ESI Preprints

Not Peer-reviewed

Concept Mapping as a Catalyst for Applied Learning and Practical Skill Development in photosynthesis at Senior High School

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Approved: 08 May 2026
Posted: 10 May 2026

Cite As:
Sam, C.K., & Owusu-Amponsem, G. (2026). *Concept Mapping as a Catalyst for Applied Learning and Practical Skill Development in photosynthesis at Senior High School.* ESI Preprints. https://doi.org/10.19044/esipreprint.5.2026.p160

Abstract

Concept mapping is recognised as an effective instructional strategy that promotes meaningful learning, particularly in science education. It facilitates planning, teaching, revision, and assessment, helping students link concepts for deeper understanding. This study investigated the impact of concept mapping on students' performance in photosynthesis at the senior high school level in the Tolon District of Ghana. A quasi-experimental non-equivalent group design was employed involving 80 Form 3 Biology students selected using simple random sampling. The results indicated no statistically significant differences in students' knowledge and understanding of photosynthesis ($t(78) = .38$, $p = .702$) between experimental and control groups. Regarding application of knowledge, the control group significantly outperformed the experimental group in photosynthesis ($t(78) = -2.23$, $p = .029$). The experimental group also showed superior practical skills in photosynthesis ($t(78) = 4.42$, $p < .001$). No significant gender differences were found. Based on the findings, it is recommended that concept mapping be adopted as a key instructional strategy to enhance students' practical skills in photosynthesis.

Keywords: Concept Mapping, science education, student performance, quasi-experimental design, practical skills development

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; Marton & Säljö, 1976). One example of this challenge is the integration and use of abstract, multi-level concepts across disciplines requested by topics such as photosynthesis (Aguiar et al. 2018; Jančaříková and 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 encourages 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 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 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, and hence 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

This study employed a quantitative research approach grounded in the positivist philosophical paradigm. In accordance with positivism, valid knowledge was derived from observable and measurable phenomena (Bajpai, 2011), ensuring that the comparison of student performance remained rooted in objective empirical analysis (Žukauskas et al., 2018). This deductive orientation allowed for the formulation of specific hypotheses and a systematic assessment of the instructional intervention's efficacy (Gummesson, 2004). To measure the impact of concept mapping on learning outcomes, a quasi-experimental, non-equivalent group design was utilized. This design is particularly appropriate for educational settings where the random assignment of individual students is restricted by established institutional structures (Cook & Campbell, 1979; Creswell & Creswell, 2018). By utilizing naturally occurring groups, the study maintained high ecological validity while providing a controlled framework for comparison.

Two intact Form 3 Biology classes were selected: Group A (G/S 3A) served as the experimental group, receiving instruction through concept mapping strategies, while Group B (G/S 3B) functioned as the control group, taught via the conventional lecture method. To mitigate teacher-effect bias, both groups were instructed by the school's regular biology faculty. In line with ethical protocols, students were informed of their right to voluntary participation and withdrawal. The instructional unit on photosynthesis spanned three days (two hours of instruction), followed by a post-test on the fourth day to measure the intervention's impact.

Population and Sampling

The target population was Form 3 Biology students of Tolon Senior High School in the Northern Region of Ghana. This is a public secondary school with about 2,343 students. The population from which the data were collected consisted of students offering elective Biology in six Form 3 classes. The two classes selected (G/S 3A and G/S 3B) used purposive sampling because they had similar academic profiles and availability. A simple random sampling was done to ensure at least 35 students were sampled from each class. As Krejcie and Morgan's (1970) sample size determination table shows for finite populations just above 100, a mere sample of 80 proved adequate. A total of 43 students were assigned to the experimental group and 37 to the control group.

Data Collection Instruments

Data for this study were collected using the Biology Achievement Test (BAT), which served as the primary instrument for measuring student learning outcomes. The BAT comprised 19 open-ended items developed in strict alignment with the West African Senior School Certificate Examination (WASSCE) and the national Senior High School Biology curriculum. To ensure a comprehensive evaluation of student performance, the test was structured to assess three cognitive domains, Knowledge and Understanding, Application of Knowledge, and Practical Skills specifically centered on the topic of photosynthesis. All items were scored using established rubrics to minimize marker bias and ensure the objective, empirical quantification of achievement levels (Creswell & Creswell, 2018).

Instrument Validation and Reliability

A pilot study was conducted with Form 3 science students from a separate school within the district to evaluate the instrument's clarity, difficulty level, and curricular alignment. Feedback from the pilot phase resulted in minor refinements to item formatting and the clarity of scoring guidelines. A reliability analysis using Cronbach's alpha yielded a coefficient of .81, indicating strong internal consistency for the Biology Achievement Test (BAT). Furthermore, content validity was established through an expert review panel comprising senior Biology teachers and university lecturers, who confirmed the instrument's topical relevance and alignment with national curriculum standards.

Data Collection Procedure

A pre-test was administered to both the experimental and control groups to establish a baseline and assess initial group equivalence. An independent samples t-test indicated no statistically significant differences between the groups, confirming their comparability prior to the intervention. Following the instructional treatment, the same instrument was administered as a post-test. The analysis of these scores facilitated an evaluation of the effect of concept mapping across the three primary performance domains: Knowledge and Understanding, Application of Knowledge, and Practical Skills.

Data Analysis Plan

Quantitative data were analyzed using IBM SPSS (Version 25). Descriptive statistics, including means and standard deviations, were calculated to summarize demographic trends and performance distributions. To assess the impact of the intervention, inferential statistics specifically independent samples t-tests—were employed to compare mean scores between the experimental and control groups. Prior to analysis, the data were screened to ensure they met the underlying assumptions of normality, homogeneity of variance (Levene's test), and independence of observations.

Ethical Considerations

Ethical approval was granted by the relevant University Review Board and the administration of the participating school. Informed consent was obtained from all participants after a comprehensive explanation of the study's aims, procedures, and confidentiality protocols. Participation was entirely voluntary, and students were explicitly informed of their right to withdraw from the study at any time without penalty. To protect participant identity, all data were anonymized and securely stored, with access restricted to the primary research team. Given the non-invasive nature of the pedagogical intervention, the 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	53.8
Control	37	46.3

Among the 80 student participants of this study, the experimental group formed 53.8% (43) and the control group was 46.3% (37) among all responders in total. Majority of the respondents who were females represented 52.5% (42) of the total sample, whiles 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 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	.000
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) were 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 2 provides specifics about how concept mapping affected students' comprehension of the 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, 6.09 (SD = 1.54) and 2.03 (SD = 1.68) for cell cycle and, 2.72 (SD = 0.45) and 0.73 (SD = 1.12) for 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. 232, p=.29] (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, it suggested that idea 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 idea mapping affects students' practical photosynthetic abilities, cell cycle and digestion system, 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), whiles 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 pupils who received idea mapping instruction performed better in the area of practical skills in photosynthesis as compared to those who are 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 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 c*onducted to determine the impact of concept mapping on pupils' achievement in photosynthesis, both male and female cell cycle and digestive system 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]). This indicated that, concept mapping in photosynthesis, cell cycle and digestive system performance was not significantly different between male and female students.

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. In addition, the study explored whether the effectiveness of concept mapping differed by gender. The findings present a differentiated and instructive pattern that deepens understanding of how concept mapping functions within Biology instruction, particularly in conceptually demanding topics such as photosynthesis.

Effect of Concept Mapping on Knowledge and Understanding of Photosynthesis

The findings revealed that concept mapping did not result in a statistically significant improvement in students' knowledge and understanding of photosynthesis when compared with conventional teaching methods. It was noted that when subjects were tested for prior knowledge before the experiment, both groups showed equivalent scores on pre-test thus making post-test comparison credible. While theoretical expectations based on Ausubel's theory of meaningful learning, which emphasizes the anchoring of new knowledge by relating it to existing cognitive structures, would suggest an increase in conceptual understanding for students that were instructed with graphical representations however these gains did not manifest.

The outcome of this study suggests that concept mapping, independent as an instructional strategy may not be effective in augmenting students' theoretical understanding of photosynthesis. Photosynthesis is a rich and abstract subject with biochemical pathways, energy transformations, and symbolic representations that often require direct instruction and step-by-step guidance. Thus, conventional pedagogies that focus on direct instruction and structured content delivery may be more optimal for initial concept acquisition in these scenarios. Earlier studies where concept mapping did not outperform traditional methods for promoting conceptual understanding have reported similar findings (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 control groups and intervention, 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 have been difficult for students to reconstruct concrete application strategies from concept maps, without gaining useful experience of techniques they planned to use during mapping. For those, traditional instruction, which emphasizes completing worked examples, direct explanations of tasks and practice may be a better fit for immediate knowledge application.

This finding points to an essential pedagogical implication: mapping concepts does not automatically translate into the application skill, unless students are specifically instructed on how to utilize these maps for analysis and problem solving. This intentional connection allows concept maps to become tools for transferring knowledge rather than just descriptive instruments through a problem that must be solved.

Concept Mapping: Impact on Photosynthesis Practical Skills

Most importantly, the most notable result of this study was the impact of the concept map on students' practical skills associated with photosynthesis. In summary, students in the experimental group significantly outperformed those in the control group, demonstrating a moderate to large effect size. This finding provides compelling evidence for the effect of concept mapping in improving procedural competence and hand-eye coordination.

Concept mapping was likely beneficial for students' practical performance because it allowed them to visualize experimental procedures, comprehend sequential relationships, and relate theoretical principles with laboratory learning. 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–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, 2020) 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 being a gender-inclusive teaching and learning that can support equitable opportunities for success in Biology classrooms.

In summary, the results indicate that concept mapping has a domain-specific impact on students' performance in the topic of photosynthesis. Although it did not make a notable difference to conceptual understanding or knowledge as application when used in isolation, it had an emphatic and positive effect on students' practical skills. Notably, its efficacy did not vary with gender — an indication that it is broad based.

This 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.

By presenting contextualised empirical data from the Tolon District of Ghana, this paper feeds into wider debate on innovative science education practice and supplies a basis for plus by which informed instructional decisions can be made. It teaches that we can pursue the most promising scientific and social change, not by throwing the baby out with the bathwater but by carefully integrating what works in traditional ideas/tools with constructivist ones that entail seeing, associating and practicing science more assuredly.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The authors did not obtain any funding for this research.

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