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An Investigation into the Effect of Concept Mapping on Students' Learning Outcomes in Photosynthesis at the Senior High School Level

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Abstract

This study investigated the effect of concept mapping on senior high school students' learning outcomes in photosynthesis in the Tolon District of Ghana. A quasi-experimental non-equivalent group design was employed, involving 80 Form 3 Biology students selected through simple random sampling. Students were assigned to experimental and control groups and taught using concept mapping and conventional methods, respectively. The results showed no statistically significant difference between the experimental and control groups in students' knowledge and understanding of photosynthesis ($t(78) = .38$, $p = .702$). For application of knowledge, the control group performed significantly better than the experimental group ($t(78) = -2.23$, $p = .029$). However, the experimental group demonstrated significantly higher practical skills in photosynthesis ($t(78) = 4.42$, $p < .001$). No significant gender differences were found across the measured outcomes. The findings suggest that concept mapping does not significantly enhance students' conceptual knowledge or application of knowledge within a short

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instructional period but is effective in improving practical skills. It is therefore recommended that concept mapping be integrated into biology instruction primarily to strengthen students' practical and process-oriented learning outcomes in photosynthesis.

Keywords: Concept Mapping, photosynthesis, students' learning outcomes, quasi-experimental non-equivalent group design, practical skills

Introduction

Teaching biology at the senior high school level is crucial for enhancing scientific literacy and understanding of ecological systems (Jančaříková & Jančařík, 2022; Bally et al., 2023). In contrast, teaching methods often rely on teacher-centered, rote learning that prevents authentic engagement (Mekonen & Kelkay, 2023). One example of this challenge is the integration and use of abstract, multi-level concepts across disciplines, as requested by topics such as photosynthesis (Aguiar et al. 2018; Jančaříková & Jančařík 2022). As a result, students often form fragmented knowledge organization and long-lasting misconceptions which restrict their applications of biology concepts in the world (Anderson et al., 1990; Messig & Groß, 2018; Tanner & Allen, 2005).

Concept mapping has been established as one such effective constructivist instructional strategy that can deal with such challenges. Concept maps are based on cognitive and metacognitive learning theories in which learners actively discuss, organise, and articulate relationships between concepts that encourage them to develop coherent and meaningful understanding that can be adapted across contexts (Kinchin, 2013). Concept maps have been shown to improve students' understanding of science concepts (Carr-Lopez et al., 2014), foster complex thinking processes, and help integrate knowledge across content areas (Schwendimann, 2011) so they are increasingly being used as both teaching and assessment tools in science. Its cross-cutting nature across biological fields and concordance with fundamental scientific proficiencies render it a potent instrument for the enhancement of Biology education outcomes.

Even though concept mapping has many documented beneficial effects, its use in Biology education in Ghana is still sparse. Reports from national examining bodies in Ghana underscore a persistent challenge regarding student achievement in biology (WAEC, 2021; WAEC, 2024); this is often linked to the observation that pedagogical practices remain largely didactic and oriented toward standardized testing (Amoah et al., 2023; Adofo et al., 2024). Biology achievement, especially with regard to photosynthesis, has been on the decline in the Tolon District of Ghana's Northern Region and

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this poor performance raises concern that students will struggle academically as well as gain admission into science-related careers.

This problem is compounded by ongoing gender disparities in STEM fields of study. Sociocultural customary practices, instructional approaches and learning styles still shape the achievement differences between boys and girls at school. Although previous studies indicate that taking a learner-centered approach, for example, through the use of concept mapping, may provide more equitable opportunities for all learners to succeed, thereby closing the gender gap in Biology learning outcomes, this has generated inconclusive empirical studies examining their efficacy on female student performance compared to male students, particularly across sub-Saharan African countries.

To fill the gap, this study examines the effects of concept mapping on students' performance in photosynthesis among Senior High School students in Tolon District of Ghana. The present study is novel in its focus on a specific local context, retention of knowledge with balanced emphasis on challenging topic conceptually under Biology curriculum, and addressing aspect considerations for performance across diverse domains of learning while taking gender differences explicitly into account. The study, then, aims to generate context-bound evidence that will inform instructional practice in ways that promote equitable learning and help advance the other strides made around meaningful and effective Biology education.

Methods

The present study used a quantitative research approach based on the positivist philosophical paradigm. This study was, therefore, deemed appropriate for a positivist orientation as it examines specific and measurable learning outcomes associated with two alternate instructional approaches in the comparison of student performance (Bajpai, 2011; Žukauskas et al., 2018). The theoretical discussions that support the study were simplified, focusing only on the methodological procedures and the context in which instruction occurred.

The study was conducted through the quasi-experimental non-equivalent group design to evaluate the impact of concept mapping on students' achievement in learning photosynthesis. The most appropriate design was clearly the quasi-experimental one because it is composed only of naturalistic data from the normal school setting, which did not allow random assignment of individual students as they were embedded in preexisting classrooms (Cook & Campbell, 1979; Creswell, 2009). Thus, intact classes rather than individual students were randomly assigned to experimental and control groups. Intact classes were used to maintain a regular instructional environment while allowing comparison of the two teaching approaches.

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The participants in this study were both intact Form 3 Biology classes at Tolon Senior High School, located in the Northern Region of Ghana. In this study, Group A (G/S 3A) was the experimental group and received instruction using concept mapping strategies while Group B (G/S 3B) served as the control group and received conventional lecture method of instruction. The two groups were both taught by the regular Biology teachers in the school to reduce teacher-related bias.

This intervention covered photosynthesis and was completed over a three-day teaching period (around two hours total lead time) [The instructional intervention targeted the topic of photosynthesis and was implemented across three instructional sessions, totaling approximately 120 minutes of cumulative contact time."]. Students in the experimental group were instructed to use concept mapping techniques—identify key concepts, organize relationships among concepts, and construct concept maps that can represent biological processes such as photosynthesis. Students were facilitated through classroom discussions and linkages to topics designed with meaningful learning in mind within the framework of active engagement on the subject. In comparison, the control group was taught through the traditional lecture-based method that included explanation, note-taking, and teacher-led discussions. On day four, a post-test measuring students' knowledge and understanding of the learning objectives for that material (knowledge application/practical skills) in photosynthesis was administered.

Population and Sampling

The target population was Form 3 Biology students of Tolon Senior High School in the Northern Region of Ghana. It is a public secondary school with approximately 2,343 pupils. The accessible population was students taking elective Biology in 6 Form 3 classes. Then purposive sampling was done by selecting two classes (G/S 3A and G/S 3B) with similar academic profiles and availability. Simple random sampling was then used to choose participants from within each class to ensure that representation was as fair as possible. Sample sizes were determined based on Krejcie and Morgan's (1970) formula for finite populations; for just greater than 100, n = 80 was enough. We randomly assigned 43 students to the experimental group and 37 students to the control group.

Data Collection Instruments

This research was based on the Biology Achievement Test (BAT), which became the main instrument analyzing students' learning outcomes. The BAT contained 19 open-ended items that were analysed based on both the West African Senior School Certificate Examination (WASSCE) and the national Senior High School Biology curriculum in Ghana. It was created to

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test relevant to 3 cognitive domains—Knowledge and Understanding; Application of Knowledge; Practical Skills (relating to photosynthesis). To minimize marker bias and provide an objective, empirically measurable quantification of levels of achievement using pre-set criteria (Creswell, 2009), all items were scored with established rubrics.

Instrument Validation and Reliability

In addition, an instrument pilot was conducted for clarity, difficulty, and curriculum consistency with Form 3 science students of another school in the same district. This iteration resulted in some minor changes with regard to item formatting and scoring guidelines based on the feedback received during this pilot. Cronbach's alpha indicated a coefficient of .81 in the internal consistency of the Biology Achievement Test (BAT). Moreover, expert review of both instruments used in this study by 2 experienced senior Biology teachers and 1 university lecturer confirmed the topical relevance and compliance with national curriculum standards of these 2 instruments.

Data Collection Procedure

Each of the research samples then pioneered an initial by-group pre-sampling phase in order to establish that both groups could then be equivalently tested at pre-test. An independent samples t-test conducted prior to intervention confirmed that groups were equivalent on their ED values ($p > .05$). This instructional treatment used the same instrument that offered a post-test. With these scores, the impact of concept mapping was measured on three core domains in performance: Knowledge and Understanding; Application of Knowledge; and Practical Skills.

Data Analysis Plan

Quantitative analysis was performed using IBM SPSS (Version 25). For summary of demographic trends and performance distributions, we utilized descriptive statistics (means and standard deviations). Inferential statistics: To test for a difference in intervention effectiveness between conditions, independent samples t-tests were calculated to compare mean scores obtained by the experimental group and the control group for each of the five questionnaires described above. Data were screened before analysis for violations of the underlying assumptions of normality, homogeneity of variance (Levene's test) and independence in observations.

Ethical Considerations

Ethical approval was received from the Office of Research Ethics at the University and, to its credit, caution was taken that participation took place on a school administrative level. All subjects provided informed consent after

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careful explanation of the purpose, procedures and confidentiality protocols. Informed consent was obtained from all eligible participants (adults) and parents/legal guardians of minors, prior to participation in the study, and students were informed that they could voluntarily withdraw from the study at any time without penalty. All data were anonymised and stored securely (only available to the organising team). Due to the non-invasive nature of data collection for this pedagogical intervention, this study posed minimal risk to participants.

Results

Socio-demographic characteristics of participants

Table 1: Socio-Demographic Characteristics of Respondents

Variables	Frequency (n= 80)	Percentage (%)
Gender of Participants		
Male	38	47.5
Female	42	52.5
Participants group		
Experimental	43	53.7
Control	37	46.3

Among the 80 student participants of this study, the experimental group formed 53.7% (43) and the control group was 46.3% (37) among all respondents in total. The majority of the respondents who were females represented 52.5% (42) of the total sample, while males formed 47.5% (38) of the respondents. Table 1 displays the sociodemographic details of the individuals.

Impact of Concept Mapping on Students' Performance in Selected Biology Concepts

Table 2: Results of Independent Samples t-Test on Pre-Test Scores of Experimental and Control Groups

Variable	Group	N	Mean	SD	t	df	P
Knowledge and Understanding of Photosynthesis	Experimental	43	7.85	1.58	0.47	78	0.640
	Control	37	7.70	1.61			
Application of Knowledge on Photosynthesis	Experimental	43	8.25	2.60	-1.21	78	0.230
	Control	37	8.74	2.35			
Practical Skills in Photosynthesis	Experimental	43	5.31	2.12	0.83	78	0.409
	Control	37	5.00	2.45			

The results of the independent samples t-test on the pre-test scores reveal no statistically significant differences between the experimental and control groups across all assessed variables. For knowledge and understanding

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of photosynthesis, the experimental group had a slightly higher mean (M = 7.85) than the control group (M = 7.70), but the difference was not significant (p = 0.640). When assessing application of knowledge on photosynthesis, the control group again scored higher (M = 8.74 vs. 8.25), but the p-value of 0.230 shows this difference was not meaningful. Practical skills in photosynthesis also showed a slight experimental group advantage (M = 5.31 vs. 5.00), yet the p-value (0.409) indicated no statistical significance. These results collectively suggest that both groups were statistically equivalent in terms of prior knowledge and skills before the intervention.

Table 3: Independent sample t-test of post- test mean scores on knowledge and understanding, on of photosynthesis, cell cycle and digestive system

Variable	n	Mean	SD	*t*	*df*	*p*
Knowledge and understanding of photosynthesis				.38	78	.702
Experimental	43	7.93	1.52			
Control	37	7.78	1.89			
Application of knowledge on photosynthesis				-2.23	78	.029
Experimental	43	8.23	2.77			
Control	37	9.41	1.92			
Practical skills in photosynthesis				4.42	78	< .001
Experimental	43	5.93	1.97			
Control	37	3.87	2.21			

A total of 80 students in this study were allocated at random to either the control group (37) or the experimental group (43). The mean and standard deviation (SD), for knowledge and understanding results for the control group and the experimental group, respectively, were 7.93 (SD = 1.52) and 7.78 (SD = 1.89) for photosynthesis.

In order to investigate the impact of concept mapping on students' comprehension of photosynthesis, a t-test using an independent sample was employed to determine if there was a statistically significant difference between the two groups' means. The experimental group of students (43 participants with 23 females and 20 males) was taught photosynthesis with concept mapping, targeting their knowledge and understanding. However, the control group (37 students with 19 females and 18 males) received no intervention.

The analysis's findings did not show a statistically significant distinction between the experimental group's and the control group's mean scores [t (78) = .38, p=.702] when the effect of concept mapping on the comprehension and knowledge of photosynthesis was evaluated. Table 3 provides specifics about how concept mapping affected students' comprehension of photosynthesis.

Their score for application of knowledge recorded the following means and standard deviation for both the control group and the experimental group respectively with 8.23 (SD = 2.72) and 9.41 (SD = 1.92) for photosynthesis,

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6.09 (SD = 1.54) and 2.03 (SD = 1.68) for the cell cycle, and 2.72 (SD = 0.45) and 0.73 (SD = 1.12) for the digestive system.

To determine whether there was a statistically significant difference between the experimental group's and the control group's mean scores on photosynthesis. Concept mapping on students' application of knowledge in photosynthesis recorded a significant difference in scores between the groups [t (78) = -2.23, p = .029] (Table 4.3). The mean score was higher in the control group of 9.41 (SD=1.92) experimental and control group than the experimental group's mean score of 8.23 (SD =2.77) and recorded an effect size of -0.486. This suggests that concept mapping had no improvement on students' application of knowledge in photosynthesis the score.

The mean and standard deviation (SD), for practical skills scores of students in the experimental group and the control group, respectively, were 5.93 (SD = 1.97) and 3.87 (SD = 2.21) for photosynthesis. In order to ascertain how concept mapping affects students' practical photosynthetic abilities, an independent-sample t-test was conducted to compare the scores for the experimental and control student groups. Concept mapping was identified to have a significant effect on the experimental group's practical skills in photosynthesis [t (78) = 4.42, p < .001]. The experimental group recorded a mean of 5.93 (SD = 1.97), while the control group had a mean score of 3.87 (SD = 2.21), with an effect size of 0.99, which was a moderate effect. This demonstrates that students who received concept mapping instruction performed better in the area of practical skills in photosynthesis as compared to those who were not taught concept mapping.

Gender Differences in Performance Using Concept Mapping in Teaching Photosynthesis

Table 4: Independent Samples t-Test Results Comparing Male and Female Students' Performance in Knowledge, Application, and Practical Skills in teaching the photosynthesis concept

Variable	N	Mean	SD	*T*	*Df*	*P*
Knowledge and understanding of photosynthesis				-0.48	41	0.635
Male	20	7.08	1.50			
Female	23	7.83	1.56			
Application of knowledge on photosynthesis				-0.62	41	0.539
Male	20	7.95	2.23			
Female	23	8.48	3.13			
Practical skills in photosynthesis				1.32	41	0.196
Male	20	6.35	1.90			
Female	23	5.57	2.00			

Among the 43 students (20 males and 23 females) who formed the research's experimental group, an independent-sample t-test *was* conducted to determine the impact of concept mapping on pupils' achievement in

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photosynthesis performance between males and females. It was found that there was actually no discernible disparity in knowledge and comprehension among males and females of photosynthesis performance [t (41) = .48, p = .635] (mean and SD for males; [7.08, SD = 1.50] and females; [7.83, SD = 1.56]).

Moreover, concept mapping on the application of knowledge in photosynthesis [t (41) = -.62, p= .539] (mean and SD for males; [7.95, SD = 2.23] and females; [8.48, SD = 3.13]) also recorded no significant difference between males and females. No significant difference was again identified between gender in concept mapping on practical skills in photosynthesis t (41) =1.32, p= .196] (mean and SD for males; [6.35, SD = 1.90] and females; [5.57, SD = 2.00]).

Discussion

This study investigated the impact of concept mapping as a learning tool on senior high school students' performance in photosynthesis, with performance examined across three domains: knowledge and understanding, application of knowledge, and practical skills. The study also explored whether the effectiveness of concept mapping differs by gender. The findings provide a subtle and thought-provoking pattern in understanding how concept mapping works in Biology instruction, especially on difficult-to-learn concepts such as photosynthesis.

Impact of Concept Mapping on the Content Knowledge and Comprehension in Photosynthesis

Data from the study indicated that, compared to conventional teaching methods, concept mapping did not yield statistically significant improvement in students' knowledge and understanding of photosynthesis. One commendable feature of the study was that when the subjects were assessed for prior knowledge before conducting the experiment, both groups were at a comparable level, as evidenced by their pre-test scores, allowing valid post-test comparisons between groups. The theoretical expectations based on Ausubel's theory of meaningful learning (according to which new knowledge is anchored, relating it to previously established cognitive structures) would suggest that the conceptual understanding in students who were taught with graphical representations should increase, but, as we can see, this gain did not appear.

This suggests that leaving concept mapping as an isolated instructional strategy is not productive in deepening students' scientific understanding of photosynthesis. Photosynthesis is an abstract concept with well-defined biochemical pathways and transformations, rich symbolism, prompting direct instruction and step-wise guidance. Therefore, traditional approaches focusing

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on direct instruction or structured delivery are likely more beneficial in these situations when it comes to learning new concepts. These results are consistent with earlier studies, which reported inverse effects, where concept mapping did not beat traditional methods for the promotion of conceptual understanding (Okoronka, 2018; Ayimbila & Akantagriwon, 2021).

A constructivist perspective suggests that for concept mapping to promote meaningful learning, learners need to be comfortable with the mapping process, and instructional scaffolding must be of sufficient quality. Indeed, it is possible that students needed more intensive training, mediated practice or prolonged experience with concept mapping before its conceptual benefits could become evident. This emphasizes the necessity of combining concept mapping with traditional pedagogical techniques to facilitate in-depth conceptual understanding, especially when dealing with complex biological content at an introductory level.

Concept Mapping and Application of Knowledge: A Study in Photosynthesis

In terms of application of knowledge, the findings showed a statistically significant difference between the control group and the intervention group, where students taught with conventional methods outperformed those exposed to concept mapping. This was despite initial expectations of improved application skills in concept mapping-teaching students, as supported by the findings from a few other studies (Crouch and Mazur, 2001; Zudilova-Seinstra et al., 2008).

Photosynthesis applications tend to rely on algorithmic problem-solving, diagram interpretations and procedural details, especially in exam-like tasks. Maps can help students plan their approach to a problem, but if alone, it may be difficult for students to reconstruct concrete application strategies from concept maps, without gaining useful experience of the techniques they planned to use during mapping. For these, traditional instruction, explain how to do the task and Practice (direct, concrete next steps) are more comfortable next steps towards use.

Which brings up an important pedagogical insight, however: that realisation does not learn the application skill in isolation — teaching students how to analyse and use those maps on their own to solve a problem is a very big part of the work. It also means that such a conscious connection changes the function of concept maps, which are sometimes just used to describe the problem under concentration into entities out there through which one moves knowledge around.

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Using Concept Mapping to Influence Practical Skills in Photosynthesis

The main finding of this study was that students' enhanced practical skills regarding photosynthesis were linked to concept mapping. A concrete evidential support was published that the students from the experimental group compared to the control on procedural competence and hand-eye coordination with regard to a moderate to large effect size

Using concept mapping to visualize experimental procedures and cognitive linkages among variables may have contributed to better practical performance, since one of the major analytical skills that industrial skill workers need is how theoretical concepts connect with experience in the laboratory. Practical learning builds on constructivist principles that participative, organized learners who reflect upon processes do not simply follow instructions. Constructing concept maps may have served as cognitive organizers that provided students with a roadmap through experimental procedures and reinforced their understanding of the cause–and–effect relationships intrinsic to photosynthetic processes.

These results are in agreement with prior studies showing that developing concept maps improves psychomotor and procedural skills in the context of science education (Zadeh et al., 2015; Ullah et al., 2021). This is especially significant for Ghanaian senior high schools, in the context of which students find it somewhat difficult to do their laboratory work well and practical examinations. This implies that concept mapping can act as a linking mechanism between theory and practice to overcome one of the most chronic deficiencies in Biology education.

Gender Differences in Performance under Concept Mapping

This study did not show statistically significant differences in knowledge and understanding, application of knowledge, or practical skills between male and female students where concept mapping was used to teach photosynthesis. This result suggests that the instructional technique of concept mapping is gender-neutral and was effective for students regardless of their gender. This lack of gender difference is consistent with other Ghanaian and non-Ghanaian studies (Ayimbila & Akantagriwon, 2021; Gongden & Delmang, 2016; Okoronka, 2018), where composite mean scores showed no differences due to the treatment of concept mapping in terms of gender. Focusing on visualization, learner independence and active learning may mitigate the effects of sociocultural bias and unequal classroom interaction that contribute to gender gaps in STEM education. These findings further validate the promise of concept mapping as a gender-inclusive teaching and learning approach that can support equitable opportunities for success in Biology classrooms. Notably, its efficacy did not vary with gender — an indication that it is broad-based.

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Only a three-day intervention was conducted in this study due to data collection during the school academic calendar and limited Biology instructional periods. It was felt that teaching students the main concepts of concept mapping and employing this strategy across several lessons on photosynthesis, had an appropriate time frame. The need for longer-term and more extended exposure to this instructional strategy is acknowledged in order to develop higher-order cognitive outcomes such as conceptual understanding and knowledge transfer. Consequently, treatment in this phase was of a shorter duration than is usually found for these interventions and may have moderated the observable learning gains between experimental and control. Consequently, future studies should continue to investigate the timing of participation (e.g., extending the time period for repeated practice with research ideas and reinforcement of concepts) as well as long-term effects on student achievement and higher-order thinking skills, where concept mapping is included in such comparisons.

Conclusion

This study investigated the impact of concept mapping on senior high school students' performance in photosynthesis in the Tolon District of Ghana. The findings revealed mixed outcomes regarding the effectiveness of the instructional strategy. Although no statistically significant difference was observed between the experimental and control groups in students' knowledge and understanding of photosynthesis, the control group performed significantly better in the application of knowledge. On the other hand, students who were exposed to concept mapping had practical skills in photosynthesis that were much better than those who used conventional teaching methods. The study also discovered no significant performance differences between male and female students, indicating that concept mapping can have similar effects across both populations. These findings indicate that mapping concepts is not a substitute for classical teaching, but a complementary approach, especially effective in the development of practical competence and vocational learning through experience. Where practical skills have been highlighted as a challenge to the development of quality Biology education, there is significant potential for further exploration into the introduction of concept mapping, especially in combination with direct instruction and guided practice.

The results suggest that in the short term, concept mapping is a more valuable tool for facilitating learning outcomes of doing or how to learn than gaining understanding or applying information. Thus, Biology teachers should introduce concept mapping in practical lessons and laboratory-based activities with a view to enhancing active learning, organisation of ideas and meaningful causal relationships of biological concepts.

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Given that future studies should involve longer intervention periods, larger sample sizes, and broader geographical settings to examine the sustained effects of concept mapping on students' academic achievement, conceptual understanding and higher-order thinking skills in science education.

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