# ADOPTING SUSTAINABLE MICRO CHEMISTRY ACTIVITIES FOR CONCEPTUAL AND FINANCIAL BENEFITS

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**ABSTRACT**

This paper examines how the use of micro chemistry equipment can support effective practical lessons in schools to minimize cost, save the environment, and promote contextualization of theory. It particularly assesses the relevance of scaling down activities to sustainable development as well as gains in scientific conception, reduced exposure to hazardous chemical, reduced waste generation, and implicit financial gains. Through a case study, data were obtained from two different groups of students totaling 115 through laboratory activities, tests, questionnaires and observation schedules to ascertain the potential of the micro chemistry equipment in four micro labs. Findings indicated that participants found the micro chemistry labs to be safe, required the use of minimal chemicals as compared to conventional equipment in standard laboratories, generated less waste, and enhanced their understanding of theoretical concepts. Implications were discussed and recommendations made from the findings. *[African Journal of Chemical Education—AJCE 12(1), January 2022]*

## INTRODUCTION

There is no doubt that hands-on activities are best practice for learning chemistry, as they make students feel like chemists and enable them to build their own concepts from first-hand experiences. However, the cost of obtaining equipment and chemicals, especially for chemistry activities is not only exorbitant but comes with its own risks and hazards [1, 2]This problem can be addressed by minimizing the use of chemicals through the use of a micro (miniature) science equipment [3]. Micro science equipment has been used in America, South Africa, Malaysia, and Taiwan with great success [4].

Chemistry educators have over the years, emphasized on the importance of chemistry practical activities to help students understand the theory, nature, and practice of science, as it influences the lives of individuals and entire communities [5]. Practical activities are important because the experiences help students to acquire variety of science skills [6]. They equip students with transferrable skills that they can apply effectively to make everyday life worth living and meaningful in varying situations.

In the school setting, chemistry practical activities avail students with enabling environments to either refute, confirm or come up with new ideas about natural phenomena [7]. Through such activities, students are able to form vivid, concrete and understandable concepts through visualization, assimilation and accommodation. The rationale for conducting practical work in chemistry is to reinforce a course through illustration and to make it real for students, as visualization is an important component that facilitates retention of knowledge. In addition, they develop techniques and skills that are either cognitive or practical in nature, such as physical manipulations, problem solving, data handling, interpretation of results, time management and dealing with errors [3]. In the absence of these, the probability of having broken linkages in concept formation and the subsequent formation of misconceptions, may arise (Author, 2017).

Quite often, non-availability of the necessary equipment for chemistry activities, the cost of expensive, delicate and complicated equipment puts the benefits of science out of the reach of most students – especially, those in less endowed communities [2]. Besides, certain chemistry activities in particular come with risks to students, and so although activities are advocated, they are not practised in reality in some institutions. At best, students may only observe demonstrations of such activities, as they are performed by teachers, or through video animations. If they are lucky to be in endowed environments that are furnished with computers and internet, they could carry out virtual laboratory activities and observe them from a 'safe distance'. For example, activities such as the reaction of some s-block metals, like potassium and caesium with water, the disintegration of radioactive materials, and fusion processes that generate massive heat, could be performed virtually and observed. Such virtual activities might illustrate or confirm theories and principles, but they do not necessarily require students to think deeply about their actions nor test hypotheses, interpret data or engage in critical thinking. Non-inquiry 'cook-book' experiments do not expose students to hands-on experiments and interactive environment [3, 7], while planned and scaffolded experiments expose students to useful, integrated hands-on activities. Hands-on activities provide opportunity to inspire students and make chemistry lively enough to remember. They help students to answer questions, prove or disapprove ideas, collect and analyse data from their experimental results and apply them meaningfully [8]. Students need real experiences to understand underlying concepts and so safe and less costly procedures must be provided to minimize the occurrence of accidents to the barest minimum, increase the practice of science and cut down costs of resources for activities.

Apart from high cost of resources and risks factors, inadequate supply of electricity, and running water have been found to be other factors that limit teachers' desires to organise practical activities for their students. The micro equipment requires the use of water as required in standard or conventional activities, but *not* in copious volumes as would be required with the use of conventional equipment. Again, the supply of conventional equipment, if available, has been a challenge due to the nature of bad access roads to schools in remote communities [9]. Most glassware gets broken by the time supply trucks reach these less developed communities. The complication is that it could hamper supply efforts and thereby reduce the possibility of students' engagement in concept-building chemistry activities. Most Ghanaian schools and many other African schools that fall within this resource-constrained category cannot have the privilege of experiencing first-hand concept-building, confirmatory, or fact-finding chemistry because they fall into this category where supply processes are hampered. Furthermore, work and storage spaces are not available in less endowed communities, some of which do not even have adequate classrooms.

Where chemistry resource supply is made available, the problem of waste chemical disposal poses a threat to human life and the environment. Propositions put up by green and micro/small-scale chemists to solve these problems are to reduce the scale of chemical use to a minimal level at which activities can be effectively performed as well as to use low-cost equipment that would make financial demands on institutions and national resources bearable [10, 11, 12, 13, 14]. These propositions were based on the inherent-concept-based nature of the micro chemistry science equipment (MCE). Thus, using micro-scale chemistry equipment could be the solution to conceptual, financial, and environmental problems associated with school chemistry activities and waste disposal, if education must reach all by the year 2030 [15, 16].

In many African communities, micro-scale chemistry equipment has been used for the past two decades yet, it is not popular as compared to the conventional macro equipment [1, 12]. The micro chemistry equipment (MCE) was introduced in underprivileged basic schools in South Africa by Bradley [17] with a lot of success. It was introduced in deprived communities where equipment and resources were scare, in order to facilitate the teaching of hands-on activities. All users (teachers and students) were enthused with its simplicity and how it aided in cognitive gains. The equipment was also successfully used in secondary schools in Tanzania by Mafumiko [2] to teach basic chemistry concepts, and by Kombo [18] to teach distance education teachers in teacher training colleges in Mozambique. The equipment offered students in all instances, the opportunity to study chemistry through hands-on activities in a safe, simple, interactive, and sustainable environment.

This idea of hands-on activities with simple equipment is supported by the United Nations Educational Scientific and Cultural Organization [19] for global use as it emphasizes sustainability and improves quality of life in laboratories. It is also to develop and design unconventional methodologies for most school activities in order to reduce environmental pollution.

The micro-scale chemistry equipment comes in the size of a lunch box, and measures 14.5cm x 11cm x 5.5 cm. It contains a range of miniature plastic wells called comboplate, forceps, a gas collecting tube, micro burner, pH guide, universal indicator, micro spatulas, syringes, and propettes, among other components which constitute almost an entire laboratory. So far, the University of Witwatersrand, North Western University in South Africa, and other institutions in the Asia-Pacific regions have produced their own more durable micro chemistry equipment for use. Some of these are made from materials (such as pyrex) that allow for heating at high temperatures and the use of stronger chemicals like tetraoxosulphate (VI) so as to expand the range of activities that could be performed at, especially, higher levels of science education [14]. Some institutions in USA and UK have also either produced their own micro equipment or adopted those produced by United Nations Educational Scientific and Cultural Organization (UNESCO) and engaged their students in ‘safe’ activities [11].

Micro-scale chemistry equipment (MCE) activities use minimal amounts of chemical substances in the range of 1mL and about 150 mg so the fear of accidents during practical activities is eliminated among students as was discovered in a study where small-sized home laboratory kits were used [3]. Since work solutions are minimal, reaction times are shorter and so more time is availed for discussions and reflections on activities for better conceptual understanding of principles. Currently, nations are bothered about the effect of hazardous waste on green life and the environment in general, as well as high cost of science education [15, 1]. It is therefore prudent to introduce students to micro scale or green science, so as to instill in them the importance of creating eco-friendly (green) work environments early. Green science is the application of eco-friendly scientific manipulations to scientific disciplines such as chemistry, physics, biology, integrated, and environmental science disciplines. Micro-scale chemistry, which is known as green chemistry in some circles [20], can easily be used to teach courses such as analytical chemistry, organic chemistry, inorganic chemistry, and environmental chemistry topics like global warming, acid rain, pollution and other impacts of chemistry activities on nature and the planet.

Employing micro-scale kits for teaching chemistry practical activities ensures miniaturization of laboratories to small portable equipment packages for teaching [10]. Wastes from the use of these miniaturised equipment and materials therefore do not pollute the environment to unacceptable levels, as could be the case with standard or conventional macro equipment. They can conveniently be used to perform majority of school science in normal classroom settings [10, 21]. The micro-scale equipment from South Africa in particular is robust, resilient, unbreakable and inexpensive, because of its plastic-like nature. It has been designed to enhance the quality, relevance and accessibility of science and technology education. Similar findings on the benefits of its robust nature were made by Hanson [21] in Ghana. It was found to generate minimal hazardous waste in a study in UK [11]. This improves the quality of air in the laboratory. According to Abdullah, Mohamed and Ismail [22] and Tantayanon [14] skills such as accuracy, precision and carefulness are heightened, especially in organic chemistry activities, where students have to ensure that they get the maximum yield of some kind of product for purification and further processes. Ogino [13] also affirms that the benefits of microscale science include reduced waste, reduced time, improved safety and major cost reduction.

The pedagogical reasons for promoting the use of low-cost equipment are to provide simplified, relevant, safe, and attractive experiences, as well as overcome psychological basis to using standard equipment when necessary [23]. Bradley [10], found that MCE experiments help to solve problems which educators face when planning practical work, such as fear of getting hurt, insufficient equipment, shortage of or inadequate chemicals, lack of work space for large classes, lack of assistants, insufficient work time, and lack of confidence on the part of inexperienced educators, and so propagated it. Micro labs provide skill and knowledge acquisition and are replicas of real-life or standard labs. Knowledge is obtained in risk-free environments with reduced periods of contact with chemicals [23].

In recent times, most developed countries are moving away from the conventional macro chemistry equipment activities to micro and nano activities, so as to cut down escalating costs of infrastructure, stocking laboratories and legal issues connected with the disposal of generated hazardous chemical waste [13, 14]. The move is also to stimulate students' interest towards chemistry in a friendly, risk-free, pleasant, and sustainable manner [20]. In this way, micro chemistry and green chemistry inherently work in consonance to conserve the environment [24]. This eco-friendly consciousness has helped in promoting a better image of science, and chemistry in particular, lately [24]. In the USA and India, sustainability and sustainable development have emerged as the core of the chemical industry, its actions, and public image. Though some institutions in the USA have developed chemical policies, yet, they still pursue micro-scale and green chemistry to ensure sustenance and maintenance of the environment, which are laudable and must be adopted by other nations.

Home-laboratory kits, which are akin to MCE have been developed in some institutions in Canada to enhance chemistry education at a distance to perform what they term 'kitchen chemistry experiments' at home in order to overcome students' diffidence as they come face-to face with supervised standard laboratory sessions [3]. According to Kennepohl, students found home-laboratory kits to be robust, portable, safe, inexpensive and precise (± 0.01g).

Increased generation of chemical waste from conventional laboratory activities, as a result of improper waste disposal is becoming an issue of concern all over the world. In the developing world proper disposal ethics are not followed– because there seems to be no institutional or national policies for managing chemical wastes in educational institutions. Some generated solid chemical wastes could be ignitable, corrosive, reactive or toxic. From the researcher's observation Ghanaian institutions do not have waste disposal containers such as chemical spill kits, hazardous waste containers or corrugated cardboard boxes for disposal of sharps and broken glass. Some seemingly harmless laboratory wastes could generate into dangerous wastes as a result of secondary reactions when they are discarded into general collection bins or drains indiscriminately. The best way to go is waste reduction. Steps must be taken to reduce the scale of chemical use to avoid environmental catastrophe in the study of science and chemistry in particular. Sustainable development must of necessity become a key issue in science education. Adding sustainable development issues to the chemistry curriculum could be laudable [24, 25] to create the awareness that waste generated in labs affect not only students and faculty in the vicinity but the entire institution and the other spheres.

In the last three decades, many scientists have been faced with issues such as maintaining clean water, managing the effects of acid rain, and searching for both renewable sources of energy and raw materials through cost-effective micro activities [24] because of pollution from chemical waste in diverse forms. The study of these social topics has been added as content in many chemistry curricula in order to portray chemistry and society as an everyday way of life. The scientific economic value of the MCE as far as reduction in budgets for laboratory activities was not found in the literature reviewed, at the time of this study. The researcher would therefore like to undertake a conceptual, financial, and laboratory waste analysis exercise of some micro laboratory activities on face value. This would enable the assessment of the possibilities that the mass adoption of the small-scale equipment could afford Ghanaian students, institutions, and science education as a whole, in terms of cognitive gains, dwindling budgets, as well as law suits over environmental pollution.

**Purpose of the study**

This study presents the environmentally-friendly, conceptual, and budget-wise micro-scale chemistry equipment by analyzing four (4) laboratory activities from a first-year undergraduate chemistry course [12]. The main objective was to assess the possibility of projecting micro-scale chemistry activities among chemistry teacher trainees, chemistry educators, curriculum developers and investors/stakeholders of chemistry education so that safer, cheaper, sustainable, environmentally-friendly and concept-based activities could be performed in many more, especially deprived schools.

The question which guided this study was:

What conceptual, financial, and environmental benefits could be derived from the adoption of micro chemistry equipment and micro practical activities (labs) towards sustainable development?

## METHODOLOGY

**Participants**

Out of eight laboratory activities for a semester, four (4) were performed on micro scale by 57 undergraduate Chemistry major students (out of 115) who were purposively assessed for conceptual, financial and environmental impact differences against similar activities performed on macro scale by another group of 58 (out of 115) Chemistry minor students. The entry points of both the Major and Minor students were similar as shown by results of a pre-test.

**Labs**

All the labs were aligned with the University of Education's (UEW) institutional and departmental curriculum requirements. These labs were:

1. Effect of temperature on equilibrium;
2. The stoichiometry of a precipitation reaction;
3. The common ion effect; and
4. Effect of sulphur dioxide from industries on open waters.

The MCE kits were ordered from the Centre for Research and Development in Mathematics, Science and Technology Education (RADMASTE) in Witwatersrand University, South Africa at eight Euros (€8.00) per kit. The introduction of the micro lab was to attempt to mitigate cost of lab work and introduce the research acclaimed conceptual and environmental benefits of the MCE [17, 2, 24, 11]. The chemicals and equipment used for the four (4) activities were test tubes, beakers, Basic microchemistry (microscience) kits, water, copper turnings, sodium chloride, sodium sulphite powder (Na2SO3) and aqueous chemical solutions of 6M HNO3, 11.7M HNO3, 5.5 M HCl, 11M HCl, 0.25 M Pb(NO3)2, and 0.25 M NaI.

**Research Procedure and Data Collection**

Prior to teaching the theory and lab practice of Le Chatelier's principle, chemical stoichiometry, and industrial pollution, all 115 students who participated in this study wrote a pre-assessment concept test. Each pre-assessment concept test (Appendix A) was followed by a theory lesson. A one-time post-assessment concept test was also administered after all the topics covered and activities were performed. Discriminatory, difficulty index, and factor analysis indicated that the test items were appropriate for their intended use. The assessments particularly covered the four labs in which MCE were employed. The chosen labs were compliant with the use of MCE.

The researcher taught and facilitated laboratory activities while one trained research assistant observed all laboratory activities (with an observation guide, noting significant events every five (5) minutes) and took anecdotal notes in the micro lab so as not to miss important and interesting occurrences that would contribute immensely to the research. A second research assistant also observed students' activities in the standard laboratory and took notes, besides the observation schedule that was used. Trained National service personnel assigned to each of the laboratories assisted in making the observations for the purposes of inter-rater reliability. An independent evaluator who was not part of the study but in a similar research assessed the lessons and helped to analyse data to remove researcher biases that could arise. By virtue of a student's status of a major or minor choice for chemistry they were assigned to use either the macro or micro equipment to perform their chemistry laboratory (lab) activities in separate laboratories.

Theory lessons lasted for two credit hours while the lab hours for hands-on practice also lasted for two hours but documented as one credit hour in accordance with institutional requirements. Each of the concept assessments and practical laboratory activities was scored over 20 marks. Students who participated in the micro equipment activities were required to answer a 10-close-ended-item and one open-ended item questionnaire which was rated with a Cronbach alpha reliability of 0.72, at the end of the study. This was to enable them to express their opinions on the feasibility of employing MCE in higher institutions and for conceptual understanding. The open-ended item was necessary to allow students to provide honest confirmatory or disapproval statements (evidence) of what was in the closed part of the questionnaire. The questionnaire is presented as Appendix B1. Students who performed the macro labs were given a similar questionnaire that was worded differently in some aspects (without the use of 'MCE') to ascertain their impressions about the macro labs. This questionnaire is presented as Appendix B2.

The prices of stock chemicals and equipment that were used to work out the exact cost of the various quantities that were needed for each macro and micro activity are shown as Appendix C.

## RESULTS

Participants' results from their pre- and post-assessment concept tests were compared to assess their conceptual gains. Their lab activities were also analyzed. The results are presented as Table 1.

Table 1: Mean score values for pre- and post- assessment tests and activities

| Group | Test | Lab 1 | Lab 2 | Lab 3 | Lab 4 |
|---|---|---|---|---|---|
| Macro (pre) | 7.36 | 8.97 | 10.00 | 12.96 | 14.86 |
| Micro (pre) | 8.01 | 9.06 | 12.47 | 16.20 | 18.25 |
| Sig. (2-tailed; Pre) | 0.16 | | | | |
| Macro (post) | 12.34 | | | | |
| Micro (post) | 17.89 | | | | |
| Sig. (2-tailed; Post) | $1.2 \times 10^{5}$ | | | | |
| Sig. (2-tail Labs Micr & Macr) | 0.117 | | | | |

N = 115; Pre = Pre-test; Post = Post-test

Results from Table 1 show that both groups had about the same conceptual entry points for concepts assessed as there was no statistical significance difference (p=0.16) in their initial content knowledge. However, after tuition and engagement in hands-on activities there was a statistical difference in students' post-concept assessment at t (56); $p < 0.00$, with post scores higher than the pre-assessment concept test scores at a 95% confidence interval of difference. Differences in the point of departure in post-assessment scores could be attributed to the type of equipment used in science practical work and its particular attributes, because all other variables remained the same except for equipment used. From observation, students in the micro lab class had more practice time as results were achieved in relatively shorter times and they could have a couple more trials as well as lengthier discussions of their results. Similar observations were made by other researchers who engaged students in micro labs [4, 2, 3]. There was no direct correlation (0.07) between the macro and micro group test scores. Neither was there much difference between their laboratory reports, statistically.

A financial analysis of the resources necessary to perform the four lab activities was also assessed in this paper. These labs were particularly chosen because they formed part of the second semester lab practice in first year tertiary Chemistry studies. They are also essential parts of high school chemistry curricula that students must be conversant with. Besides, the activities required the use of chemicals, some of which when carelessly disposed could cause damage to the environment and had to be used in moderation.

Table 2 shows the costs involved in purchasing resources for the activities on equilibrium, chemical stoichiometry and pollution studies in Euros (€).

Table 2: Comparison of cost of chemicals for activities (in euros)

| Lab | MAch | MIch | MAch-MIch |
|---|---|---|---|
| Effect of temperature on equilibrium | *45.19* | *8.26* | *36.93* |
| Stoichiometry | *7.29* | *1.43* | *5.86* |
| Common ion effect | *8.40* | *1.77* | *6.63* |
| Industrial pollution | *5.79* | *1.24* | *4.55* |
| Cost saved with use of microkit (N=57) | | | ***€53.97****/ $63.50* |

MAch = Macro chemical; MIch = Micro chemical

Table 2 showed a comparative picture of prices of chemicals required in the conventional (macro) and micro activities for the three activities.

The actual quantities of chemicals required for the activities for whose costs are shown in Table 2 are presented in Table 3.

Table 3: Quantities of equipment and chemicals required for the three lab activities

| Activity | Equipment/chemical | Macro quantity | Micro quantity |
|---|---|---|---|
| Temperature on equilibrium | *Beaker | 58pcs | 0pc |
| | *Test tube | 58pcs | 0pc |
| | *Micro kit | 0pc | 57 kits |
| | Cu(s) | 239.54 g | 57 g |
| | 6M $HNO_3$(aq) | 580mL | 28.50mL |
| Chemical stoichiometry | *Test tube | 58pcs | 0pc |
| | *Micro kit | 0pc | 57 kits |
| | 0.25M $Pb(NO_3)_2$ | 24.01g | 4.72g |
| | 0.25M NaI | 10.87g | 2.13g |
| | 0.25M $Pb(NO_3)_2$ (aq) | 290mL | 57mL |
| | 0.25M NaI (aq) | 290mL | 57mL |
| Common ion effect | *50 ml Beaker | 184 | 0 |
| | *Micro kit | 0 | 57 |
| | 11M HCl(aq) | 58mL | 57 drops (1.27mL) |
| | 11.7M $HNO_3$ | 58mL | 57 drops (1.27mL) |
| | NaCl(aq) | 81.54g/58mL | 285 drops (6.3mL) 54.15g |
| Industrial pollution | 5.5M HCl(aq) | 58mL | 6.16mL |
| | $Na_2SO_3$(s) | 114.84g | 28.50g |

* Microkits, beakers and test tubes were not priced because they are not 'consumables'.
*1mL of solution = 45 to 47drops from a propette;

Table 3 showed quantities of resources that were required by the macro and micro groups in performing their activities at the same concentrations of chemicals but different volumes.

The volumes of waste chemicals which were generated from the activities and wrongly discarded into drains are presented in Table 4.

Table 4: Volumes of generated liquid chemical waste from macro and micro scale activities

| Activity | Summation of toxic waste | Macro waste | Micro waste |
|---|---|---|---|
| Temperature on equilibrium | Macro:<br>580mL of $HNO_3$ and 2,900mL of water<br>Micro:<br>28.50mL $HNO_3$ and 1,425mL water | 3,480mL | 1,453.50mL |
| Stoichiometry | Macro:<br>290 ml of 0.25M $Pb(NO_3)_2$ (aq)<br>290 ml of 0.25M NaI (aq)<br>Micro:<br>57 ml of 0.25M $Pb(NO_3)_2$ (aq)<br>57 ml of 0.25M NaI (aq) | 580mL | 114mL |
| Common ion effect | Macro:<br>58mL each NaCl, HCl and $HNO_3$<br>Micro:<br>1.3mL each NaCl, HCl and $HNO_3$ | 174mL | 8.90mL |
| Industrial pollution | Macro:<br>58mL of HCl, 114.8g $Na_2SO_4$ 11,600mL $H_2O$ (acidified)<br>Micro:<br>6.2mL of HCl, 28.5g $Na_2SO_4$ and 285mL $H_2O$ (acidified) | 11,658mL | 291.2mL |
| Total waste | | 15.892mL | 1,867.6mL |

N = 58 for Macro & N = 57 for Micro

From Table 4, it is evident that about eight and half (8½) times more of liquid toxic waste chemical was generated in the macro lab as opposed to the micro lab and discarded inappropriately into the environment as there were no special containers to store the waste chemicals.

Quantities of solid wastes were precipitates from the stoichiometric activity which were not dried and weighed, as they were accounted for as part of aqueous waste. Thus, the true solid waste resulted from unreacted parts of the copper turnings, which were negligible.

Students' opinions about the MCE were gathered from those who used them through a 10-item closed and one-item open questionnaire. The analyzed mean responses to the 10 close-ended items are presented as Table 5.

Table 5.1: Students' opinions about the MCE

| | Students' views on the MCE activities/approach (%) | Positive | Negative |
|---|---|---|---|
| 1 | Helps to unearth and correct wrong ideas | 88 | 12 |
| 2 | Activities enable the understanding of chemical principles | 76 | 24 |
| 3 | Exposure to better way of saving the environment | 80 | 21 |
| 4 | Opportunity to use simple materials in a safe environment | 86 | 14 |
| 5 | Equipment too tiny to see and read results clearly | 51 | 49 |
| 6 | Allows for increased skills acquisition, critical thinking, discussion & reflection | 84 | 16 |
| 7 | Employs minimal resources that generate little waste | 75 | 25 |
| 8 | Interactive nature of MCE (collaboration) | 77 | 23 |
| 9 | Time saving; confident, faster way of interpreting results | 63 | 37 |
| 10 | Possibility of using MCE in Pre-tertiary schools without labs | 83 | 17 |

From Table 5.1, we see the pattern of students' impressions about their engagement with the MCE and its activities.

The most common remarks from the open-ended questionnaire item were about the flexibility offered by the MCE which motivated them to try out activities that they had not understood in the past. Some of their statements were:

i. The activities were fun and easy to understand after all, unlike before.

ii. We carried out the activity on common ion effect two times in my group because of misunderstanding but we finished both activities in no time at all and we didn't require much chemicals after all.

iii. The waste produced was very small, unlike the volumes we got from the regular activities.

iv. Government must seriously supply schools with the MCE. It will facilitate practical work and ground students in science.

v. The schools without the ordinary laboratories will benefit a lot from the MCE. It is portable and works like equipment in the real labs and also gives good results, but fast.

Students' impressions about the regular macro labs are as shown in Table 5.2.

Table 5.2: Students' opinions about the Macro lab

| | Students' views on the Macro activities/approach (%) | Positive | Negative |
|---|---|---|---|
| 1 | Labs help to unearth and correct wrong ideas | 63 | 37 |
| 2 | Activities enable the understanding of chemical principles | 70 | 30 |
| 3 | Waste produced is too small to harm the environment | 37 | 63 |
| 4 | Opportunity to acquire skills in a safe environment | 44 | 56 |
| 5 | Activities are simple, safe, and interactive | 50 | 50 |
| 6 | Concepts understood through directed discussion & reflection | 65 | 35 |
| 7 | Employs minimal quantities of resources | 38 | 62 |
| 8 | Use of small-sized equipment could hasten activities | 55 | 45 |
| 9 | Activities are often completed on time | 45 | 55 |
| 10 | Possibility of using small-sized equipment in Pre-tertiary schools that have no laboratories | 72 | 28 |

From Table 5.2, participants alluded that lab practice enabled them to understand concepts, especially if they were directed. The students were divided over the simplicity, safety and interactive nature of the macro (regular) activities as observed in item 5. They, however, overwhelmingly (72%) agreed that there was the possibility of using micro equipment in schools that had no laboratories. This latter view on the use of micro labs could be inferred from their responses in item 4, where they did not feel safe (56%) during lab practice with standard equipment.

From the open-ended items they indicated that macro labs were often entailing and took up their report writing sessions, such that they could not complete reports on time. In other words, macro labs were time consuming. Therefore, although they had not practiced working on small scale, they saw a possibility completing their lab sessions on time and would not feel threatened by large explosions during practice, if mini versions of activities were introduced.

## DISCUSSIONS

Hands-on activities have been known to enhance students' understanding of theoretical chemical principles [6, 3]. In this study, the entry level of 115 undergraduate students were compared with their post-test scores in the concepts of periodicity and chemical stoichiometry. Their pre-assessment concept test analysis (Table 1) showed that there was no significant difference in performance of students, meaning that their entry points at the time of the research were at par. However, results from classroom (post-test) and laboratory performances indicated that students in the micro lab group performed significantly better than those in the conventional lab group. Inter-rater observation of students at work showed that those in the micro lab worked with as little distraction with the equipment (MCE) as possible. They appeared to collaborate with each other, worked confidently and completed activities in time, unlike the students in the control group who used conventional standard-size equipment. They demonstrated high critical thinking, deductive, interpretive, predictive and time management skills with confidence. The conventional group did not exhibit the same degree of confidence and sometimes could not complete their lab reports on time. In the lab on stoichiometry, they had to work on their data and complete their lab reports at home as they could not complete their reports within the given lab session.

An interpretive study of lab reports revealed that the micro lab group presented more logical and scientific answers than their conventional group colleagues. Some of the scientific answers given by the micro group in their concept assessment test were:

- The color differences observed in the gaseous mixture at high and low temperature is due to the production of nitrogen dioxide and dinitrogen tetroxide. They explained that temperature affects the equilibrium $NO_2(g)$ and $N_2O_4(g)$ so that at higher temperatures the concentration of $NO_2(g)$ was higher and was therefore the higher energy molecule.
- Doubling volumes of reactants do not affect mole ratio since fixed proportions come together to react each time. Change in volume does not change the reacting ratios.
- A precipitate can form only when the concentration of the common is high.

- Increasing the number of spatulas of $Na_2SO_3$ would increase the production of $SO_2$(g). Acidification of systems is not uniform in the environment because Wells closest to the source of $SO_2$(g) were more acidified.
- If CaO is added to the $Na_2SO_4$, the water that should have absorbed $SO_2$(g) will not be acidified because CaO will absorb the $SO_2$(g) that is produced, according to the reaction equation. Therefore, acidification varies with conditions.

Participants in the micro group were able to distinguish between higher energy molecules and tell the direction of exothermic reaction according to Le Chatelier's principle in Lab 1, which most students in the macro lab could not. In Lab 2, micro lab students could explain that which caused precipitates to form as well as the changes in heights of the formed precipitates. Although the macro group attempted logical explanations their statements were not as apt, logical, and scientific-based as those in the MCE lab. A similar observation was made in the other lab reports that they submitted. A couple of their answers were:

- Increasing concentration or volume of reactants could affect mole ratio.
- Common ion effect is when some ions are the same.

However, in the micro lab, 'common ion effect' was explained more elaborately. One explanation was:

- When two or more different ions in solution are in equilibrium with a solid, the equilibrium can be disturbed by extra ions, heat or pressure. If another substance is added it will form ions, and if one is the same as ions present in solution, then it is common to the two substances. If the concentration of the common ion is high, then solid will precipitate. (Examples were given in this instance.)

From observation, it was obvious that the micro lab group had adequate time to carry out their activities in several dimensions and more than a couple of times. It was observed that a few students in the macro lab group did not want to carry out the activity between copper and nitric acid. A comment that was captured in the supporting field book was, 'There could be an explosion to hurt us. $HNO_3$ is dangerous strong acid'. They were encouraged to do so, though reluctantly. This fear and reluctance were not observed among the micro lab group. The perceived diffidence was observed by Kennepohl [3] in a similar study. He noted that some students were intimidated when working in a formal laboratory environment because of the presence of specialized equipment, procedures and particular hazards which pose barriers to 'free' learning. He further observed that increased student freedom with home laboratories and individual choice of activity motivated learning.

From Tables 2 and 3, cost and quantity analysis showed that using the micro chemistry equipment could save money for institutional and national development (on a larger scale) in health, housing, food supply, clean water, affordable energy and industrial growth. Such accelerated development would subsequently (long term) eradicate poverty, create well-being in body and mind and lead to the achievement of the sustainable development goals targeted for the year 2030 [15, 16]. These sustainable development goals will not be elaborated upon as they are not part of the current study.

From Table 2, the difference in chemical expenditure alone between the simple macro and micro activities is quite enormous- €53.97 or $63.50. It must be noted that the multifunctional comboplate in the microscience kit has both big and small wells which serve for different purposes such as conical flasks, beakers and test tubes. Thus, the possession of one microkit with such multi-purposes means that the purchase of different vessels for activities such as titration and basic qualitative analysis, would not be necessary; save in budgets could be higher than has been shown in Table 2 if cost of equipment were considered.

The cost of work and storage space, lighting, and all other fittings have not been considered in this study for the use of macro equipment in conventional laboratories. Yet, as discussed earlier, a surplus amount of €53.97 ($63.50) in favor of the micro science equipment was obtained. Micro science equipment is easily used in classrooms and do not require laboratory fixtures or rooms. Thus, a true analysis and extrapolation of the differences for four more activities within a term or semester program could run into a profit of several hundreds of dollars for other developments if micro scale science is adopted. In addition, challenges with waste management and the attendant negative impact on the environment would be reduced. From Table 4, it was observed that the macro group produced eight and half (8½) times more chemical waste than the micro group. This could be harmful to both the individuals who generated the waste, those within the vicinity on campus, and the entire environment.

Besides reduction in budget, the micro equipment proved to be useful in motivating students to engage in meaningful chemistry activities as observed in other studies [9, 22]. Experiments which could otherwise not have been performed in conventional school laboratories for various reasons were performed on micro-scale. Like Hanson [21], Mafumiko [2] and Bradley's [10] studies identified, it was found in this current study that students showed positive attitudes towards learning chemistry through safe learning environments. They were observed to work with greater ease, precision, confidence, and flexibility as they constructed their own ideas. Students' responses from the questionnaire (Table 5) revealed that the MCE was versatile, easy to use, robust, breakage-free, and interactive (play-like). It enhanced their predictive, measurement, analysis and reflective skills. They felt at ease in trying out other ideas (extending learning) without fear of getting hurt. They added that, because they had shorter reaction times as a result of reduced quantities of chemicals, their results were obtained quickly and so they had adequate time for reflection and discussions. This collaboration, they said, helped them to understand the scientific concepts better. They further added that if they had their own personal kits, they could try out simple verification activities with basic home chemicals. Similar observations were made by other researchers who used small scale and green chemistry in their institutions and for teachers at in-service workshops [25, 4, 26].

Participants in the macro or control group did not appear to find the labs to be as exciting as those in the micro lab, though their performance increased a little higher than their entry point; as expected when new knowledge is acquired. They expressed diffidence in handling of chemicals in large quantities and preferred working with smaller quantities if results could be observed and obtained as with the macro quantities they work with.

In other studies, participants reported that the fear, diffidence, and dullness associated with the traditional macro activities were reduced with the use of micro equipment [4, 3]. They also commented on the environmentally friendly nature of the MCE. These global observations with the use of MCE buttress the fact that its adoption could enhance the study of chemistry. The reduced chemical use would result in less generation of chemical waste which could impact less negatively on the environment [11, 14, 13]. The adoption of the MCE activities would put less pressure on school budgets, require minimal use of resources, and can help reduce levels of pollution [12]. Indeed, the scope and practice of micro chemistry go beyond apprehensions over hazardous experiments and costs. It reduces the generation of waste in such a manner that leads to sustainability and the improvement of quality of life, especially in the chemical working environment. Furthermore, though not assessed in this research, micro chemistry activities could reduce reliance on fume chambers. This could result in an improvement of students' perceptions about chemistry, which could be further analyzed.

Findings from this study explicitly highlight some identified principles of microchemistry activities which are:

i. Reduction in chemical waste generation
ii. Less use of chemicals
iii. Inherently safer activities
iv. Shorter time-scale activities
v. Minimum use of energy
vi. Development of newer and expedient methodologies
vii. Linkage with green or sustainable chemistry concepts
viii. Avoidance of unsafe and time-wasting activities
ix. Improvement of perceptions of chemistry

## CONCLUSIONS

This study looked at how the use of micro kits in the study of chemistry to scale down macro (standard) chemistry activities could impact on students' understanding of concepts, an institution's finances and the environment. The MCE activities provides pre-emptive avenue for sustainable chemistry studies. Other findings that emerged indicated that the use of micro chemistry kits could be feasible for the Ghanaian economy and other middle-income and low-income economies, as found from literature [25, 1, 2, 8, 4]. They are safe, portable, easy to use and inexpensive to maintain. The independence and freedom that the MCE offers is vital to the success of student learning as the questionnaire (survey) and actual student performance indicate. This would ensure that meaningful science education with its bountiful benefits reach all by the year 2030 [16]. This assertion is confirmed by Bradley's [10] findings that proved that the pedagogical reasons for promoting low-cost equipment to provide simplified, relevant, safe and attractive experiences as well as to overcome psychological basis [3] to using standard equipment when necessary was a fact.

The adoption of these micro, yet robust, and multipurpose equipment would be a potential powerful tool to change the face of chemistry education, help students to build their own chemical concepts, develop useful learning skills and communicate logically. Well-designed activities that carry the potential of alleviating misconceptions through confirmatory or inquiry approach labs would ensure conceptual understanding of chemical principles. Furthermore, the MCE could help to save on chemical and equipment cost, ensure shorter reaction times, reduce reliance on sophisticated ventilation systems, smaller storage space, reduce wastes, and create a safe, healthy, interactive and friendly environment for all. The analysis of budget lines for four activities indicated that 'doing science' with micro chemistry equipment could save cost and help students to develop positive attitudes as well as gain new knowledge on environmental sustenance.

## IMPLICATIONS

Implementation of micro-scale chemistry activities and its linkage with environmental sustainability could be expanded through teacher training and in-service programs. This implies that the pedagogy and philosophy behind sustainability must be necessary topics in teacher-training curricula. Chemistry teacher education should be a channel to allow students to actively learn how to shape their society in a positive and sustainable manner, besides cognitive gains and improved performance.

Contribution of this paper to literature

- This study contributes to literature, the importance of adoption of micro labs through the use of micro chemistry equipment, especially in resource constrained communities (like Africa) to ensure that scare resources suffice for maximum concept-based experiments in a safe and congenial environment.
- It also provides a novel way of connecting how cognition, sustainability and prudent use of funds could all be achieved through the use of micro equipment in four labs.
- Furthermore, it contributes to literature by advancing the importance of effective teaching, lab safety, reduction in science budgets, and how they interconnect to ensure cognition.

## RECOMMENDATIONS

Time spent in doing activities and amounts of waste produced in macro and micro labs could be assessed in follow-up activities, in order to buttress the usefulness of micro-scale activities or otherwise as against the traditional macro activities. The MCE approach and other risk-free active learning environments should be provided for students to help them to develop strategies for conceptual change. Incorporation of green science could transform classroom teaching and learning to reflect on the promotion of values, attitudes and knowledge.

## LIMITATIONS

This study was carried out among only one-year group in one full semester. It would be useful to try it out among other year groups and different aspects of chemistry to be able to draw a more definite conclusion on how MCE could save institutions a lot of cost on science education, equip students with the needed cognitive skills, and develop the needed awareness and skills in practical activities.

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**Appendix A: Sample of concept assessment test**

1. How would you explain Le Chatelier's principle, using the dissolution of salt in water at varying temperatures?
2. A precipitate form as soon as two clear-looking aqueous solutions are put together in a test tube. What could be the reason for the formation of a precipitate?
3. How can a sulphur-producing plant affect three rivers in your locality that are three meters away from each other?
4. The concentration of two reacting chemicals, $Pb(NO_3)_2(aq)$ and NaI (aq) were increased from 0.02M to 0.10M and from 10cm3 to 15cm3 each. How would these changes affect their mole ratios?

5. What could be the reason for a given substance in a container presenting a certain color in cold surroundings and changing to a different color when temperature is increased, and then changes back to the original color in the cold once temperature is reduced?
6. Explain whether acidification of River Muni from the Bonsa tyre factory fume (pollutants) would show the same pH throughout its length and breadth.

**Appendix B1: Students' questionnaire sheet on microscale activities**

This evaluation sheet is to assess your candid opinions about the micro-scale equipment. Do not write your name or identity. Opinions will be treated as confidential.

Ratings for choices are interpreted as: SD= Strongly negative (1pt) D = Negative (2pts) N = Not sure (3pts) A = Positive (4pts) SA = Highly positive (5pts). Answer Q11 also.

| | | 1<br>SD | 2<br>D | 3<br>N | 4<br>A | 5<br>SA |
|---|---|---|---|---|---|---|
| 1. | Lab activities unearth my naïve ideas | | | | | |
| 2. | The MCE is helpful in understanding concepts | | | | | |
| 3. | The MCE produces minimal chemical waste | | | | | |
| 4. | The MCE gives opportunity to acquire skills and act like a scientist | | | | | |
| 5. | The MCE is like any other lab equipment and not extraordinarily helpful; too tiny to see results well | | | | | |
| 6. | Concepts were understood through discussion, repeated activities and directed reflection | | | | | |
| 7. | Minimal resources are employed | | | | | |
| 8. | The MCE is quite interactive | | | | | |
| 9. | MCE makes me finish my activities on time | | | | | |
| 10. | Possibility of use of MCE at Pre-tertiary levels | | | | | |

11. What are your general impressions about the Micro labs?

**Appendix B2: Students' questionnaire sheet on standard activities**

This evaluation sheet is to assess your candid opinions about standard labs. Do not write your name (identity) for confidentiality. Ratings for choices are: SD= Strongly negative (1pt) Negative = (2pts) N = Not sure (3pts) Positive = (4pts) SA = Highly positive (5pts). Q11 and 12 require your candid impressions.

| | | 1<br>SD | 2<br>D | 3<br>N | 4<br>A | 5<br>SA |
|---|---|---|---|---|---|---|
| 1. | Lab activities unearth my naïve ideas | | | | | |
| 2. | Labs are helpful in understanding concepts | | | | | |
| 3. | Lab activities produce minimal chemical waste and not harmful | | | | | |
| 4. | Lab activities provide opportunities to acquire skills and act like scientists | | | | | |
| 5. | The labs were interactive | | | | | |
| 6. | Concepts were understood through discussion, repeated activities and directed reflection | | | | | |
| 7. | Confidence gained through activities /results | | | | | |
| 8. | Use of smaller equipment that require small quantities of chemicals would hasten activities (results) | | | | | |
| 9. | Activities are always completed on time | | | | | |
| 10. | Possibility of using small-sized equipment in schools | | | | | |

Open questions:

11. What do you think about performing activities on microscale always, if possible?

12. What benefits could be gained from scaling down activities to observable ranges?

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**Appendix C: Price list for Chemicals and equipment (in Euros)**

| Name of chemical | Quantity | Stock price | Quantities (Tables 2 & 3) |
|---|---|---|---|
| Hydrochloric acid | 1L | €19.60 | |
| Nitric acid | 1L | €20.50 | |
| Sodium iodide | 100g | €69.93 | |
| Sodium sulphite | 250g | €116.00 | |
| Sodium chloride | 1000g | €38.30 | |
| Copper turnings | 250g | €34.85 | |
| Lead nitrate | 1000g | €93.60 | |
| Micro science kit | Basic | € 8.00 | |
| Test tube (Pyrex) | 18mm x 150mm | €1.02 | |
| Beaker (Pyrex) | 250mL size | €5.91 | |
| Beaker (Pyrex) | 50mL | €3.00 | |

(All quotations from sigmaaldrich.com, 2020 & www.fishersci.com, 2020)