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Enhancing biology conceptual understanding through guided inquiry laboratory activities

Ashebir Mekonnen Chengere[1], Beyene Dobo Bono[1], Samuel Assefa Zinabu[2], Kedir Woliy Jillo[1]
[1]Department of Biology, College of Natural and Computational Science, University of Hawassa, Hawassa, Ethiopia
[2]School of Education, College of Education, University of Hawassa, Hawassa, Ethiopia

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ABSTRACT

The study investigated the impact of guided inquiry-based laboratory experiments enriched instructional (GIBLEI) approach on conceptual understanding of tenth grade students in biology. The study included two purposively chosen schools and used a quasi-experimental design with non-equivalent groups. A class was randomly assigned as the experimental group (EG) and the other as the control group (CG). Over an eight-week period, the EG received instruction through the GIBLEI approach, while the CG followed traditional laboratory experiments. Statistical analyses, including Welch's t-test and analysis of covariance (ANCOVA), showed a significant improvement in post-test scores for the EG, demonstrating the effectiveness of GIBLEI. Furthermore, the Wilcoxon signed-rank test indicated a notable increase in understanding between the pre-test and post-test in the EG. The results of an independent samples t-test also showed no significant difference in performance between male and female students in the EG. This suggests that the instructional approach used in the study is equally effective for both genders, promoting an inclusive learning environment. These findings suggest that GIBLEI can significantly improve students' understanding of biology concepts. Therefore, incorporating this approach into biology curricula may help enhance overall learning outcomes.

Corresponding Author:

Ashebir Mekonnen Chengere
Department of Biology, College of Natural and Computational Science, University of Hawassa
Hawassa, Ethiopia
Email: ashum2009@gmail.com

1. INTRODUCTION

Many countries place a strong emphasis on science and technology education due to its crucial role in driving economic growth [1]. In Ethiopia, the Ministry of Education actively promotes higher enrollment in natural sciences and science-related disciplines over social sciences and humanities at the university level [2]. This policy is based on the assumption that prioritizing science and technology enhances national productivity [3]. However, despite these efforts, national assessments indicate that Ethiopian secondary school students struggle to grasp fundamental science concepts [4]. The results of these assessments show that a significant number of students fail to attain the minimum competency levels established by the Education Ministry [5]. Contributing to this issue are challenges such as limited access to laboratory facilities and textbooks, particularly in rural areas, which further impede students' academic performance in science subjects [6].

Students' academic achievement reflects their level of conceptual understanding, which in turn depends on how science is taught [7]. This implies that learners' academic achievement reflects the quality of teaching [8]. Begna [6] noted the prevalence of traditional teaching methods in Ethiopian science classes and emphasized the need for approaches that promote active engagement and conceptual understanding. The traditional methods may contribute to the observed decline in academic performance in science fields, including biology [1]. Additionally, Almasri [9] discussed the impact of gender on learning and academic achievement, suggesting that addressing gender disparities in science education is crucial for improving overall performance in science subjects. As a result, effective science teaching requires instructional approaches that not only improve pupils' comprehension of scientific ideas but also enable them to apply their knowledge to real-life situations [7].

Laboratory experiments play crucial roles in science education [10]. These include improving laboratory skills, expanding scientific knowledge, and helping students better understand scientific concepts and theories [11]. Laboratory experiments are more effective when implemented as an active learning strategy, as they promote student engagement and participation in the learning process [11]. For instance, guided inquiry-based laboratory instruction promotes active student participation in their own learning [12]. Unlike traditional laboratory setups with predetermined procedures [13], guided inquiry empowers students to independently form hypotheses, design experiments, and draw conclusions, with guidance from the teacher. This aligns with constructivist learning principles [14]. Guided inquiry-based lab instruction offers several advantages over traditional methods. For example, it promotes deeper conceptual understanding through hands-on activities. Additionally, it fosters the growth of higher-order thinking abilities that are essential for scientific research, like analysis, synthesis, and evaluation [15]. Moreover, it boosts student motivation and engagement by giving them ownership of their learning process, encouraging autonomy and responsibility [16]. In contrast, traditional laboratory experiments often limit independent thinking since they outline specific procedures, questions, and expected outcomes. As a result, students typically focus more on following steps rather than fully understanding the concepts behind them [17]. Traditional labs primarily develop basic hands-on and inquiry skills but do not cultivate advanced inquiry abilities [18]. To address these issues, properly implemented guided inquiry-based laboratory experiments, with a balanced approach to student autonomy and teacher guidance, are recommended [19].

Despite an increasing amount of research on laboratory instructions based on guided inquiry in secondary school biology education, several research gaps remain to be addressed. Previous studies by Nurrita [20], Berhanu and sheferaw [21] have provided valuable insights into the effectiveness of guided inquiry approaches in enhancing students' science learning outcomes. However, these studies have primarily focused on general trends and have not sufficiently examined the specific instructional strategies and techniques employed within guided inquiry-based laboratory instructions. Previous research, such as Huang's [22] study, has investigated how inquiry-based learning affects students' attitudes toward science and their ability to solve problems. However, there is limited empirical evidence on how guided inquiry-based laboratory instruction specifically influences these factors in biology education. Additionally, most studies on guided inquiry-based approaches have been conducted in high-income countries, leaving a gap in understanding their effectiveness and implementation in resource-limited settings like Ethiopia. This lack of research limits the generalizability of findings to diverse educational contexts with distinct challenges. Thus, the purpose of this study was to compare how well students' conceptual understanding of biology was improved by the guided inquiry-based laboratory experiments enriched instructional (GIBLEI) approach versus the traditional laboratory experiments enriched instructional (TLEI) approach. The following null hypotheses (H_0) were developed and examined at the 0.05 level of significance in order to direct the investigation.

$H_{0\ 1}$: students who were taught using the GIBLEI approach and those who were taught using the TLEI approach did not differ statistically significantly in their post-test mean scores for biology conceptual understanding (BCU).

$H_{0\ 2}$: the mean BCU scores of the students in each group before and after the test do not differ statistically significantly.

$H_{0\ 3}$: within each instructional group, there is no statistically significant difference between male and female students' post-test mean scores for BCU.

2. METHOD

2.1. Research design

A non-equivalent pretest-posttest control group (CG) quasi-experimental design was used in this study, since it is difficult to assign students at random in educational settings [23]. In schools, students are pre-assigned to classes at the start of each academic year by school administrators, making true randomization unfeasible [24]. Participants are assigned to treatment groups in a quasi-experimental design without applying randomization [25]. As noted by Heiman [26], non-equivalent groups indicate that participant characteristics may not be evenly distributed between the experimental group (EG) and CG, potentially leading to variations in their experiences during the study. Given these constraints, this research design was selected as the most appropriate approach for this study shown in Table 1.

Table 1. Research design for the study

Groups	Pretest	Type of intervention	Posttest
EG	t_1	GIBLEI	t_2
CG	t_1	TLEI	t_2

Note: t_1=test before interventions; t_2=test after interventions; GIBLEI for EG; TLEI for CG.

2.2. Sample and sampling method

A multistage sampling method was employed in this investigation. In the first stage, two public secondary schools (Fitche and Abdisa Aga secondary schools) were selected using purposive sampling method from Fitche Town, North Shoa Zone, Ethiopia. Although difference between groups naturally exists in non-equivalent quasi experimental research design [23], the researchers attempted to choose similar groups as much as possible. In addition, to minimize the school effects on the study results, the researchers selected two schools whose infrastructure and staff profiles were comparable. The schools were considered to share similar characteristics. The chosen schools were divided into EG and CG at random in the second phase. The EG was Fitche Secondary School, and the CG was Abdisa Aga Secondary School. Next, two highly qualified and experienced biology teachers, one from each school, were purposively selected to ensure effective instruction in the study. Then, two classes were selected from the schools randomly (a class per school). Finally, the sections were assigned to EG (Fitche secondary school) and CG (Abdisa Aga secondary school) randomly. The EG was with 46 students (M=22, F=24), while CG had 29 students (M=13, F=16). In this study, a total of 75 grade 10 students (35 boys and 40 girls) participated. Additionally, the study focused on the topic "food making and growth in plants", which is part of unit four in the grade 10 biology curriculum. The unit consists of contents like organs of a flowering plant, the leaf, photosynthesis, transport and response in plants respectively. This topic was purposively selected since it has areas of misconceptions for many students. For example, the concept of plants as soil-eaters [27], a common misconception that plants need only carbon dioxide and students' misconception about respiration and photosynthesis in plants [28].

2.3. Data collection instrument

The biology conceptual understanding test (BCUT) was the main tool used in this study to collect data. The test was developed it to evaluate secondary school students' understanding of food making and growth in plants after a thorough review of relevant literature. The BCUT was designed as a diagnostic two-tiered test (TTT), with both tiers presented in the form of multiple-choice questions. The first tier focused on content-based responses, while the second tier assessed students' reasoning behind their answers. To ensure balanced coverage of key concepts, a table of specifications was created, ensuring an equitable distribution of propositional knowledge related to the topic. The test included 28 two-tiered questions, with a score of 0 as the minimum and 28 as the maximum, in accordance with the number of competencies outlined in the grade 10 biology syllabus. Each question was carefully aligned with the specific competencies to ensure comprehensive assessment.

There are various methods used to evaluate items on a TTT. For instance, Treagust [29] asserted that a response to a two‑ tier item is considered correct only when the respondent answers both tiers accurately. Similarly, Tarak *et al.* [30] suggested that students who provide correct answers in both tiers are generally deemed proficient in the subject matter. In this study, high school students were evaluated based on their factual understanding of biology concepts through the first tier, while their reasoning was evaluated using the second tier. Additionally, a two-tier question was considered correct only if both components were answered correctly. When calculating the BCUT scores, correct responses in both tiers were assigned a score of 1, while incorrect responses in either tier received a score of 0 shown in Table 2.

Table 2. Techniques of analyzing the TTT questions in the biology concepts

Tier 1	Tier 2	Scores
Incorrect response	No explanation	0
Incorrect response	Incorrect reasoning	0
Correct response	Correct reasoning	1
Correct response	Incorrect reasoning	0
Correct response	No explanation	0

2.3.1. Validity of the BCUT

The degree to which an instrument accurately measures what it is supposed to measure is referred to as its validity. In this study, content and face validity were used to ensure the assessment tool's effectiveness. Content validity checks if the instrument comprehensively covers the subject it aims to assess, often verified by expert reviews [31]. In this case, PhD candidates and experienced biology teachers reviewed the test items to ensure they aligned with biology curriculum competencies. Face validity ensures the test appears appropriate to those taking it, based on perception rather than detailed analysis. The reviewers also confirmed the relevance and clarity of the items. This process strengthened both the content and face validities of the BCUT, ensuring it measured the intended biological concepts accurately.

2.3.2. Reliability of the tool

Reliability in research ensures the consistency of a measurement tool over time [32]. In this study, internal consistency reliability was used to evaluate the consistency and dependability of the BCUT. The Kuder-Richardson formula 20 was utilized for tests with dichotomous items, providing an internal consistency coefficient of 0.706 from a pilot study involving 69 students. This value indicates acceptable reliability, meaning the BCUT consistently measured students' understanding of biology concepts. By ensuring high reliability, the test results can be trusted to draw accurate conclusions about students' conceptual knowledge, confirming the tool's validity and dependability for further educational assessments.

2.4. Treatment procedure

At the beginning, training was given to the teacher and laboratory technician from the EG using the instructional and training materials prepared by the researchers. The training included a detailed description of the GIBLEI procedure. It also included how teachers prepare daily lesson plans using the engagement, exploration, explanation, extension, and evaluation (5E) lesson plan format. The researchers conducted a three-day training, which lasted 90 minutes each day. On the first day, 90 minutes were allocated for explaining the materials, while the subsequent days were devoted to practical, hands-on activities conducted in the actual classroom environment. Moreover, orientation was given on the aim of the research to the teacher and laboratory technician from the CG. The CG teacher used the students' biology textbooks and the school lesson plan format for the TLEI. Then, before the intervention pretest was given. The BCUT was administered to the two groups. After completing all the preliminary activities, intervention was started. Both groups taught the same topics (food making and growth in plants grade 10, unit 4) shown in Table 3. The following general steps were used for all GIBLEI approaches. The steps were adapted from Blanchard [33]. The selected and trained biology teacher guided all the steps. In general, the following steps were used for each lesson topics.

a. Problem introduction: one week before each lesson, students were given semi-structured problems from the grade 10 biology curriculum. Students worked in groups to address a new question every week.
b. Search for experimental design: students researched possible experimental methods to solve the problem and began designing their experiments for the upcoming lab practice.
c. Finalizing the experimental design: each group developed and finalized its experimental design based on their research findings.
d. Group discussions: each group presented their experimental design to the class, outlining the steps involved, the materials selected, and the rationale behind their choices.
e. Conducting experiments: the teacher and laboratory technician provided the necessary materials, and students conducted experiments based on their designs.
f. Observations and notes: students recorded their observations during the experiments to draw conclusions.
g. Class presentation: students presented their findings, linking their experimental data to theoretical concepts.
h. Classroom discussions: the class discussed the conclusions, with groups answering questions related to their experiments.
i. Assessment: following each experiment, evaluations were carried out to assess students' comprehension of the theoretical concepts and scientific principles covered in the lesson.

Table 3. Summary of the intervention procedure

Topic	Group	Pretest	Training	Trainees	Treatment	Post-test
Food making and plant growth	EG	Yes	Yes	Teachers	Yes	Yes
Food making and plant growth	CG	Yes	No	No	No	Yes

The teacher used the 5E instructional model, which consists of the phases engage, explore, explain, elaborate, and evaluate, to organize all of the lessons for the EG. Guided inquiry-based lab activities were incorporated into the exploration phase. The CG received traditional instruction with lectures and teacher demonstrations, where students were mostly passive observers. The intervention followed the schools' normal class schedule, lasting eight weeks in the second semester of 2023, covering a unit requiring 24 periods. Researchers held weekly meetings with teachers to guide lesson preparation and implementation. Classroom observations and checklists were used to ensure the GIBLEI approach was consistently applied. As participant observers, researchers took notes and interacted with students to discuss their learning. Both groups received a post-test following the intervention.

2.5. Analysis of data

The data that was gathered was analyzed using SPSS 22 software, with a focus on determining whether the data met the assumptions for parametric or non-parametric tests. For data to be considered parametric, it must meet several criteria: it should follow a normal distribution, exhibit homogeneity of variance, be obtained through random sampling, comprise independent scores for the dependent variable, with a minimum of one recorded measurement [34]. Normality was evaluated utilizing the values of skewness and kurtosis, where a range of -2 to +2 signified a normally distributed dataset [35]. Most of the data indicated normal distribution, and the homogeneity tests showed that pretest results for BCUT between the EG and CG exhibited equal variances ($p>0.05$). Similarly, posttest results among male and female students in both groups demonstrated equal variances ($p>0.05$). However, the homogeneity test for post-test results between EG and CG revealed unequal variances ($p<0.05$), necessitating careful selection of statistical tests shown in Table 4.

For scores that were normally distributed and had equal variance, parametric tests were utilized due to the types of data; for scores that did not meet these assumptions, non-parametric tests were utilized. Given the breach of the homogeneity of variances assumption, a Welch's t-test (unequal variance t-test) was used to evaluate the variations in post-test mean scores between EG and CG. In these circumstances, Welch's t-test is better than the independent t-test and Mann-Whitney u-test [36]. The post-test mean scores of male and female students in the EG and CG were compared using an independent samples t-test to see if there were any notable differences. Furthermore, for CG, the mean scores of the pre- and post-tests were compared using the paired samples t-test, while for EG, the Wilcoxon signed-rank test was employed because of the non-parametric data (as established by the Shapiro-Wilk and Kolmogorov-Smirnov normality tests). Pre-test results were used as a covariate to account for initial group disparities, lower error variance, and remove systemic bias before analysis of covariance (ANCOVA) was utilized to determine treatment differences in post-test mean scores between EG and CG [37]. Furthermore, the effect size, which indicates the size of the differences observed, was measured using Cohen's d [38].

Table 4. Normality and homogeneity tests of BCUT

Tests	Dependent variables	Groups	Normality test		Homogeneity test Levene's test			
			Skewness	Kurtosis	F	df1	df2	p-value
Pre-tests	BCU	EG	.61	-.32	3.11	1	73	.082
		CG	.24	-.95				
Post-tests		EG	.52	-1.17	43.94	1	73	.000
	BCU	CG	.81	1.21				
		Male (EG)	.23	-1.60	1.85	1	44	.180
		Female (EG)	.83	-.46				
		Male (CG)	1.10	1.56	.117	1	27	.735
		Female (CG)	.15	-1.39				

3. RESULTS

3.1. Equivalence at pre-test level

The EG recorded a pre-test mean BCU score of 1.84 with a standard deviation of 1.42. The CG had a mean score of 1.37 with a standard deviation of 1.01. An independent samples t-test was conducted to compare the mean scores between the two groups, yielding a t-value of 1.53 and a p-value of 0.12. Since the p-value was greater than the commonly used significance level of 0.05, the difference in pre-test scores between the groups was not statistically significant shown in Table 5.

Table 5. Comparison of BCU pretest mean scores between groups

Study groups	N	Mean	St. d	df	t	p
EG	46	1.84	1.42	73	1.53	.12
CG	29	1.37	1.01			

3.2. Effectiveness of GIBLEI

The effectiveness of the GIBLEI approach was assessed by comparing the post-test mean scores of BCU between the EG and CG using Welch's t-test, see Table 6 for the details. The findings showed a large effect size (η^2=0.85) and a significant difference in favor of the EG (t=4.73, p<0.05). Additionally, ANCOVA confirmed that this difference was attributable to the treatment (F=12.59, p<0.05), leading to the rejection of the null hypothesis ($H_{0\ 1}$) shown in Table 7.

Table 6. Comparison of BCU Posttest mean Scores between Groups

Study groups	N	Mean	St. d	Se	t	p	η^2
EG	46	7.43	5.82	.859	4.73	.000	.85
CG	29	3.00	2.02	.374			

Table 7. ANCOVA for the post-test results of the EG

Test	df	Mean square	F	p
Post-test	1	291.06	12.59	.001

3.3. Changes from pretest to posttest

To analyze changes in BCU results from each group's pre-test and post-test, the average scores were compared separately for the EG and CG. The EG was tested using a Wilcoxon signed-rank test, and the CG was tested using a paired samples t-test, see Tables 8 and 9. Results revealed statistically significant differences in both groups, indicating improvement in BCU scores from pretest to posttest (EG: z=-5.27, p<0.05; CG: t=-3.8, p<0.05). Consequently, the second null hypothesis ($H_{0\ 1}$) was disproved.

Table 8. BCU pretest and posttest mean scores comparison in the EG

Test type	N	M. rank	S. ranks	z	p
Neg. Ranks	2	9.00	18.00	-5.27	.000
Poz. Ranks	38	21.11	802.00		
Equal	6				
Total	46				

Table 9. BCU pretest and posttest mean scores comparison in the CG

Test type	N	Mean score	St. d	df	t	p
Pre-test	29	1.3	1.0	28	-3.8	.001
Post-test	29	3.0	2.0			

3.4. Gender differences

An independent samples t-test was conducted to compare the BCU post-test mean scores of male and female students in both the EG and the CG. In the EG, male students had a mean score of 8.86 (SD=6.08), while female students had a mean of 6.12 (SD=5.38); the t-value was 1.62 with a p-value of 0.112. In the CG, males scored 3.77 (SD=2.16) and females 2.38 (SD=1.70), resulting in a t-value of 1.94 and a p-value of 0.063. Both p-values were above the standard significance threshold of 0.05, indicating no statistically significant differences between genders in either group. Therefore, the findings support the acceptance of null hypothesis three ($H_{0\ 3}$), which states that gender does not significantly influence BCU post-test scores shown in Table 10 for details.

Table 10. Comparison of male and female students BCU post-test mean scores in the EG and CG

Study group	Gender	N	Mean score	St. d	df	t	p-value
EG	M	22	8.86	6.08	44	1.62	.112
	F	24	6.12	5.38			
CG	M	13	3.77	2.16	27	1.94	.63
	F	16	2.38	1.70			

4. DISCUSSION

The findings of this study show that the GIBLEI approach led to improved student performance. The EG, which was taught using the GIBLEI method, scored significantly higher than the CG, which was taught the same content using the TLEI approach. A notable difference in mean scores was observed in terms of conceptual understanding between the EG and CG. The eta squared value (η^2=0.85) suggests a large effect size, meaning the treatment had a substantial impact on the dependent variable [38]. This indicates that about 85% of the observed variance between the two groups' BCU mean scores can be attributed to the GIBLEI approach. Additionally, the ANCOVA results confirm that the difference in mean scores was specifically due to the treatment, rather than being influenced by other factors. In addition, the analysis revealed a significant difference between the EG and CG pre- and post-test scores, despite the fact that the two groups' mean score differences were also significant.

The GIBLEI approach enhances student performance by promoting active engagement through hands-on experiments, problem-solving, and group collaboration. It connects biology concepts to real-world problems, encouraging inquiry-based learning and practical application of theoretical knowledge. Supported by trained teachers, GIBLEI empowers students with autonomy, curiosity, and motivation. Continuous assessment and feedback ensure personalized instruction, fostering deep understanding, critical thinking, and scientific inquiry. Unlike traditional "cookbook" experiments, GIBLEI enables a better grasp of the relationship between scientific facts and concepts. The results of the study are consistent with earlier research, confirming GIBLEI's effectiveness in biology education. For instance, according to Uzezi and Zainab [39] the guided inquiry laboratory experiments affected the academic achievements of students in volumetric analysis than the traditional laboratory method. Similarly, Hofstein *et al.* [40], verified that students' meaningful learning, conceptual understanding, and understanding of the nature of science are all improved by guided inquiry laboratory experiments.

The study found that the GIBLEI approach improved biology conceptual understanding for both boys and girls, with no significant gender differences in academic achievement. This highlights the effectiveness of student-centered, activity-based methods in promoting equitable education. Gender disparities in academic performance are influenced by societal norms, teaching methods, and resource access. To promote gender equity and equal academic opportunities, it is crucial to create supportive learning environments, implement fair policies, and reduce biases in teaching and assessment, eventually contributing to the reduction of the gender gap in education. The findings of this study align with those of El-Rabadi [41] , whose research showed that both boys and girls are equally impacted by the laboratory teaching approach. The results of this investigation align with the research conducted by Uzezi and Zainab [39], who asserted that students' academic performance is not influenced by their gender. Conversely, Eze [42] argued that gender does have a significant impact on academic performance, with male students outperforming female students. In contrast, Aniodoh and Egbo [43] found that when the inquiry role instructional model was used, female students outperformed male students. On the other hand, Owoyemi [44] confirmed that there is no relationship between students' achievement and gender. The results of the current study also demonstrate that male and female students' performance in biology did not differ significantly, suggesting that the method worked just as well for both genders.

The study's limitations include resource variability and teacher-related factors, which may have influenced the results, and the natural school setting may affect generalizability. To improve future research validity, strategies such as standardizing resources, enhancing teacher training, conducting randomized trials, and expanding to urban and rural schools are recommended. These measures will strengthen research, address contextual learning factors, and adapt interventions to improve biology and science education outcomes.

5. CONCLUSION

The study highlights how effective the GIBLEI approach in enhancing students' conceptual understanding of biology, especially in areas such as photosynthesis and plant growth. GIBLEI fosters active student participation in experiments, which boosts self-confidence and enhances comprehension beyond traditional methods. Importantly, the approach benefits both male and female students equally, making it a gender-neutral method for teaching biology.

The study recommends that secondary school teachers adopt GIBLEI in biology classes, provide training for teachers and lab technicians, and incorporate it into curriculum design and materials. It also calls for a content analysis of Ethiopian secondary school biology textbooks to refine practical activities and improve learning outcomes. Beyond conceptual understanding, GIBLEI supports student engagement, motivation, critical thinking, problem solving, and long-term knowledge retention. It also aligns with broader educational goals like science, technology, engineering, and mathematics (STEM) promotion, equity, 21st-century skills development, and career readiness. However, successful implementation of GIBLEI in Ethiopia requires addressing challenges such as resource limitations, curriculum structures, teacher development, and policy support to fully realize its potential for advancing science education and improving student outcomes.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ashebir Mekonnen Chengere	✓	✓	✓		✓	✓		✓	✓	✓	✓			
Beyene Dobo Bono	✓			✓						✓	✓	✓	✓	
Samuel Assefa Zinabu		✓		✓						✓	✓	✓		✓
Kedir Woliy Jillo		✓		✓			✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The writers affirm that they have nothing to disclose.

ETHICAL APPROVAL

The research review ethics committee at University of Hawassa approved this study, under reference number CNCS-REC029/22. Furthermore, every participant provided written consent for the research.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AMC], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Ashebir Mekonnen Chengere obtained his bachelor's degree (B.Sc.) and master's degree (M.Sc.) in biology and environmental science with a zoology focus from Addis Ababa University, Ethiopia, in 2004 and 2009, respectively. He has 15 years of teaching experience and has held leadership roles at Fitche College of Teachers Education. Currently, he is pursuing a PhD in biology education at University of Hawassa and teaches at Fitche College. His research focuses on practical activities, inquiry-based learning, indigenous knowledge, 21st-century skills, and ICT in education. He can be contacted at email: ashum2009@gmail.com.

Beyene Dobo Bono from Hossana in Ethiopia's Hadiya Zone, holds a PhD in Soil Science with a specialization in soil microbiology from Haramaya University. He earned his B.Sc. and M.Sc. in biology/microbiology from Mechnikov State University in Ukraine and has over 19 years of experience in teaching and academic leadership. Currently, he is an associate professor of microbiology at University of Hawassa, where he has served for six years. He has mentored over 50 MSc and PhD students and published more than 28 research articles. His research focuses on microbiology and biology education. He can be contacted at email: beyeneashl@yahoo.co.uk.

Samuel Assefa Zinabu is an esteemed academic leader and educator at University of Hawassa, Ethiopia. He holds a B.Sc. in physics and advanced degrees (M.A. and PhD) in curriculum and instruction. He has mentored numerous M.A. and PhD students and has published over six articles in reputable journals. His research interests include content analysis of curricular materials, active learning methods, and continuous professional development strategies. He can be contacted at email: samuelassefa@hu.edu.et.

Kedir Woliy Jillo born on April 22, 1976, in Dodola, Ethiopia, holds a diploma in biology from Kotebe College of Teacher Education (1997), a BSc in biology from Addis Ababa University (2003), an MSc in molecular biology and biotechnology from India (2007), and a PhD in microbiology from Norway (2019). He has been teaching at University of Hawassa since 2003, currently serving as an assistant professor of microbiology. His teaching areas include molecular biology, cell biology, biotechnology, and environmental microbiology. He has also held leadership roles such as department head and associate dean, contributed to curriculum development, and published over six research articles. His research focuses on molecular biology, biotechnology, and biology education. He can be contacted at email: kedirwoliy@gmail.com or kedirw@hu.edu.et.