

Transforming Food Chemistry Education for Sustainability: A Critical Synthesis and Dataset-Based Analysis of Learning Outcomes, Food-Waste Prevention and Circular-Economy Thinking

Nwokorie O. Smart

Department of Science Education, Abia State University, Uturu, Abia State, Nigeria

ABSTRACT

This research explores the incorporation of sustainable food chemistry in secondary school education in Nigeria. This teaches students molecular level foundation of food and chemicals, and aids food waste prevention through the lens of the circular economy. It reviews previous research on chemicals learning, applauds practical and food literacies, circular and waste management, and reports the results of a survey on education. The survey was designed to evaluate the effects of traditional, practically structured, and sustainability-integrated education on 360 students. It also assessed circular economy thinking of the students based on 30 items. Researchers analysed the 360 students' food chemistry literacy, 1080 food-waste audit sheets, and 1080 fidelity-to-instruction sheets. The researchers also verified the records, which students created during the food-waste audit and instructional fidelity. Lastly, researchers used "numerical consistency" to validate their assessment. Prior to the intervention, 50% of the students could not define food chemistry and 98% of the students did not demonstrate thinking about the circular economy. Numerical edible-discard (food-waste) loss of the students' meals decreased by 7.81 g, 3.86 g, and 1.96 g, following the intervention.

KEYWORDS

Circular Economy, Food Waste, Preventative Sustainability, Food Literacy, Guided Inquiry

I. INTRODUCTION

Molecular representations of Food Chemistry, i.e. the changes of food due to Acid/Base and Oxidation reactions or preservation and storage changes are common lessons presented at the senior secondary level. Teaching these concepts in isolation often creates difficulty in understanding their relevance beyond the lab. Students can identify examples of food spoilage, or enzymatic browning and state how they will change over time, but are unable to address sustainability challenges in an evidence-based way. For instance, may state that lack of temperature control in food storage may lead to spoilage, but may not be able to reflect on how it challenges food security in a given area. Similar challenges occur with other chemistry concepts including solubility or coagulation and levels of food additives. Teaching the application of these concepts may help address some of the challenges students face in drawing evidence-based sustainability conclusions.

Assessing the relationship between food loss and waste offers a challenging yet illustrative example. There are biological and chemical processes at work in food, such as spoilage, preservation, and manufacturing. There are other social and economic factors at work that influence the final disposition of food. Morgenstern et al. (2022) found food loss is a highly contextual phenomenon and depends on the definition, the quality of the data and several other factors. The UN Environment Programme (2024) asserts that prevention of food waste and reduction of food system-related impacts are essential elements to achieving a sustainable food system. It is this area where educational programmes have the greatest opportunity. Research provides ample evidence of the opportunity for loss prevention and wastage in food systems. It is beyond the purview of the research to address all the social, economic, political, and other barriers that prevent the realisation of these opportunities.

Tension exists in the Nigerian context. Abulude and Wahlen (2024) point to the interconnected nature of limitations in food production and storage, and underdeveloped and unsupportive infrastructure and governance. Sunday et al. (2022) explore food waste at the household level and relate it to social class, financial status, and lifestyle. Other studies indicate that advocating for loss prevention, and awareness thereof, does not mean loss prevention practices are adopted. Infrastructural limitations, food systems and wastage, and Cooking practices and portion control have been explored and inform this paper.

This study synthesised the existing literature on food chemical literacy, food waste prevention, and the circular economy and conducted an empirical analysis of data integrity on these three aspects. The study classified three types of teaching methods: traditional teaching, teaching supported by laboratory work, and practical teaching methods integrated with sustainability. The analysis included grouping and contrasting assessment records, food-waste analysis, and assessment of fidelity to instruction. The outcomes of the study reflect the properties and limitations of the data and do not confirm the implementation of the intervention in the classroom. The study also did not assess the impact of the intervention and, therefore, did not measure any outcome that might support the conclusion that the intervention improved the understanding of sustainable chemistry.

II. LITERATURE REVIEW

A. Chemistry education, inquiry and sustainability

A second position considers active learning and inquiry to serve as instructive approaches to teaching science. Furtak et al. (2012) found that when teachers integrated inquiry into their practice, there was an average positive effect. However, Furtak et al. (2012) noted that the extent to which teachers directed inquiry, as well as the nature of inquiry, impacted the outcomes of instruction. In a similar vein, Lazonder and Harmsen (2016) found that providing children with inquiry guidance and facilitation impacted their achievement. At the level of STEM, Freeman et al. (2014) observed that replacing traditional lecturing with techniques that incorporated greater participation impacted learning. In addition, Theobald et al. (2020) reported that achieving learning equity in the discipline of science requires the routine use of activities that engage students in higher levels of critical thinking. Overall, the approaches to learning found in these studies validate the use of a food chemistry inquiry activity as an acceptable practice to compare against the control group.

There are at least three possible shortcomings of laboratory work. First, although some experiments may require consideration of the cost of resources and safety, that may not necessarily result in students developing a deep understanding of the costs associated with the processes. Second, not all students may have the opportunity to perform an investigation due to a number of limitations, such as lack of appropriate equipment. Third, improvements in student achievement may not mean students have developed the understanding required to address the issues in less familiar contexts. Deslauriers et al. (2019) demonstrate that in some cases, perceived learning and actual learning may not necessarily be concurrent, and as a result, reliance on learning satisfaction as evidence of achievement may not be appropriate.

Some studies have researched systems thinking and its applicability in chemistry education. Mahaffy et al. (2019) support the notion that the teaching and learning of chemistry should promote the understanding of the interactions of chemical substances and the overall systems that integrate the processes. The fact remains that the instructional materials that have been described and examined encourage students to critically think about the interaction of a given chemical process. It is understood that the frameworks do not promote sustainability as an overarching goal of the other learning disciplines; rather, they help students integrate their understanding of chemistry in critical analyses of real world situations.

B. Chemical awareness and understanding of food systems

This is not the same as everyday food literacy or an understanding of chemistry as evaluated in a traditional chemistry context. Vidgen and Gallegos (2014) described food literacy as the abilities, knowledge and skills required to obtain and evaluate food, and to eat in ways that benefit health and wellness. Other definitions of food literacy described by Truman, Lane and Elliott (2017) encompassed food and the systems that promote, maintain and sustain health as well as food and the culture in which it is produced and consumed. Knowledge-based outcomes have been the focus of the research, and end of the assessments have been the definition.

For the purposes of this analysis food chemistry literacy included the ability to explain the composition of foods and changes that occur to foods and related chemistry and to apply concepts of chemistry to the understanding of the quality of foods and methods of food preservation. The concepts included the chemistry of the deterioration of food, enzymatic browning, the difference between pH and acidity, and food preservation. Assessments of food preservation and processing rely on a understanding of these concepts. Chemical explanations do not define food safety. The assessment of food chemistry literacy evaluated what students understood within the bounds of the construct.

The assessment framework outlines the recognition of concepts, depth of explanations, and the ability to apply understandings to new situations. The framework also incorporates knowledge of food preservation, food quality, and food quantity. Numerous other elements of the framework reflect the transfer of food industry-related learning. This study analysed the framework, delineating the aspects that consist of composite scores and evaluating the numbers that comprise the scores. Other evidence of validity, such as expert opinions, were not considered. Thus, numerical agreement across the different sections of the framework

was not evaluated to determine if it supported the interpretations drawn from the different framework sections.

C. Food Waste Prevention and Behaviour Change

Efforts aimed at the reduction of food waste through education tend to take a linear approach, whereby knowledge is presumed to lead to concern which, in turn, is expected to result in less food waste. Research based on actual behaviour has challenged the presumed linear relationship. Food waste is considered to be the consequence of a number of habitually and psychologically charged behaviours. A better understanding of the emotional contexts associated with food preparation and consumption as well as the interrelationships between various activities and the role of planning in relation to food wasting is needed. Similar to the case with food spoilage, fluctuations in the reliability of the food supply and the circumstances of food service, coupled with the need to prepare and provide food in excess, might, on their own, provide strong incentive to act against the teaching of food spoilage and food preservation.

The score analysis completed by the researchers defines the data and addresses performance related to the prevention of food loss and waste (FLW) in the school food service system. It encompasses prevention of FLW loss and the rationale and justification for prevention. The term food safety is also included. The analysis describes evidence-based planning. It defines criteria for improvement and distinguishes the sustainable development goals from basic sustainability terminology.

The analysis focuses on the waste audit register for the school food service system. The target edible discard was measured in grams and compared to other data to assess potential improvement. Because documentation related to food safety, weighed food, and menus was unavailable, calculations and interpretations related to edible discard and food waste were unsubstantiated. Due to the variation in the interpretation of the data, it was often difficult to make conclusions related to improvement.

The interpretation of the data must include consideration for adequacy and the consequences of the change on the school food service system. Improving the school food service system to increase (or decrease) the provision of food must be balanced with protection of the safety of the food provided, and the rationale for the change must be evaluated. Improvements must also be weighed against the needs of the school food service system and the protection of the school food service system. A deeper analysis of leftover foods may bring improvement, but it could ultimately lead to a negative consequence.

D. Circular-economy thinking, trade-offs and safety

One perceived advantage of using circular economy language is that it provides a coherent structure from the point of waste prevention to subsequent stages of reuse and recovery. However, Kirchherr, Reike and Hekkert (2017) report that definitions and examples in the literature place more emphasis on the need for reduced, reused and recycled materials, and less on social equity and transformation at the system level. Geissdoerfer et al. (2017) argue that circularity and sustainability should be treated as separate concepts. Thermodynamic and other physical and systemic limits are addressed in the literature on the circular

economy. Approaches to slow, narrow and eventually close material loops have been described (Bocken et al., 2016). The reuse of food by-products, and other materials, should be distinguished. Reuse is permissible, whereas other materials should not be allowed to enter the food chain. The literature should address the unsafe and/or inefficient uses of circular economy technologies. Trade-offs are needed to consider the accumulation of environmental burden and resource requirements.

The emphasis of the circular-economy assessment framework was on decision-making rather than attitude assessment. A case involving by-products of fruit-processing plants and the distinction among prevention, safe non-food reuse, reusing, and responsible disposal, was included. A sound response could rule out a cyclic option, e.g., safe reuse, if energy and/or transport requirements or other considerations make the option less desirable. Such a response would be sound. The scores provided in the case did not constitute proof that respondents based their decisions on the reasoning contained in the case.

E. Nigerian Food Systems and academic viability

Food-processing chemistry instruction cannot, in the foreseeable future, assume the presence of adequate post-school environments in Nigeria to absorb chemical education technologies as described in textbooks. Postharvest food-loss practices in Nigeria are dependent on the state of the national food market and the food-handling infrastructure. Food waste and over-preparation in Oyo State have also been documented. Other factors affecting food storage and leftovers in homes have also been documented. While these works provide a basis for incorporating case examples that address food systems in Nigeria, the samples and instruments used cannot be extrapolated to all children and adolescents in the country.

In terms of actual consequences, it can be noted that in certain cases, 'school wealth' as assessed by a school's laboratory may far exceed 'chemical reasoning' as assessed by a school's classroom. Evaluating what school's laboratories lack can be as illuminating as determining what school classrooms lacks. Many assessments based on simple technology can incorporate consideration of tomato drying, acidity and mass. Reliable changes in the nature of tomatoes can be used to explain the complexities of pre- and post-harvest changes, for example, effect of transportation and storage, to the students. Chemical change has to be studied with reference to other biological changes and vice-versa. Appropriate design of experiments can help students use laboratory equipment to a far greater extent, however, in the absence of required equipment, group B and C teachers should not become demonstrators only.

This local relevance has to be supported against two dangers. The first is deficit framing. By saying that Nigerians don't know how to handle waste properly because of their lack of knowledge about waste management systems overlooks a number of other factors such as organisation and reliability of the power supply, finance and transport systems, as well as the government's overall policy framework. The second danger is uncritical cultural substitution. It is culturally relevant to use food that is familiar to students. However, using food to represent students' cultural values is culturally relevant to students, and is pedagogically responsive, only if students' experiences and context shape the problems and case scenarios. It is likely that students are different with respect to their economic status

and the food they have access to at home. It is inequitable to presume that the ability to pay for the use of a refrigerator is an accurate indication of the level of environmental literacy among students.

This research has defined the boundaries of what it seeks to achieve and has evaluated how disciplinary learning in chemistry is documented and represented via food resource decision making. It shows what has been accomplished and outlines what has not been achieved. This research values school-based food insecurity and waste management initiatives and offers insights on how to accomplish equity and makes a case that chemistry instruction should not be the primary determinant of national food policy initiatives.

F. Theoretical framework and rival explanations

The theoretical model incorporated contextualised learning of chemical principles, guided inquiry, and systems thinking. Contextualised chemical principles, for example, linked tannins to food preservation, and inquiry and systems thinking integrated explanations. In some cases, the involved teachers added videos to support students' understanding of chemical changes and the role of ingredients in food processing, thus providing relevant expertise to enhance contextual understanding.

The available data and the theoretical model allowed identification of several possible learning mechanisms. In some cases, students pointed out the role of ingredients, and teachers supported students' understanding with relevant videos and materials. Analysis of the data did not allow establishing the relative importance of the observed mechanisms, which could depend on the academic preparation and predisposition of the students, and previous environmental interest.

Alternative explanations for the findings include the "additional instructional intensity" hypotheses. According to these hypotheses, Group C's advantages over the other groups could be explained by a number of factors including the teachers in Group C providing more feedback and using better instructional materials and giving additional lessons. Teacher enthusiasm could also explain Group C's advantages.

It is possible that teachers, because of their beliefs in the benefits of the intervention, could be unintentionally providing performance benefits to the groups for which they have the most positive feelings. Assessment of students' learning of waste-reduction practices could also explain the test performance differences among the groups. There are a number of factors that could explain differences among the groups, including activities undertaken by members of the groups' families and communities, outside-school factors, and the school's food policy. Balanced scheduling, common, aligned practical work, and different assessors could be used to address the alternative explanations.

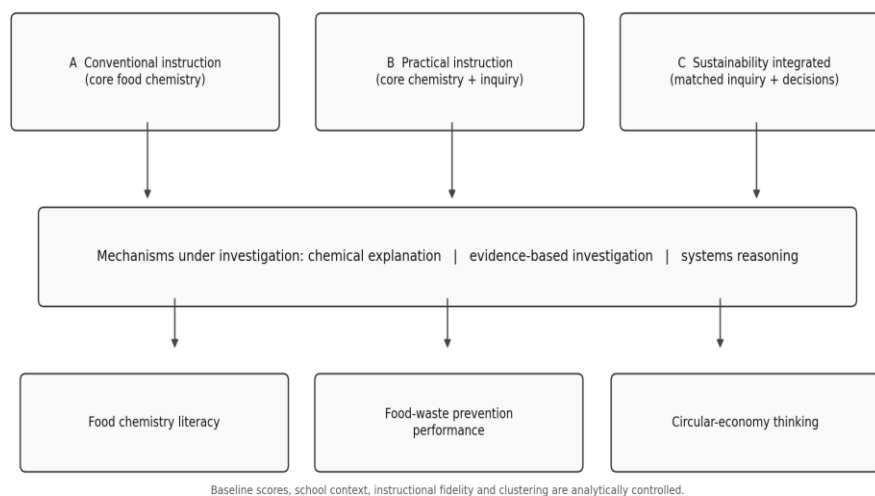


Figure 1. Instructional conditions, learning mechanisms and three assessment domains

Source: Author-developed synthesis of the literature. Arrows express theoretical relationships, not verified treatment effects

III. METHOD

A. Research questions and analytical contrasts

The study addressed four research questions: do the three instructional conditions relating to food chemistry literacy differ in any way; do the conditions relating to food waste prevention differentiate in any way; do conditions relating to circular economy thinking differ in any way; and are there any other types of differences that exist between instructional conditions (C) and (B) that relate to sustainability. The five analyses were summative, and the nature of the differences, if any, were reported. They did not access or assess the cause for the differences that may exist in the classroom.

The core differences comprising the comparative structure were C-A, C-B and B-A, across the pre-defined outcome measures. The B-A comparison was the most informative as it enabled assessment of sustainability beyond the other comparisons and in the context of practical work. The data in the case study was constructed algorithmically and lacked evidence of intent in the form of allocation and/or first-hand assessment. Therefore, the current case study did not perform hypothesis testing. Gradients in the data were interpreted in the context of their measurement and other limitations.

B. Study Design and Data Structure

The case study adopted a comparative analysis of three groups (conditions A, B and C) of a structured educational activity workbook based on food and chemistry. Condition A described the typical classroom teaching of food chemistry; condition B described teaching of practical chemistry with guidance; and condition C described teaching of practical chemistry with a focus on food waste prevention and the principles of a circular economy. Each group/student was described in terms of baseline and post-intervention (if any)

assessment scores of the pre-defined outcomes. The end-of-term assessment scores were classified and interpreted based on the workbook's 8-week teaching schedule. The case study did not provide any documentation to support the workbook was implemented with students in an 8-week instructional period.

The data structure consisted of 15 schools and 45 classes, and included 8 learner records per class. Each condition was represented by a single class. There was no actual assignment mechanism depicted by the school and class identifiers. Quasi-experimental studies that utilise intact classes, like the one in the work sample, create a high risk for selection bias, as well as institutional imbalance and contamination. The work sample contained no description of a randomisation process or permission and allocation records, therefore the analysis of the work sample was approached as if it depicted a study of structured data, rather than a field experiment.

The studies described the membership of classes and schools, and made use of the 360 lower level records. Since the work sample contained no other information, such as employment records, school resource records, or teacher records, the analysis was constrained and did not include any records depicting the allocation of teachers. The analysis also did not make any fictitious allocation decisions or suggest the existence of unmeasurable teacher characteristics.

Table 1. Instructional arms and threats to a fair treatment comparison

Condition	Shared disciplinary content	Distinctive learning experience	Main comparability risk
A — Conventional	Composition, oxidation, acidity, preservation	Exposition, worked examples, curriculum exercises	Unequal teaching time or teacher expertise
B — Practical only	Same concepts and learning objectives	Guided experiments, observation, data explanation	More laboratory access than C
C — Integrated	Same concepts and matched practical content	Guided experiments plus prevention decisions and circular trade-offs	Additional coaching or rehearsed test prompts

Source: Instructional classifications examined in this analysis; all three conditions share core chemistry content by design.

The three instructional conditions above share core chemistry content.

C. Indicators of Fidelity and Integrity

The instructional content of the programme has been structured to fit within an 8-week curriculum framework. Week 1 was about the basics of measuring and representing food. Week 2 was food composition and chemical properties. Week 3 was about food quality and changes. Week 4 was about food acidity and preservation. Week 5 was about food waste. Week 6 was about food processing and residues. Week 7 was about food processing and a case study involving a school canteen. Week 8 was a unit summative assessment. Other

components of the school curriculum were integrated across the three conditions. The equivalent conceptual content allowed comparison of types of practical activities and sustainability.

The definitions for the conditions allowed the authors to distinguish among conventional instruction (A), guided practical work (B), and practical instruction integrated with sustainability (C). Recorded variables allowed the authors to compare practical time and the reasoning and instructional time delivered across arms. Numerical time limits for practical activities do not ensure equivalence of apparatus, teacher feedback, instructional quality and/or assessment, which required direct classroom observation. Therefore, the focus of the analysis was to describe the coded instructional condition.

The foods studied were safe-to-eat time limit activities related to food safety including the browning of foods and the developing of acidity. The exercise on fruit discolouration differentiate enzymatic changes from microbiological hazards; an activity on acidity differentiates the evaluation of pH and risk; and an activity on food drying differentiate water loss and food spoilage. Thus, the activities represent and assess the disciplinary nature of the field of food science. The workbook did not include dated laboratory notebooks or any other evidence to confirm that the practical activities were completed by students.

The integrated food resource case employed students' decisions to sustain food processing and safety to eliminate food waste. Students made trade-offs to balance a combination of prevention, recovery, and safety within the scope of affordability. This example promoted students' understanding of circular economy thinking, and did not rely on students' prior understanding or experience with recycling and sustainability. While the case provides a total assessment score, the case did not include students' explanations which would indicate the reason for students' trade-off decisions.

We examined instructional fidelity by analysing each lesson's coding of delivered time, practical activity, sustainability reasoning, cross-group contamination and safety adherence. These elements allow for the description of the differences in training participants' exposure, and, to some extent, depend on the accuracy of observations. In this study, we analysed the teaching activity rates, and, where applicable, identified and documented inconsistencies. In most cases, coding was interpreted in the context of equal instructional status. Due to recorded exceptions to safety adherence, and because multiple categories of practical activity appeared in the coding, interpretive conclusions regarding instructional equivalence were limited.

The documented curricular structure, which spans a period of eight weeks, describes assessment activities associated with the core focus of each week.

In the absence of independent verification of implementation, the study documents curricular structure and associated assessment activities.

Table 2. Eight-week curricular structure and associated assessment activities

Week	Core focus	Evidence or teaching activity
1	Baseline	Pre-tests, school context and baseline attainment
2	Composition	Food constituents and properties
3	Chemical quality change	Controlled observations of oxidation and browning

4	Preservation	Acidity, moisture and limits of safety indicators
5	Waste prevention	Evaluation of avoidable loss mechanisms
6	Circular alternatives	Critical examination of safe resource recovery
7	Integrated case	School canteen and fruit-processing evidence challenge
8	Evaluation	Posttests and intervention-fidelity review

Source: Curricular structure encoded in the study documentation; implementation was not independently authenticated.

D. Instruments, scoring and validity

In this study, the construct of food chemistry literacy encompassed understanding of food composition and changes in food quality and transformation, as well as concepts of acidity and preservation. The evaluation of the instructed evidence included the interpretation and application of evidence. The source workbook, however, did not provide sample responses or explanations to the constructed-response items. Thus, the analysis was limited to confirming the 0 to 40 score range, and assessing the consistency of references used for scoring. As such, no claim of the calibration of the instruments, validity of Chemical Reasoning, or other issues related to teaching and learning were made. It was, however, acknowledged that score validity may differ from the scores achieved by learners.

Food Waste Reduction Performance was assessed by 6 domains, scored 0 to 4, and combined to give a total score out of 24. The domains are: definition of the problem; chemical rationale; prevention strategy; food safety; justification and resource efficiency. The assessment team verified 1,080 criterion-related items and confirmed these were scored correctly. The assessment team ensured score distributions aligned with the constraints of the scoring structure; however, they could not confirm students' logic or provide evidence of rater agreement or reliability.

The same limitations also applied to the Circular Economy Thinking Assessment. It also emphasised that if a reuse of an unsafe by-product is refused, then a recovery of the by-product should be evaluated. Total scores out of 30 were assessed. The case studies did not always provide enough evidence of logic or justification to provide absolute certainty that a score reflected judges' multi-criteria.

All assessment domains cannot be assumed to be identical or distinct from one another. Relative score groups were interpreted in conjunction with evidence of score ceiling and alignment. If similar groups were observed in different assessment domains, this may reflect convergence of student thinking; however, evidence to support confidence in this conclusion was lacking.

Table 3. Primary outcomes, indicators and validation priorities

Outcome	Example assessed capability	considered instrument	Major validity safeguard
Food chemistry literacy	Explain and transfer chemistry to unfamiliar food-quality cases	FCLT: test and applications	Blueprint, piloting, item performance and cognitive interviews

Waste-prevention performance	Identify, justify and evaluate safe preventive choices	FWPR: six-domain 0–4 rubric	Blind dual marking, anchored descriptors and inter-rater agreement
Circular-economy thinking	Compare prevention, reuse and recovery with explicit constraints	CETA: unfamiliar multi-criteria scenario	Reward justified rejection of unsafe or unsupported options

Source: Author-developed measurement specification. FCLT = Food Chemistry Literacy Test; FWPR = Food-Waste Prevention Rubric; CETA = Circular-Economy Thinking Assessment.

The predominant means of analysis was the waste data from 270 teaching sessions. Baseline and post-intervention data from the waste audits from each treatment arm were captured. Edible food discards were determined as the mass of food discarded from each meal served. The audits captured a total of eight meals. Outcomes were described in a decontextualized manner. Evidence of student behavioural change was not described. Data were described as work book features, rather than first-hand accounts of behavioural change. Because the workbook was supplemental and not the primary source of teaching or instructional material, contextual reassurance for behavioural changes of student institution-level food waste prevention was lacking.

A reduction in waste can sometimes occur even in the absence of improvements to school food. School food systems may be adjusted by school administrators to produce smaller meal portions, alter school menus or change the number of meals served (e.g. by offering school meals only during certain school campaigns). A negative control can help understand the extent to which waste prevention measures improved food system outcomes. In some cases, safety concerns may require the removal of food from the school food system (e.g. due to spoilage or contamination). In these situations, the removal of food from the system should not be considered a school food policy failure. In addition to the type, amount, and reason for the discarded food, the quality of school food systems should also be monitored. Examples include the knowledge and task levels of school food personnel. Convincing school food personnel prevention plans should not be considered a substitute for assessing the overall performance of school food systems.

Circular economy principles may also help resolve issues related to the balance between food system prevention and redistribution. The canteen may adopt several processes to improve the balance of its system at the expense of others (e.g. improving its material balance by increasing the quantity of food that is sorted to be provided to unpaid agents). Students should analyse the people impacted by the food system, determine the unit of the food system, and interpret the outcomes of the food system in relation to the counterfactual. From a circular economy perspective, school food systems should evaluate both waste and the quantity of food produced by the school food system.

These questions are also essential for interpreting the results of studies that have reached contradictory findings. If literacy rates rise but the discard rate does not change, we need to determine if the participants did not have the authority to make decisions about disrespected intentions, and/or if the school's functioning and procedural safety guidelines prohibited further safe removal of discourtesy. If the discard rate falls but literacy rates do not change, we may need to look into the administrative changes that occurred. A school-

wide initiative that commences in Week 4 may influence (or contaminate) different conditions (favourably or otherwise) depending on the time of observation. These initiatives need to be entered into the research log in a timely manner. Hypothesis evaluators may need to consider that more careful disposal of ambiguous food by participants may have occurred, resulting in a net increase of food safe to remove and/or a net decrease in the food remaining (and therefore an increase in weight of food discarded). Thus, a more integrated consideration of multiple safety and sustainability indicators (including food removed by participants) would be more adequate.

Completed analyses yielded various sorts of means, standard deviations, changes (pre- and post-test, percent of maximum, etc.), mass-weighted edible discard rates, and fidelity in instruction (Hooper et al., 2018). Most comparisons included the C–B difference and were supplemented by C–A and B–A differences. An inferential (or adjustment) model, considered for methodological reasons, assessed the potential effect of pre-test difference and clustering; it was not considered as a model that was fit to educational data (i.e. evidence) in an unconstrained manner. As Hooper et al. (2018) note, such models must be based on known (i.e. sampled) population units and (measured) educational interventions.

The three comparisons (C–A, C–B and B–A) were interpretively distinct. The C–A comparison referred to the total difference in score series (integrated vs. conventional) and the C–B comparison referred to the next level of detail in the difference in the integrated (i.e. practical) score series. The B–A comparison referred to practical (i.e. unmeasured) differences relative to conventional score series. The differences in the score series were based on the teaching data. Multiplicity was considered for verification. P-values were generated for the artificially constrained score series and discussed in the context of what they might suggest.

The source records showed complete data for the learner profiles; however, completeness does not ensure that participant retention rates are high and that records are available for all participants. This analysis checked for duplication and described the relationships between learner profiles and outcomes. It analysed the class/school hierarchy. The analysis did not assume independence of students in the same class and school. It was found that in the absence of adequate adjustments, measurement of unmeasurable confounders would not be possible and allocation bias would not be resolved.

Comparison of subgroups and answers to mechanism based questions were not possible since the records did not explain teacher practices, household conditions and contexts, learner engagement and how these are distributed. The analysis also did not examine the post-test scores in constructed response format to determine if mediation exists.

Expression of interpretation based on the baseline adjustment model

$$Y_{ij, post} = \beta_0 + \beta_1 B_{ij} + \beta_2 C_{ij} + \beta_3 Y_{ij, pre} + u_j + \varepsilon_{ij}$$

Here, instructional adjustment and school/class terms are included to define the statistical framework to enable interpretation.

E. Considerations of Ethics and Safety

When researching school pupils, the granting of ethical approval is only one of several factors to be considered. Other considerations include the processing of responses in such a way as to protect the respondent's identity and the right to withdrawal. Sensitive withdrawal procedures and confidential responses must be in place should the research require the identification of participants. Research participants must not be coerced to monitor waste to reveal personal information concerning their socio-economic status, cultural food preferences and health, as this can affect their self-esteem and shame them. Students should not be rewarded or penalised for participation or lack of participation. In the control condition, the researcher should not withhold instruction from participants and teaching from the control group. Where teaching is withheld, the school has a right to be fully informed about the reason for the withholding of teaching and the reasons for focusing on one group rather than all pupils.

Safety considerations in laboratories should take precedence over the consideration of performing an elegant experiment. The use of sharp objects should be closely monitored. So should heat and chemical experiments. Food should not be judged safe to eat based on appearance or experimental manipulation of pH. Researchers should take into account the potentially harmful effects of models on health and safety and, if this is the case, be prepared to make recommendations on the need for disposal.

IV. RESULTS

A. Dataset composition and provenance

The excel workbook includes a substantive and a reference series of registers. For analysis, the reference series Students Reference table, comprising 360 students' records (120 in each experimental arm), was considered the main data source. The Students Register, which contains the 360 students' records, should not be used to represent an independent student cohort. The two fidelity and audit reference registers, comprising 270 records each, and their respective primary registers, were also used in this study. The three primary registers, in conjunction with the 1,080 rubrics associated with 360 students, provide the framework to analyse assessment and teaching in this study. Since there are three assessments, with 360 learners for each assessment, it does not mean that 1,080 learners were assessed. This is a necessary check, because if the fidelity of the reference registers was not ensured, there would be a misleading impression of the extent of participants assessed.

The encoded data, at the class level, consists of 15 classes in each of the three conditions, with each class comprising eight students. The ceiling scores for the three assessed conditions (FCLT, FWRP and CETA) are 40, 24 and 30, respectively. The 1,080 domain scores of students also conform to the ceilings (FWRP scores) for the respective assessed conditions. The data gives the impression that students were assessed and lessons were taught. However, there is no evidence to corroborate this. Tables 4-6 provide descriptive statistics for the data. Figures 2-5 provide other corresponding information.

B. Educational outcome profiles

Table 4 shows what was measured at baseline, post-instruction, and at the delayed measurement for each construct of interest. Even though all respondent groups showed improvement, it cannot be said that the positive changes are gains made by the

respondents. At baseline, the average FCLT scores were 19.56, 18.69 and 19.17 for A, B and C, respectively. A smaller imbalance in the FCLT scores supports the case that post-test changes, in general, should not be interpreted in the absence of prespecified changes. Adjusted comparison. From the estimated changes, mean gains in the FCLT were 2.71 (A), 4.72 (B) and 6.20 (C) units. The difference in mean change between the groups (B – C) was 1.48 units of FCLT, however, no general or educational claim can be made regarding the difference. A similar estimation for the changes in the FWRP and CETA showed a mean difference of 1.69 and 3.80 units, respectively. It should be noted that the differences in the systems components are, in general, in agreement with what was intended by the instructional intervention.

Table 4. Outcome score distributions in the structured learner reference series

Outcome	Arm	N	Pre-test mean $\pm$ SD	Post-test mean $\pm$ SD	Delayed mean $\pm$ SD	Mean change
Food chemistry literacy /40	A	120	19.56 $\pm$ 4.46	22.27 $\pm$ 5.22	21.20 $\pm$ 5.62	+2.71
	B	120	18.69 $\pm$ 4.66	23.41 $\pm$ 5.47	22.35 $\pm$ 5.93	+4.72
	C	120	19.17 $\pm$ 4.97	25.37 $\pm$ 5.52	24.10 $\pm$ 5.71	+6.20
Waste-prevention performance /24	A	120	9.51 $\pm$ 2.85	11.14 $\pm$ 3.51	10.11 $\pm$ 3.93	+1.63
	B	120	9.11 $\pm$ 2.97	12.74 $\pm$ 3.91	11.88 $\pm$ 4.38	+3.63
	C	120	8.77 $\pm$ 2.89	14.09 $\pm$ 3.64	13.78 $\pm$ 3.92	+5.33
Circular-economy thinking /30	A	120	11.72 $\pm$ 3.00	12.95 $\pm$ 4.30	11.76 $\pm$ 4.77	+1.23
	B	120	11.82 $\pm$ 3.52	14.37 $\pm$ 4.41	13.35 $\pm$ 4.88	+2.55
	C	120	11.29 $\pm$ 3.49	17.64 $\pm$ 4.40	16.68 $\pm$ 4.82	+6.35

Source: Author calculations from Students Reference (n = 360). SD, sample standard deviation; change = post-test minus pre-test. All scores represent generated workbook entries, not verified learner assessments.

Outcome measures were designed as multiple choice questions and included 3 arms for each variable assessed (i.e. Food Chemistry Literacy /40; Waste Prevention Performance /24; and Circular Economy Thinking /30). Each arm included 120 responses.

Mean change = post-test minus pre-test. All mean values are adjusted for guessing. SD, standard deviation.

Not all responses showed improvement, and some even showed deterioration as evidenced by negative mean change (i.e. participants answered questions incorrectly on the post-test than they did on the pre-test).

Result score distributions for waste prevention (Table 4, arm B) indicated that approximately 1 out of 3 responses were filled out correctly on the post-test, resulting in a mean score improvement of +3.63. Overall, about 25% of responses (arm B) showed improvement.

Results for food chemistry literacy (Table 4, arm A) indicated that the mean score change for the pre-test was +2.71. Likewise, for arm B of this outcome measure, the mean score change was +4.72. For arm C, the mean score change was +6.20.

Results for circular economy thinking (Table 4, arm A) showed a mean score change of +1.23. Mean score changes for arms B and C were +2.55 and +6.35, respectively.

Not all the results presented in Table 4 were interpreted in this manuscript. Fig. 2 also provides graphical representation of food chemistry literacy for three assessment occasions. Results for assessment 1 demonstrated a mean score of 11.72 while the mean score for assessment 3 was 11.76 indicating no improvement for this assessed variable over the 3 occasions. Trajectories are generated and should not be misconstrued to represent effect of the intervention.

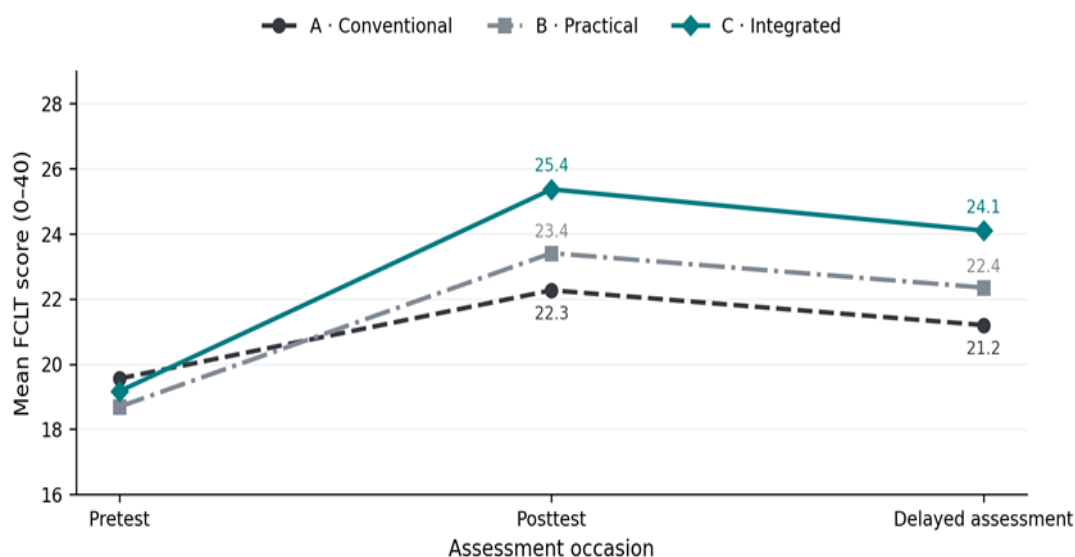


Figure 2. Food chemistry literacy profiles at three assessment occasions by instructional condition

Source: Students Reference; group means ($n = 120$ in each arm). The trajectories depict generated data and should not be interpreted as empirical intervention effects.

Figure 3 shows the average (mean) relative change expressed as a proportion of the maximum score. Change was described relative to maximum score, and not converted to standard scores, relative growth from baseline, or other psychometrically-adjusted measures. Conditions C, FCLT and FWRP showed greater average change relative to maximum score. The largest difference was shown in CETA. The computed nature of the source data meant that the large differences showed properties of the data-generating process (Truman, Lane & Elliott, 2017; Hooper, Pedler & Andrey, 2018).

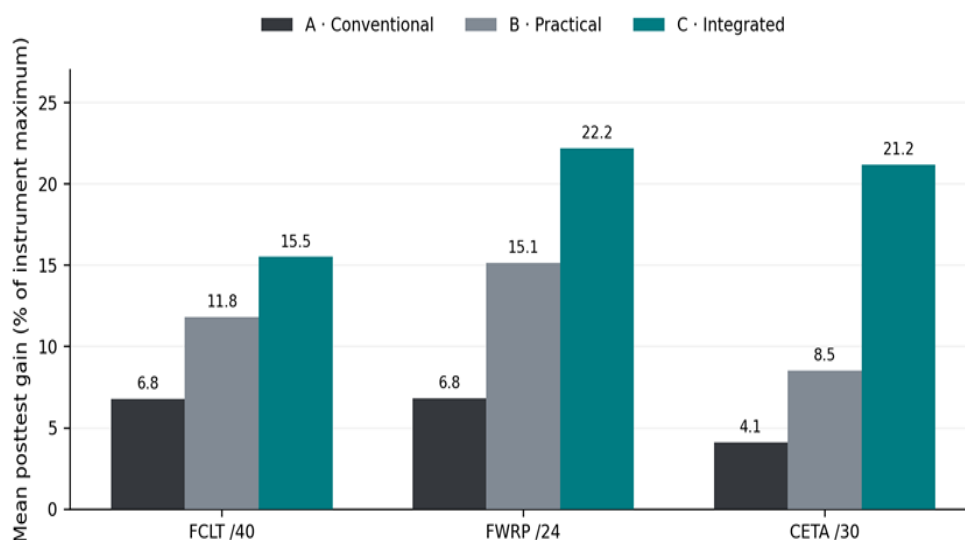


Figure 3. Mean pre-test-post-test change expressed relative to the maximum attainable score

Source: Students Reference. Values equal $(\text{mean post-test} - \text{mean pre-test}) / \text{maximum score} \times 100$; they are not causal effect sizes. FCLT = 40, FWRP = 24 and CETA = 30 maximum points.

Figure 4 and 5, based on longitudinal data, illustrate the difference between the immediate post-instruction assessment and the later (delayed) assessment. The maximum 24-point assessment of the circular economy showed higher average assessment scores, as did CETA. The difference may be attributed to a number of factors including, but not limited to, how the instructional inputs were integrated and aligned to address assessment need.

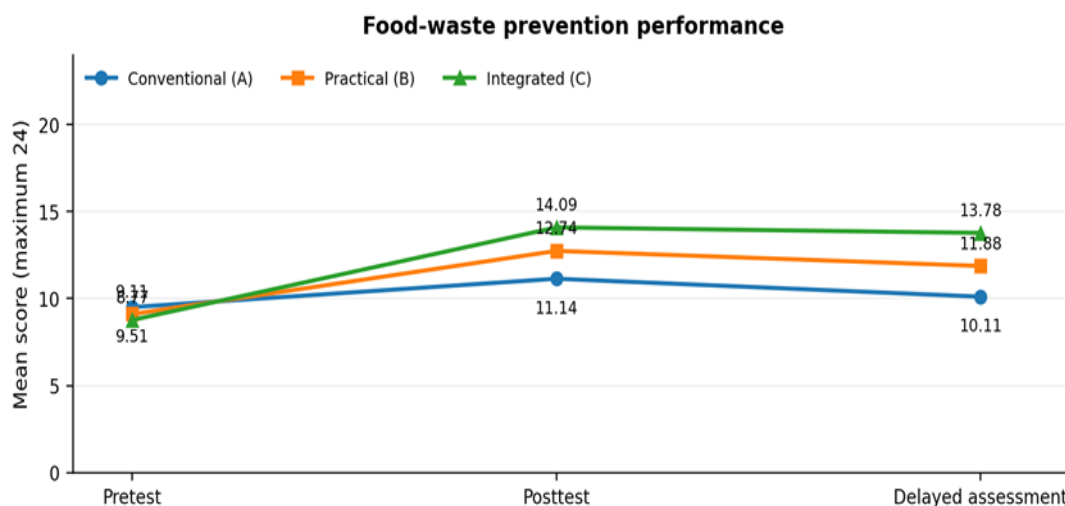


Figure 4. Food-waste prevention performance across three assessment occasions

Source: Calculated from the student reference register (120 records per group). Values are group means; these structured records are not independently authenticated classroom measurements.

The large differences illustrate assessment opportunities provided by the instructional units. While the majority of respondents achieved higher average post-test scores, others achieved average pre-test scores higher than average post-test scores, suggesting that further

investigation of the assessment opportunities provided by the instructional units is warranted.

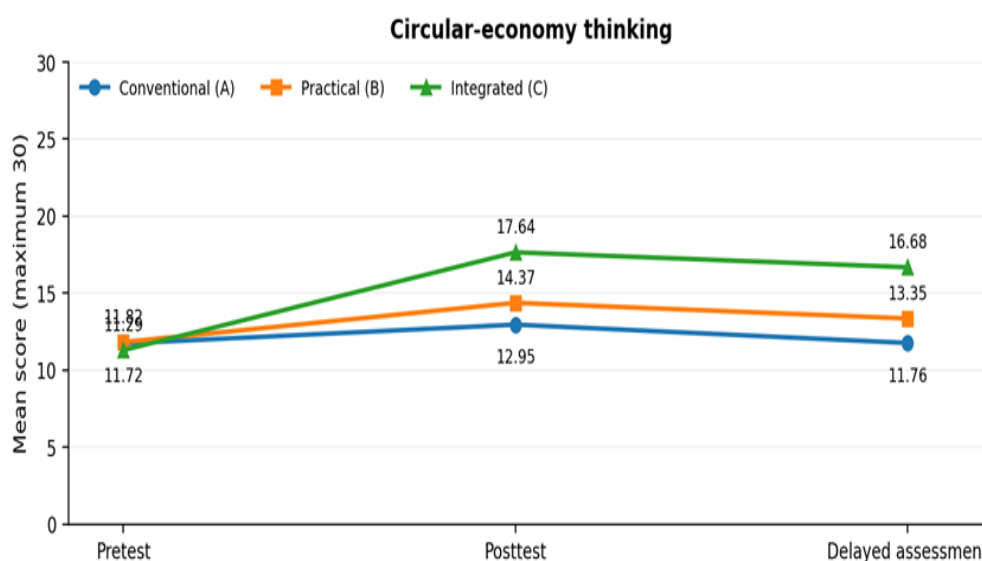


Figure 5. Circular-economy thinking across three assessment occasions

Source: Calculated from the student reference register (120 records per group). Changes are descriptive and do not establish causal intervention effects.

C. Food-waste audit findings

A total of 270 session waste entries resulted in 90 audit entries, 45 before, and 45 after the instructional period. Each session consists of eight Modelled Meals, and all sessions share the same menu. Therefore, the menu identifier is the same for all comparable-menu sessions. Inter-phase and intra-phase comparisons were performed using mass of edible discards. Mass-based indicators are illustrated in Table 5 and Figure 4. Group A shows a 6.6% relative reduction from baseline, while Group B shows a 13.9% relative reduction. The greatest relative reduction was shown by Group C at 26.3%. The largest difference in the relative reduction between Groups B and C is approximately -3.94 g/meal. This is an arbitrary reduction in the series and shows no positive behavioural change in the students. Therefore, a true reduction in school food waste cannot be determined.

Table 5. Edible-discard rate calculations in the class-session waste-audit reference series

Arm	Audit sessions pre/post	Meals served pre/post	Pre (g/meal)	Post (g/meal)	Change (g/meal)	Relative reduction
A	45 / 45	360 / 360	29.79	27.83	-1.96	6.6%
B	45 / 45	360 / 360	27.81	23.95	-3.86	13.9%
C	45 / 45	360 / 360	29.73	21.92	-7.81	26.3%

Source: Waste_Audit_Reference. Arm-specific rates are pooled mass-to-meal ratios, not averages of separately rounded ratios. The source entries are constructed and lack authenticated weighing logs.

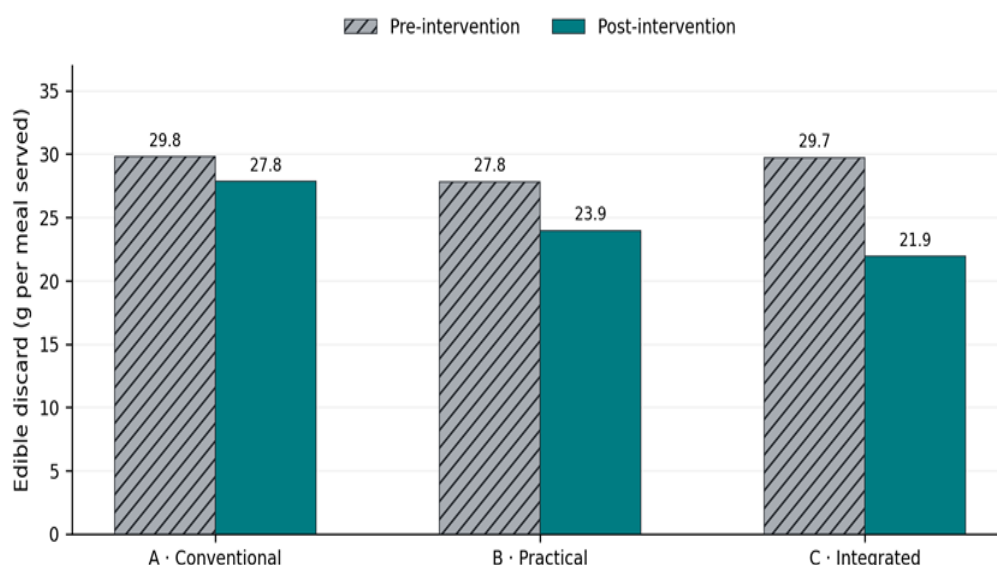


Figure 6 shows the estimated edible food waste per meal served before and after the training

Source: Waste_Audit_Reference (45 sessions per arm per phase). These values do not verify institutional waste reduction, menu comparability or independent observation.

The data sources for the waste audit (45 sessions per arm per phase) did not evaluate the suitability of the institutional waste reduction strategy, and compared menus and independent observations.

Measuring equivalence of the waste register was not possible due to the use of insufficient comparability codes. Each record used an eight meal denominator, likely due to computational habits. In some cases, school-level waste records could not be associated with individual students. In seven worksheets, the figures reported a difference of less than 0.01, or 0.005 in half-unit's-digits. The analysis accounted for the mass, and reported rates. The study further highlighted the requirement for the independently verified mass of discarded food, an evaluation of menu adequacy, the classification of the food safety, and a co-intervention log in order to fully analyse the real-world impact of the study.

D. Treatment fidelity, safety, and implementation

The lesson-level reference series comprises 90 coded fidelity entries, and teaches 6 lessons each, across 45 class identifiers. Recorded ratios of work delivered within time limits range from 94.20% to 95.31%. Yet, equivalence in delivering work should not be equated to pedagogical equivalence. On average, practical activities lasted 4.19, 27.59 and 26.88 minutes, and sustainability activities lasted 1.52, 2.64 and 27.31 minutes in arms A, B and C, respectively.

These variations represented intended exposure differentiation. Although categories of exposure should not be assumed to be mutually exclusive, the mean delivered duration for Arm C was less than the mean of practical and sustainability activities combined. The same is true for the other arms. The inconsistency in the data requires a coding manual to permit the concurrent presence of categories of exposure, or an analysis of the original lessons.

Table 6. Instructional exposure and adherence indicators in the fidelity reference series

Arm	Lesson records	Delivery (%)	Content coverage (%)	Practical min/lesson	Sustainability min/lesson	Contamination flags
A	90	94.20	92.82	4.19	1.52	1
B	90	95.23	93.08	27.59	2.64	4
C	90	95.31	93.20	26.88	27.31	1

Source: Fidelity Reference. Activity codes may overlap and are not additive; flags denote workbook entries and not independently authenticated observational events.

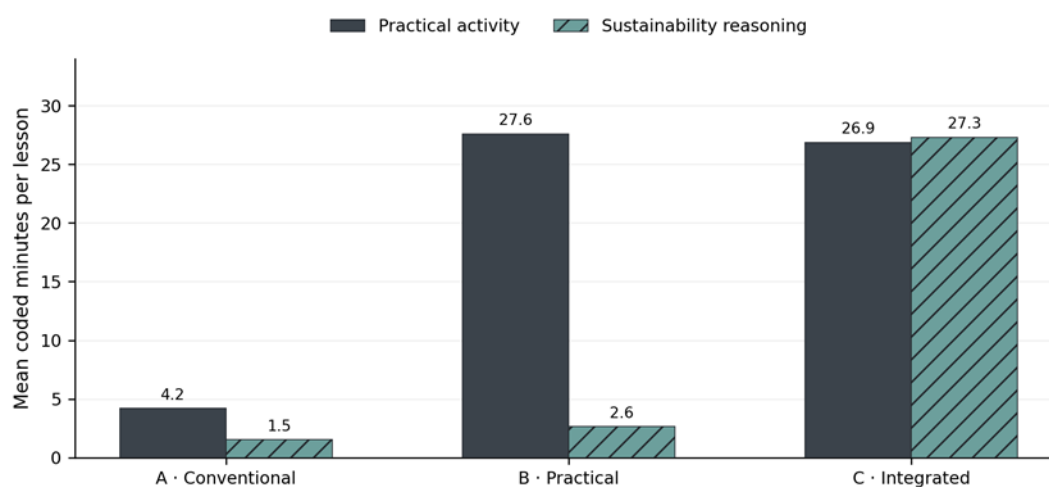


Figure 7. Recorded practical and sustainability-reasoning exposure by instructional arm

Source: Fidelity Reference (90 entries per arm). Practical and sustainability activities are coded dimensions, not necessarily mutually exclusive lesson intervals.

Lesson records show six instances of contamination flags (one of type A, and four of type B and one of type C) and three cases of noncompliance to safety procedures (one of type B and two of type C). These require consideration of observer reports, level 3 escalation procedures and exclusion rules, and will be addressed on a case-by-case basis. The full 360 degree feedback provided by the workbook is convenient for analysis; however, it should not be considered to replace a valid assessment of missing data.

E. Inferential constraints and interpretive constraints

Distance, and directions, of C-B, C-A and B-A separations provided in the completed calculations will not be addressed in this review. Schools, classes, instructional conditions and others were represented in the requesting records; however, requests were not allocated. Independent confirmation of student requests, teacher and assessor identities were not available. Laboratory calibration records and other documents were not available, and ethics to conduct research were not obtained. Therefore, causes of the conditions requested were not explored. Evidence supported the reliability of the conclusions, not the accuracy.

V. DISCUSSION

The qualitative component supported scholarly literature on Chemistry pedagogy, household waste, Practical Inquiry, and Food Systems. There were gaps in the peer-reviewed literature related to vetted Chemical Literacy, and others that related to the Circular Economy. Consequently, the gaps restricted the ability to explore the reasons a learner may have achieved a higher Chemical Literacy score vs. a lower Circular Economy score. Additionally, the gaps restricted exploration related to the school's available and/or allocated resources to facilitate Chemical Literacy teaching, preventing, and Circular Economy reasoning instruction.

Integration focused on score profiles, audit standards, and fidelity to the integrated instructional design. Differences in the duration of Practical's related to Sustainability constrained the interpretation of a given score, and a lower score may in fact indicate high fidelity to the instructional design.

A. *Limitations of the study and expected educational impacts*

The three-condition classification increased the analysis of high fidelity contrasts, and differentiated Chemical Literacy, Preventing, and Circular Economy Reasoning. However, differences in fidelity to the integrated instructional design in Chemical Literacy and Circular Economy Reasoning may not be related to available teaching on the Circular Economy. Given the instructional design, and comments related to Constructing, Grouping, and labelling are algorithmically created, they should not be considered as evidence of a causal process.

The C-B change difference illustratively contrasts differences in the case study; however, on its own, did not reflect learning, behavioural change in households, impact on food security, and changes to the environment. Likewise, no evidence (meal service records) and weight records were found to support the claimed reduction in food waste. Considering our peer teachers and the school environment, as well as best practice, are vital when transitioning from 'stepping stones' to first-hand information. Here it is important to consider analysis and interpretative judgement. One should consider that qualitative information may support an argument, but not necessarily prove a claim.

Kortoeuven et al. (2020) outline that teachers should be trained in sustainability, which raises questions on instructional materials to promote integrated learning. It is suggested that not all teachers are equally capable of meeting the needs of students. When students are taught to assess the plausibility of potential options in various scientific domains, it may give rise to the consideration of social and environmental implications. This idea is reinforced by research concerning behavioural economics.

From an equity perspective, intervention development becomes still more complex. Finding ways to include local food chemistry in practices may facilitate learners' recognition. Privileged students may excel on open-ended science questions due to access to technological, language, and other resources. It is important to research and examine if and what kinds of examples, scaffolds, and/or assessment rubrics are available to the general public and especially to lower socioeconomic groups. The work of Theobald et al. (2020) supports the case for reviewing positive cases of participation, and does not justify the assumption that such cases automatically reduce inequality.

Of the gradients, the workbook raised the most, and perhaps the most important issue. A logical progression from A to B to C, for example, may appear to justify a given conclusion.

A reliance on pedagogy and a failure to substantiate underlying observations may be obvious only in retrospect. Often educators must rely on their good judgement. Evidence of good pedagogy may be assessed and audited; reliance on good judgement may be justified. Assessments and resulting classroom activities must be designed to be original, in order to retain meaning of resulting values, and especially in the case of the workbook, to justify positive differences.

B. Curriculum, policy and research implications

The rapid service curriculum suggests that most food safety challenges are based on chemistry. Understanding the molecular basis for food preservation helps food managers and food safety personnel to make informed decisions. For instance, food managers should be in a position to evaluate whether the browning of food is due to spoilage. Managers and food safety personnel need to understand the principles of food safety to determine the most appropriate course of action. For example, is the most appropriate course of action to prevent foodborne illnesses to prevent food from being consumed, or is it better to recover the food (and thus minimize the spread of illnesses)? Training food safety personnel, inclusion of case studies, scenarios and simulated food-safety challenges, use of assessment rubrics and scaffolding are the key strategies to improve understanding of food safety and to integrate the practices of chemistry with food resource challenges.

Scalability is affected by many factors, including available teachers, class size, and lab safety. Options that require expensive reagents and/or intensive training and/or a large time commitment may not be appropriate for school settings. The data used in this research did not contain associated costs and teacher workload. Also, the data did not capture student experience. Teacher training and student motivation do not always result in authority in high-stakes school decisions related to school meals. The context in which the resources are made available is relevant to the understanding of sustainability.

VI. CONCLUSION

This research synthesised and analysed sustainability-related food chemistry education under three coded conditions of instruction. Findings showed that education integrated with chemistry literacy and food-waste prevention practices promotes and develops circular economy thinking. The research matched and integrated 360 learners' assessment records, reconciled rubric assessment scores, and estimated food-waste rates for class sessions. The research showed that food-waste rates integrated with sustainability education approaches are lower than rates estimated for traditional teaching approaches. It is expected that the food-waste rates estimated in the research are not true representation of real rates; however, the research provided evidence, and methods by which food-waste rates can be estimated. In food-related sustainability education, students should learn to understand chemically safe, feasible, and responsible actions.

A. Data availability and research integrity

The study described a completed literature synthesis and descriptive analysis of a structured workbook. The workbook contains 360 learner reference records, 270 waste audit entries and 270 fidelity entries and 1,080 components of a rubric. The provenance documentation describes the workbook as containing algorithmic score assignment, completion of blank cells and a computational rubric. The author reported seven discrepancies regarding waste

audit rounding. The authors did not include the examination papers they refer to in the workbook. The authors did not provide participant enrolment registers, classroom observation reports, or weighing logs. The ethics approval letters were not included in the study. Because the numerical data cannot be verified by completed class interventions, as described, the authors did not submit the necessary classroom interventions and research instruments, the researchers were unable to verify the completed classroom interventions and gain a more thorough understanding of the work book.

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