freeman et al., 2014). By engaging students through simulations, concept mapping, videos, collaborative discussions, and evidence-based learning activities, the intervention provided opportunities for students to confront misconceptions and construct more scientifically accurate explanations (Balgopal et al., 2025; Peel et al., 2019). These findings support conceptual change perspectives, which emphasise the restructuring of existing conceptions through active engagement with scientific evidence (Demastes et al., 1995). The

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effectiveness of the intervention may be attributed to the complementary nature of the instructional strategies employed. Simulations and modelling activities provided opportunities for students to visualise evolutionary processes that occur over extended periods of time, while concept mapping supported the organisation of relationships among key concepts such as variation, natural selection, adaptation, and common ancestry. Collaborative discussions and evidence-based learning activities encouraged students to compare alternative explanations and justify their ideas using scientific evidence. Together, these experiences may have facilitated the revision of existing conceptions and promoted deeper conceptual understanding.

In relation to RQ3, the intervention also resulted in considerable improvements in students' critical thinking about evolution, with a large effect size (r = .72). Critical thinking requires learners to evaluate evidence, examine alternative explanations, and apply scientific reasoning when interpreting scientific claims. The active-learning strategies incorporated in the intervention encouraged students to analyse evolutionary explanations rather than rely solely on intuitive explanations or authority-based assumptions. This finding is consistent with previous studies reporting positive effects of active-learning approaches on scientific reasoning, conceptual understanding, and the application of evolutionary concepts (Freeman et al., 2014; Peel et al., 2019). The improvement in critical thinking is particularly noteworthy because understanding evolution requires students to evaluate evidence that is often indirect and accumulated across multiple sources. Many of the misconceptions identified during the interviews reflected a reliance on intuitive explanations rather than evidence-based reasoning. By engaging students in analysing evidence, discussing alternative viewpoints, and evaluating scientific explanations, the intervention may have encouraged more reflective and analytical approaches to reasoning about evolutionary phenomena. This finding suggests that evolution education can serve as an important context for fostering broader scientific thinking skills.

Taken together, the qualitative and quantitative findings suggest that addressing teleological and essentialist reasoning through multi-strategy instruction can support both conceptual understanding and critical thinking in evolution education (Refer Fig.1). The findings highlight the importance of instructional approaches that actively engage students in evaluating evidence and reasoning about evolutionary processes rather than simply memorising biological facts. The findings also demonstrate the value of integrating qualitative and quantitative evidence within evolution education research. While the interviews helped identify specific reasoning patterns that hindered learning, the quantitative results provided evidence that instructional strategies designed to address these patterns can produce meaningful learning gains.

4. Conclusion

This study examined the impact of a multi-strategy instructional intervention on junior college students' conceptual understanding of evolution and critical thinking. Pre-intervention interviews revealed teleological and Lamarckian reasoning, essentialist reasoning and common ancestry misconceptions, and difficulties distinguishing between microevolution and macroevolution. Quantitative findings demonstrated significantly higher conceptual understanding and critical thinking among students who participated in the intervention compared with those who received conventional instruction. The large effect sizes indicate that the intervention produced notable

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improvements in students' understanding and reasoning about evolution. The findings suggest that instructional approaches designed to challenge intuitive reasoning patterns and foster evidence-based reasoning can enhance students' understanding of evolution and their ability to think critically about evolutionary concepts. The study highlights the importance of identifying students' pre-existing reasoning patterns for refining instructional interventions that promote conceptual change and scientific reasoning. Future research may further examine how instructional interventions facilitate conceptual change in evolution education. Longitudinal studies could also examine whether improvements in conceptual understanding and critical thinking are sustained over time.

5. Declarations

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Ethics Approval

The study was conducted with permission from the authorities of the participating educational institutions. Informed consent was obtained from all participants and from their parents or guardians prior to data collection. Participation was voluntary, and participants were informed of their right to withdraw from the study at any stage. Confidentiality and anonymity were maintained throughout the research process. Formal institutional ethics committee approval was not required for this study.

Responsible Use of AI

Artificial intelligence (AI) tools were used to support language refinement, grammar checking, and improvement of manuscript clarity. All study design decisions, data collection, data analysis, interpretation of findings, and final content were undertaken and verified by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

Author 1 conceptualised the study, designed the instructional intervention, collected and analysed the data, and prepared the manuscript. Author 2 supervised the research, contributed to the study design, reviewed the analyses, and critically revised the manuscript. All authors read and approved the final manuscript.

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