ACHIEVING THE AIMS OF SCHOOL PRACTICAL WORK WITH MICROCHEMISTRY

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ABSTRACT

"*Chemistry is fundamentally an experimental subject…education in chemistry must have an ineluctable experimental component*".

This quote from an IUPAC report reflects a core belief of all chemistry educators. However we must define our aims for practical activities, and design and prepare for them in the context of national curricula. All this is necessary whatever the scale (macro or micro) of equipment that might be employed. At the present time traditional macroscale equipment dominates the school scene and penetration of microscale use is slow. This dominance is not because there are no problems with the status quo; quite the opposite. Most schools have no equipment at all or, if they have some, never use it. This despite national curricula explicitly encouraging practical science activities. Based primarily upon the experiences of our group in South Africa, this paper addresses the following questions:

1. what are the aims of school practical work?
2. can microscale chemistry deliver as well as, or better than, macroscale?
3. why is practical work (macro or micro) problematic in schools?
4. can microchemistry ameliorate these problems?
5. could recognition of the concept of Zone of Feasible Innovation help us?

Microchemistry has so much to offer school chemistry, that answering these questions and acting accordingly should be a priority. *[African Journal of Chemical Education—AJCE 6(1), January 2016]*

INTRODUCTION

"Chemistry is fundamentally an experimental subject…education in chemistry must have an ineluctable experimental component."[1]

The IUPAC quote is one of a number of similar affirmations that practical activities are an inescapable part of chemistry education. Most chemistry educators at all levels share this view, and national school curricula express the same view at least by implication. Yet there is a steady rumble from doubting administrators and researchers, who question what evidence we have for our beliefs [2]. Indeed the World Bank some years ago decided that investing in laboratories for schools in developing countries was such poor value for money that it would be discontinued [3]. Despite these serious contrary views, other important organizations like UNESCO, have continued to try to promote practical science in schools. Over decades, they have supported projects devoted to improvisation, to low-cost, locally-produced equipment and, in the most recent period, to the Global Microscience Project – a project in which we have participated for several years [4].

Located as our group is in South Africa, the UNESCO – promoted call for Education for All is one which has strong appeal for us [5]. We see the Global Microscience Project as an important element in achieving education for all. We understand that education for all must include science education for all, and ineluctably there must therefore be practical science education for all. In our view there is no other way of achieving this except by low-cost, microscale science.

Twenty years after the start of the Global Microscience Project, it is appropriate to take stock of how far we are along this developmental road and to look ahead to see how best to reach the goal of practical science education for all.

WHAT ARE THE AIMS OF SCHOOL PRACTICAL WORK?

So what are the desired outcomes of practical work in science education? Scores of educational experts have proposed lists expressed in sufficiently general terms that they should be applicable around the World, whatever the national curriculum and the science subject. Woolnough and Allsop [6] have a brief listing that is useful and has wide support:

1. Motivation
2. Developing Practical Skills
3. Learning the Scientific Approach
4. Gaining a Better Understanding of Theoretical Aspects of the Subject

Criticisms of the investment in practical work are not about the worth of these aims, but about the lack of sound evidence that they are achieved. In part this may be due to the fact that most national examination systems depend heavily upon written testing of “theory” or factual content of the curriculum. Awareness of this has a massive influence on what teachers do; they teach as best they can towards the success of their learners in those exams and think that relentless emphasis on drill and practice is the right method. They do not believe that the fourth aim of Woolnough and Allsop (gaining a better understanding of theoretical aspects of the subject) is achievable through practical work, failing to acknowledge the educational implications of the fact that, historically, theory grew out of experiment. They see practical work rather as a separate and additional task that takes up valuable time that would be better spent on simply telling learners what they must learn.

WHY IS PRACTICAL WORK PROBLEMATIC IN SCHOOLS?

Some problems have already been mentioned, and we can add others which are familiar:

- aims often confused and unfocused;
- emphasis on achievement in written exams;
- insufficient time in the curriculum;
- poor quality/inexperience of some teachers;
- inadequate or no technical assistance;
- cost too great for what it could achieve;
- safety and environmental regulations limit scope.

All of these have been long-standing complaints around the World, and by implication they inhibit practical work of any scale. Universal education/Science for All has exacerbated these problems because the burden of numbers acts against individual hands-on activities. The cost burden weighs more heavily also, as do the concerns for safety and environmental impact. In poorer countries all these issues tend to be magnified, as Kahn [7] and Lewin [8] have described.

So, one needs to realize that practical work in schools is challenged by a number of problems, and these have to be faced whether macro or micro is your scale. Yet we still have this widespread belief that practical work is important, and we think there are sound aims to strive for through this activity. So it is not an option to give up, nor is it an answer to say we can achieve the aims virtually (although virtual support can assist) [9]. What evidence can we find to be able to recommend microscale chemistry to teachers and educational planners?

CAN MICROSCALE CHEMISTRY DELIVER ON THE AIMS AS WELL AS, OR BETTER THAN, MACROSCALE?

Motivation is a potent outcome because it can feed into all aspects of learning. We have gained evidence from our experiences in South Africa, a developing country, that practical work is enthusiastically enjoyed by most learners, and with microscale equipment this outcome is certainly no less successful than with traditional equipment. For such learners the novelty of hands-on activities may enhance the impact recorded in more developed countries, but everywhere the effect is qualitatively similar. Girls seem to particularly express enthusiasm, perhaps related to a sense of greater safety with microscale activities. But we have also seen that where the teacher is poorly prepared or incompetent, there is no motivation, so the hands-on activities at whatever scale must be appropriately managed.

As for the gaining of a better understanding, we have been able to make direct comparisons in certain cases: for example, Sebuyira found that those doing the microscale version of a particular activity, achieve somewhat better than those doing the macroscale [10]. This, despite the fact that the students state it is more difficult to see things on microscale! I think we have learned that “more difficult” does not mean a problem, but rather that close attention is required – and that is an advantage.

Developing of practical skills is an aim that is interpreted by some in a very limited sense. They think only of the handling of traditional equipment, and cannot imagine how microscale equipment can possibly fulfill the aim. However in my mind this is not the intention of Woolnough and Allsop, and other similar authors. They know very well that no school can provide experience of a wide range of science equipment. It is not the specifics of particular items such as test tubes and burettes, but the considerations and techniques that go into how they are used. Glass is a very robust material insofar as chemical attack is concerned; there are good reasons why it is the material of choice for most professional laboratories. But it comes at a price and is rather easily broken – even one might say, dangerously so. Plastics are today more the common experience than glass, and learning to exploit their good properties and avoid the poor ones is a useful life skill. Similarly, although today they build bigger cruise ships and bigger bridges, these are not for individuals: these are for our growing population. For individuals the trend is opposite, towards miniaturization – above all exemplified in the all-pervasive cell phones, etc. So for hands-on use, small has become the norm and this is the same trend evident in doing practical chemistry [11]. What matters is choosing the right tools for the job, taking care of the tools, appreciating that observations may be qualitative or quantitative, and understanding significant figures.

Which brings us to the aim of learning the scientific approach. This aim requires not only practical skills but meaningful interplay between theory and observation. This should not be interpreted as just confirming an already established theory. It means applying a theory in practice, seeing whether or not it works whilst guarding against prejudice, suggesting alternative ways of thinking, thinking of logical extensions, planning a new experiment, etc. In other words, not just busy work, but thoughtful work. This kind of scenario is rarely played out in a school classroom, but lies at the heart of the movement for inquiry-based science education. Lamba [12] puts this emphatically as inquiry-based, student-centred instruction, and reports consistent, significant learning achievement gains. There is no evidence of differences between macro and microscale in this context, but we may reasonably expect that there are big advantages to microscale.

CAN MICROCHEMISTRY AMELIORATE THE PROBLEMS OF SCHOOL PRACTICAL WORK?

If microchemistry can be at least as successful as traditional scale chemistry in achieving the aims of practical work, does it offer advantages in regard to the wider contextual problems faced by practical work in schools? I think there are indeed three features of microchemistry that can help.

Low-cost: The cost advantage of microscale chemistry needs no argument. If we use a figure like 10% of traditional, then this means that 10 times as many learners and/or experiments could be done with the same budget as traditional scale. And this is just initial cost. Taking into account consumables this advantage is amplified, partly because plastic equipment is not so breakable. So Lamba's inquiry-based, student-centred instruction becomes a whole lot more feasible! Furthermore, development of learner- centred teaching, (a threatening prospect for many teachers!), can be facilitated in a natural way when hands-on practical activities are introduced.

Safety & environment: The heightened interest we all have in safety and in pollution is appropriate in an increasingly crowded World. There is no question that both these problems are greatly reduced on microscale. Furthermore the continued use of excessive volumes of chemicals sends the wrong message as regards the attitudes of chemists. Whilst everyone around the World is working towards using less energy, and engineers are working day and night to reduce fuel consumption, are chemistry teachers going to be the glaring exception in resource consumption? [13]. Using microchemistry it is also no longer necessary to limit practical chemistry to a laboratory; of course care is required. But then care is always required, whether in or out of a laboratory and all the rules of good practice apply regardless of location. So this now becomes learning a life skill rather than just a laboratory skill. When science budgets for school systems can be relieved of laboratory building and maintenance, they will look much more palatable. Mobile laboratories have often been touted as a way of spreading scarce traditional resources and reducing the cost burden of building laboratories; the portability of microscale resources (equipment and chemicals) means that mobility is built in and no laboratories are needed at all.

***Easy use/convenience**:* Most novices feel more comfortable with microchemistry than macrochemistry activities. Other than a small number of physically challenged there is no reason and no evidence to support claims that microscale is too small for ease of handling. Older chemistry teachers who envisage such problems are only expressing their own sense of uncertainty in the face of innovation. This is like the familiar distinction between the old and the young as regards cell phones and electronic gadgetry. It is consistent with the easy use and convenience that it is frequently reported that experiments are significantly quicker on microscale. This helps the motivation and permits classroom time for the discussion and reflection needed to gain that better understanding.

There are many potential consequences for chemistry teaching and learning in these three simple characteristics. It is not just that microscale equipment can substitute for traditional scale. Taken together they can liberate chemistry teaching from a number of restraints and limitations and open the way for methods of teaching that science education experts advocate. In brief they make feasible the inquiry-based, learner-centered style now seen as our best hope for the future of chemistry! [12] [14]

It remains important to express our convictions in terms that capture the interest of decision-makers, such as Ministries of Education. Here the "trinity of the 3 Es", identified by Kahn [7], provides an appropriate framework:

- Equity: speaks to even-handed provision for all (EFA)

- Efficiency: refers to the cost devoted to achieving the aims
- Effectiveness: refers to the extent to which aims are achieved.

Microscale chemistry is recommended above macroscale on all three counts!

CAN THE CONCEPT OF ZONE OF FEASIBLE INNOVATION (ZFI) HELP US?

Reflecting on the numerous advantages that microscale chemistry has over macroscale chemistry, it is perhaps surprising and disappointing that the trend from macro is not more marked within the school systems around the World. There is such a trend (as Beasley and Chant asserted several years ago [11]), but in general in school systems progress has been slow. To be sure there is evidence for example that introductory workshops sponsored by UNESCO have left a trace but the gestation period is remarkably long. This may be illustrated by the case of Guyana. A UNESCO-sponsored introductory workshop on microchemistry took place in Georgetown in 2000 but it was only quite recently (2014) that a report appeared, showing that the little seed sown more than a decade earlier had germinated, and that the Ministry of Education had slowly prepared the ground for a pilot project, and then a wider implementation [15]. They solicited donor support and ordered a significant quantity of equipment from the manufacturers of RADMASTE microscience kits last year and another order is likely to be placed this year. They are evidently pleased with the outcomes. UNESCO has publicized the development in its own publications and reports, and the tone of these reports shows they are also extremely impressed and pleased.

The table shows the African national experience with microscience since UNESCO-sponsored activities started in 1998.

The African National Experience with Microscience

Country	Introductory Activity	Follow-up
Cameroon	1998	UNESCO-assoc Centre opened and national implementation started 2001.
Kenya	1998	Univ of Nairobi and KNAS promotion over several years; AAS/IOCD round-table 2013 recommends to MoE.
Cote d'Ivoire	1998	National training 1999. Nothing further.
Tanzania	1999	National tender for kits and training for 180 schools won by RADMASTE; implemented 2011-12; UNESCO evaluation report due soon.
Senegal	2000	National consultation 2003. Nothing further.
Sudan	2002	National tender issued 2010. No award made.
Mozambique	2002	National consultation 2007. National tender for 200 schools issued 2012- awarded to lowest bidder with very bad consequences. National tender for pilot project in 10 schools with M&E issued 2014, awarded to RADMASTE. Implementing 2015 for 6 months.
Angola	2003	National training 2008; signs of intent to follow up.
Rwanda	2003	National training 2006. Nothing further.
Ethiopia		National training 2011. Nothing further.

NB. This table records information we have on national-level actions/inactions and does not record efforts of various individual educators to promote and research the microscience concept.

Although this table shows some encouraging developments, it should be borne in mind that more than 40 countries in Africa hosted introductory workshops sponsored by UNESCO since 1996. In most cases there has been no known national development subsequently. Follow-up on introductory workshops is what has mostly been lacking, and progress depends absolutely on the chance that somebody with influence is convinced and determined. This was the fortunate case in Cameroon.

A similar low probability of longer-term impact attends the occasional opportunities presented by such events as the International Year of Chemistry (IYC 2011), with its Global Water Experiment. It was evident to us that despite all the hype and noise leading up to this admirable project, that much of the World's population would not be able to participate. These unfortunate children in poorer countries had neither equipment nor chemicals and often teachers who could not access the internet to get guidance either. We motivated to UNESCO and IUPAC that here was an opportunity to do some global good by sponsoring a special pack of microchemistry equipment for schools in such circumstances. In the end this was undertaken and 32 less-developed countries received school packs for 5 schools so that they could participate in the Global Water Experiment [16]. We know the outcome from a few such school packs but mostly there has been no feedback even though UNESCO has representation in each country. Yet again therefore one feels that an innovative idea was let go through lack of follow-up.

The message for us all is loud and clear. If we want to see our innovations making appropriate impact, we have to live long and be very determined! This glacial progress reflects mostly upon the normal pace of government implementation of innovations.

Where government makes a commitment to a pilot project, they also need to be sensitive to the situation in which they may be trying to promote the innovation. This is the central idea located within the ZFI concept. The success and uptake of any innovation depends upon several factors and one must take these into account or most likely die disappointed! The ZFI concept has been introduced by Rogan and Grayson [17] with several propositions (paraphrased below) regarding success:

1. Innovation should be just slightly ahead of existing practice.
2. Capacity to support innovation needs to be developed concurrently.
3. Outside support should not exceed the capacity of a school to use it.
4. All role players need an opportunity to re-conceptualize intended changes in their own terms and for their own context.

5. Changing teaching and learning practices should be seen as a culture change, not just a technical change.
6. The ultimate aim must always be an improved learning experience.

If we believe in these propositions, we can see why we have problems in our microchemistry mission! Our experience within South Africa, for example, is sobering. When our RADMASTE kits were made known locally, there was great interest: corporate donors were eager to buy kits for schools they supported. Many hundreds of kits were distributed and the media exploited for publicity. Government agencies, national and provincial departments of education were also excited and invested in the kits for schools on a substantial scale. Some provincial departments took the trouble to follow up after several months, and found that many kits were never used, many kits were already lacking components or had not been maintained, and only a limited percentage were actively and consistently in use[18] [19]. It must be noted that sponsors often provided for very limited teacher training only; after a one afternoon workshop teachers were truly excited until they got back to school! Most of the teachers and schools involved would have found the innovation a completely new experience and the projects predictably failed at proposition 1!

At a later stage more effort was put into teacher training, and in a quite major national project implementation the district subject specialists were themselves very much involved. But again, when everyone (400 teachers!) went back to their schools little or nothing happened – and the subject specialists who were to support them rarely visited [20].

These experiences not only wasted a lot of money; they were interpreted by some to mean that microscience is no good! For workers to blame their tools for failure is of course a familiar excuse.

We do not really know how things stand now in South Africa. Practical work in school science is still very weak; we have been told that probably more microscale chemistry is practiced hands-on than traditional scale, but cannot verify this. We continue to get requests for kits, but government tenders normally specify traditional equipment (and serve the needs of a minority of schools).

So let us learn from this depressing experience and think about the way forward with the aid of the ZFI. Consider two rather extreme situations; one perhaps typical of a poor country and one typical of a relatively richer country. Both situations are however, very likely to occur within one country.

In the poorer country, proposition one represents an impossible demand because practical work is not part of existing practice! There is a need for nucleation (to use the term associated with creating a new state or phase of matter) which requires a strongly focused project located in the best possible schools (but not the exceptional ones who already have everything however). Even with such schools the outside support must be strong, continuing and sympathetic. Initial experience with the innovation must be good, and sufficiently so that there is courage to try more. Motivation is the one aim above all that should be stressed as achievable for such teachers, and in addition the learning of practical skills.

In the richer country, schools are probably already committed to practical work, and innovation has different implications. The teacher most likely sees that practical work is necessary but perhaps follows existing routines rather thoughtlessly. Such a teacher could be open to a culture change where hands-on practical activities generate more motivation by virtue of their integration into an inquiry-based approach to science education. However, a lot of thought has to go into how this will be done, and the old familiar issue of focusing on a written exam will have to be confronted sympathetically. In this situation, the aim of gaining a better understanding of theoretical aspects of the subject (chemistry) can be made emphatically by reference to evidence of how suitably-designed practical actvities can facilitate conceptual change and correction of misconceptions [21]. Similarly, learning the scientific approach could be emphasized within the framework of an inquiry-based, learner-centred teaching and learning of chemistry.

CONCLUSION

We continue to learn as we go forward with microchemistry and continue to believe that most of its potential benefits for chemistry education have yet to be realized. We admire and are thankful for the persistence and vision of UNESCO and others in this cause [22]. And we draw strength from the foreword to the recent book (2015) - Chemistry Education: Best Practices, Opportunities and Trends – in which Peter Atkins [23] writes:

> *Crucial to this endeavour (chemistry education) is the demonstration that the concepts and calculations of chemistry relate to actual physical phenomena (or should) and that experiment and observation, not ungrounded algebra, lie at the heart of science. The contributions acknowledge this core feature of science, and although microscale experiments, which are discussed here, are not to everyone's taste, they are far better than unsupported printed assertion and unadorned abstraction.*

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