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Building Improvised Microbial Fuel Cells: A Model Integrated STEM Curriculum for Middle-School Learners in Singapore

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Abstract: The benefits of STEM education for learning important knowledge, skills, and affect are widely accepted, though the former is currently absent in Singapore's formal curriculum. This study therefore describes a model-integrated STEM curriculum at the middle-school level for developing scientific as well engineering literacy. Based on design-based inquiry (DBI), it incorporated inquiry science learning with an engineering design challenge for students to build improvised microbial fuel cells (MFC). Co-planned with science teachers from various disciplines, the curriculum was implemented as a 10-week enrichment program with two groups of Grade 8 students (N = 77) from one secondary school in Singapore. Through the use of vignettes, we show how learning about/of science and engineering occurred in the conceptual, epistemic, and social domains. In addition, students applied evidence-based reasoning, various epistemic skills, and a variety of problem-solving approaches as they iteratively improved their MFC set-ups, which often outperformed commercial kits. This proof-of-concept case study represents the first successful implementation of a STEM-integrated curriculum for middle-school students and can serve as a model for the development of similar programs elsewhere.

Keywords: scientific literacy; engineering literacy; integrated STEM curriculum; microbial fuel cell; design-based inquiry

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1. Introduction

1.1. STEM Education in Singapore

That science, technology, engineering, and mathematics (STEM) education offers a number of benefits for learning disciplinary knowledge and skills and increases learner interest or affect is not usually disputed. "STEM education" here refers to the general pedagogical approach where there is a conscious attempt to integrate teaching and learning across two or more STEM disciplines, as opposed to a traditional approach, where the focus is almost exclusively on learning in only one of the disciplines during instruction. What remains unresolved are, however, not to be underestimated, including questions regarding what might be the legitimate disciplines that make up STEM, how they are related, and what it means to achieve integration in STEM, among other issues see [1–3]. As science teacher educators from Singapore, what is perhaps more disconcerting to us is that STEM education is a relative latecomer to the local system; it does not appear within the official curriculum and has only recently been offered as part of voluntary, school-based after-school programs for primary and secondary levels [4,5]. Arguably, STEM education is a relatively new construct that is attempting to gain entry in an already crowded science curriculum in this country. For example, there are content-heavy courses in the three major science disciplines (i.e., chemistry, biology, physics) from Grade 9 onwards, while integrated science is taught from Grades 3 to 6 at the primary as well as in Grades 7 and 8 at the middle-school level. This information must also be seen in the light of high-stake examinations at the end of Grade 6 as well as in Grades 10 and 12. With respect to other subjects typically associated with STEM education, mathematics is regarded as an important albeit standalone subject appearing right at the start of formal education at Grade 1, whereas some aspects of engineering education such as its iterative problem-solving nature of design thinking may be located in the subject of Design and Technology that is mandatory for all middle-school students here.

Given this background, where STEM education—not just its component disciplines as standalone school subjects—is just starting to make inroads through the informal curriculum into local schools, we argue that it is timely to showcase a newly created integrated STEM curriculum involving microbial fuel cells (MFC) (explained later). This study functions as a proof-of-concept for local policymakers to show that, with school teachers as partners in planning, it is possible to enable middle-schoolers to experience authentic, complex STEM activities normally reserved for undergraduate students [6]. While this MFC curriculum faced its share of challenges and tensions, we explain that basing it on design-based inquiry (DBI) incorporated inquiry science learning with an engineering design challenge. In the qualitative vignettes in the Results section, we show how the former resulted in students successfully accomplishing a number of measures of integrated STEM learning. For these reasons, we believe that this MFC curriculum can serve as a model for the development of similar integrated STEM programs elsewhere. Our research question that guides the remainder of the paper is thus: what are the affordances for STEM integration and learning through a DBI-based MFC curriculum for middle-school learners in Singapore?

1.2. The Microbial Fuel Cell for STEM Education

Microbial fuel cells can take a wide variety of forms, but are essentially bio-electrochemical devices that produce electricity by tapping on the biological processes of microorganisims [7]. As with any fuel cell, electricity is produced as long as a "fuel" is supplied to it. Typically, small amounts of electrical energy are produced by an MFC, as long as the microorganisms are provided with a source of food (which is its fuel). A scan of the literature suggests that very little work has been done at the pre-collegiate level to employ the MFC in school, let alone develop inquiry-driven experimental protocols, investigate the efficacy of the MFC as a teaching tool, or to determine how it facilitates the learning of science. The few papers have described the MFC as suitable for school contexts due to its "interesting" [8] and "stimulating" [9,10] nature. Despite an attractive feature of incorporating scientific principles from all three natural science disciplines—biology, chemistry, and physics—in its fundamental mode of operation (see Figure 1), relatively little has been written about how this cross-disciplinary intermingling of school science subjects can be capitalized in science education, and there has been even less discussion on the MFC in the context of integrated STEM education.

The paucity of such reports and apparent infrequent use of the MFC in teaching may be due to several factors. Firstly, the MFC remains a somewhat niche area of scientific research. First described by Michael Potter in 1912 [11], the discovery languished for decades because the curious generation of electricity from microbes could not be adequately explained. Briefly considered as an energy source for space travel applications during the space race of the 1960s, current research and development of MFC technology focuses on electricity generation and energy recovery as part of an industrial-scale treatment of municipal sewage and other effluents [12–14]. Smaller-scale applications, such as its potential for powering various electronics, household power generation, and implantable biomedical devices [15], or the use of MFCs as biosensors [16], have also been proposed and are being developed. Outside of the technical research literature, MFCs and other forms of biological fuel cells have only been occasionally cited in popular science articles, typically when used in unusual applications or simply as curiosities. For example, articles have been based on research on the use of urine as a fuel [17], implantable MFCs powered by human saliva [18], and biological fuel cells implanted in rats [19], snails [20], or plants [21].

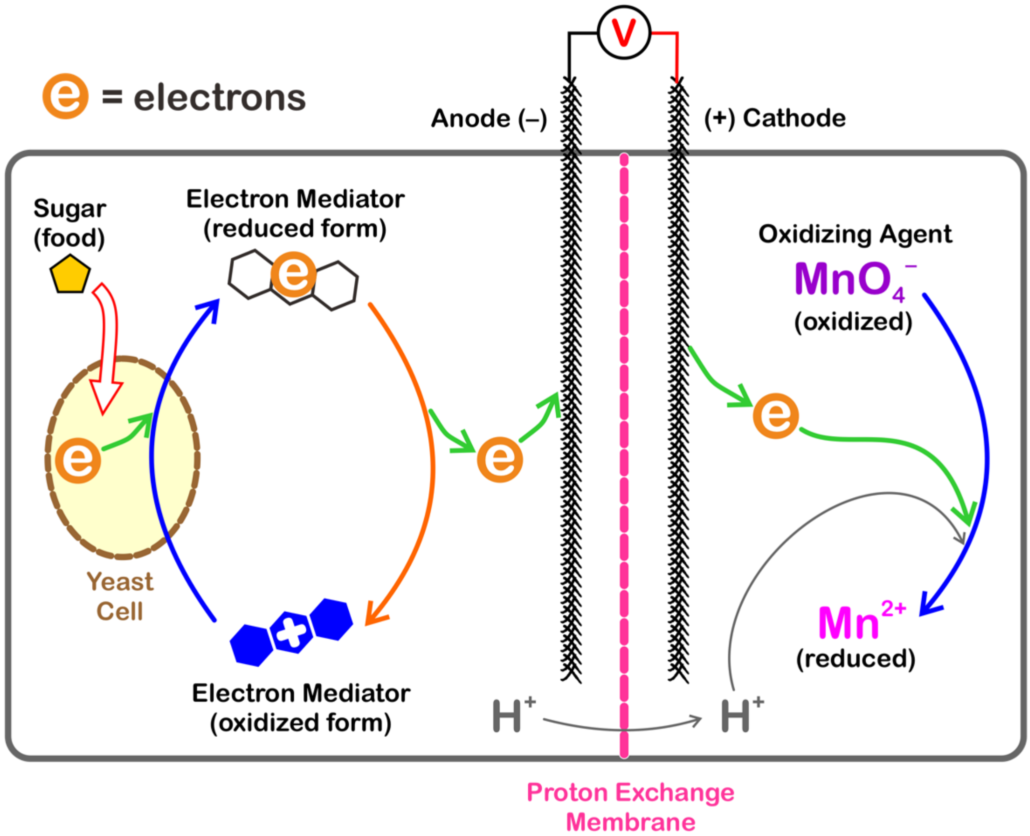

Figure 1. How a simple two-chamber microbial fuel cell works.

Secondly, it is important to note that only miniscule amounts of power can be generated in such smaller scale MFCs, and that they are only suitable for specialized low-power applications. The power produced by tiny MFCs that can be made in school, may be able to illuminate light-emitting diodes (LEDs) and possibly run simple electronic circuits; however, it would not be sufficient to charge a smartphone. Hence, the MFC is not a commonplace technology or device within the everyday experience of most people.

Thirdly, some aspects of the fundamental mechanisms of operation of MFCs remain obscure, even in the technical literature. Designs and operating principles of MFCs are also diverse and generally quite complex. There is a general lack of concise elementary information on the fundamental science behind the MFC, which could make it difficult for an educator to make use of the MFC for teaching, particularly at the pre-collegiate level. This is especially so given that understanding and describing its operation requires broad, cross-disciplinary knowledge across biology, chemistry, and physics. It would be a challenge for an individual teacher to develop the expertise, and even more so to have the pedagogical content knowledge necessary across all the disciplines involved. Because it does not belong within any one discipline, it cannot be neatly pegged into the subject-based curricula so dominant in school systems around the world.

Therefore, the inherently cross-disciplinary nature (mainly science and engineering) of the MFC has hitherto limited its use in the classroom due to a lack of teacher readiness and an appropriate niche in the school curriculum. However, it is this very cross-disciplinary nature that holds much promise for integrative STEM education. There are few, if any, comparable learning activities that intrinsically combine various aspects of biology, chemistry, and physics learning with the opportunity to engage in engineering design tasks. This unique combination is also naturally placed within the context of alternative energy technologies and sustainability issues, which are topical and likely to engage youthful learners. Furthermore, the dearth of accessible "textbook" information on the MFC or its workings, especially for non-experts, makes the MFC very suitable for discovery-based and inquiry-driven learning. It should be clear, then, that the MFC is a very promising STEM teaching tool because it requires learners to actively learn and apply a range of knowledge and skills across science and engineering in the design and iterative refinement of functional prototypes in a manner that more closely resembles real-world work in the scientific and engineering milieu, rather than that of the traditional classroom. In other words, it is more likely to afford the development of authentic scientific and engineering literacy while being more engaging than more conventional curricula.

1.3. Design-Based Inquiry as Pedagogy of Choice

Because using the MFC in school requires knowledge of science content as well as engineering design principles, the pedagogy of choice was design-based inquiry (DBI). It is known by other names, for example, the National Science Teachers Association [22] also refer to it as *Science by Design*. Within science education, DBI was adopted in curriculum packages such as the *Design-Based Science* [23] and *Learning By Design*™ [24].

In DBI, the collaborative construction of an artifact is the driving goal of the activity which activates relevant and just-in-time learning [25–27] rather than heavily frontloading content that occurs in most classrooms. DBI affords agentic learning, where the learner is able to set his or her own goals, as well as present in a classroom context the occasional "dead-end" that scientists typically encounter [28], for example, where designs simply fail to work and/or cannot be made to perform any better due to some inherent limitation. DBI also encourages the application of intellectual reasoning that is often "on the back burner" when teachers say that they are performing an inquiry. Rather than students using a tool in order to learn science prior to applying a technology, in DBI, these processes are intertwined in an ideal case. The DBI approach typically involves setting an initial design problem or challenge for learners to develop or improve upon: for example, designing a mechanically propelled model vehicle that must complete an undulating route, or an assistive device for persons with a disability to lift heavy objects [24]. By working in small groups on authentic real-world design tasks, students perform better on intellectually challenging tasks, develop self-concept and science-based identities, and improve the interaction and communication skills that comprise social literacy [29]. These students also consistently perform measurably better at learning content as well as the science procedural, collaborative, and epistemic skills that are aspects of scientific literacy [29]. For example, students who designed and built working models of the respiratory system were reported to "think more systemically and understand more about the structure and function of human lungs" [30].

A longstanding threat in DBI, however, is the frequent disconnect between the design-goal driven problem-solving and actual conceptual understanding of the science underlying it [29,31]. Some students who had completed DBI projects remained unscientific in their understanding of the underlying concepts [32], or they remained steadfast in their prior scientific beliefs in the face of observed experimental evidence [33]. Relatedly, completion of the artifact might take precedence over the learning, or the authenticity of the tasks may add too much superfluous or confusing material. Special care must be taken to minimize the effect of these pitfalls in the design of the activities.

Incorporating *iteration* into DBI tasks may go some way towards addressing or ameliorating these pitfalls. Requiring students to revisit their findings or improve upon their artifact, especially where the "performance" of the artifact is used to inform the redesign, should provide some impetus for students to "think". It should also remove some of the focus on artifact completion and place emphasis on the development process. Additionally, by breaking the task into iterative steps, problem-solving can be attempted in smaller, less overwhelming chunks. DBI activities naturally afford such iteration as they are typically prone to failure, e.g., failure of prototypes to meet design expectations, naturally requiring further action to correct or adjust for the failure experienced. This type of task iteration is variously described in the *Design-Based Science* "learning cycle" [23] and in the "ritualized activity structures" of *Learning By Design*™ [34], and has been found to be an important feature of DBI [30,35].

We posit *collaboration*, *challenge*, and *competition* as three essential features of DBI-based laboratory activities. DBI-based activities naturally lend themselves to the incorporation of a *challenge*; hence, the grouping of students should be carried out in such a way as to capitalize on this. These challenge goals could be set by the teacher, by consensus at the class-level, or at the group-level. An example goal would be to design and make an MFC that is capable of lighting a high-efficiency LED for 24 h. Students could be organized into persistent groups of perhaps three to five students to work *collaboratively* throughout the MFC activities to attain the challenge goals. The degree of heterogeneity among the group, in terms of ability level, learning style, and so on, would be dependent on the teachers' intended objectives for the program and group dynamics. For example, groups could be intentionally related to mixed-ability, with either fixed or rotating roles within the group. This organization of students into small groups also enables the organization of inter-group *competition* for motivational purposes. The *MFC Challenge* could thus be a *competitive* one between groups. Examples of such a goal would be to design and make an MFC with the highest voltage or with the greatest longevity before falling below some threshold voltage. Organized and managed appropriately, such a *cooperation–competition* instructional strategy can be highly effective for learning [36,37].

The goals for the *MFC Challenge* are introduced to student groups early in the program. The highest voltage of a single MFC from a battery (multiple cells), as well as the ability to light up LEDs with increasing power requirements, the ability to turn a micromotor, and/or the longevity of the MFC, were typical goals [7]. Student groups were free to select the goal(s) they wanted to design towards and later pit their design against other teams. This not only gave students a motivating sense of *agency*, but also required them to make collective design decisions on which goal(s) to focus on, since some goals presented opposing requirements. Building an MFC for a high initial peak voltage tends to have different requirements from those of a long-lasting MFC, while illuminating LEDs tend to require a threshold voltage (via MFCs wired in series), and turning a micromotor requires substantial current (from a battery of MFCs wired in parallel). During the *MFC Challenge*, the MFCs from every group were each tested against all the design goals, and winners could thus be decided for each category.

1.4. Objectives of This Study

The main goals of this work were to develop an integrated STEM curriculum incorporating cross-disciplinary integration of the natural sciences (biology, chemistry, and physics) with collaborative design-based inquiry as a key pedagogical feature for the purpose of developing aspects of scientific and engineering literacy among middle-school learners and to evaluate the curriculum package and the learning that is possible.

The key research question: Can students develop scientific and engineering literacies through learner participation in design-based inquiry using the microbial fuel cell? This was examined using qualitative methods in a case-study approach.

2. Materials and Methods

2.1. Participants

Teachers from a government-aided, mainstream co-educational secondary school in Singapore attending a presentation by the authors expressed interest in the use of the MFC curriculum as the core of a "scientific thinking program" that they were formulating. This was intended as an academic enrichment program for selected lower secondary (middle school) students. A total of 77 Secondary (Grade 8) students in two cohorts (2015 and 2016) were selected by the school for this program. They were generally higher-progress learners with an aptitude for science based on their test scores at the end of Grade 7 and, in some cases, on teachers' recommendations. A total of six teachers were directly involved in the development and implementation of the curriculum—four in each of the two cohorts, with two teachers who were involved in both. In addition, the teacher in charge of the science department had been actively involved in the development of the curriculum. Students were organized into groups of four (three in some groups), where students in a group were typically from the same form class. Groupings were arranged by the teachers involved. For analyses, groups were assigned a letter from A to K (2015 cohort) and L to W (2016), while students were given a pseudonym beginning with the group letter. The letters I, Q, and U were skipped in the group names for easier naming of student pseudonyms.

The research team consisted of the authors who are education faculty members. At the time of the first cohort, T.T.M.T. had 12 years' experience as a science and technology teacher-trainer, which included five years as a science education researcher, while Y.-J.L. had 16 years' experience as a professor of science education and eight years prior experience as a school science teacher.

2.2. Development and Implementation of the Curriculum Package

The structure of the MFC curriculum (see Table 1) was conceptualized to consist of ten weekly sessions in four phases: introduction, experimentation, design-based inquiry, and consolidation, in order to provide a runway for students to engage in iterative experimentation and prototyping in a learning progression from guided to more open inquiry learning approaches. Details of the MFCs used as well as the key parameters suitable for student-led experimental investigation and for which design choices need to be made when constructing their own improvised MFCs can be found in Appendix A. The final implemented curriculum was co-developed with experienced science teachers from the cooperating school, and was further refined between the implementations with the first and second cohorts. The teachers contributed in the creation of structured worksheets, the adaptation of instructional materials to suit their own teaching, conduct, and facilitation of sessions, as well as in the overall refinement into a complete curriculum package.

Implementation of the MFC curriculum was enacted by the teachers involved with the authors present as research observers and were, on occasion, called to answer questions or provide technical expertise to teachers or students directly. In each session, there were typically several teachers present, with at least one teacher with disciplinary background in each of the natural sciences of biology, chemistry, and physics. The Introduction phase was conducted in a standard classroom through direct instruction in requisite prior knowledge and skills in biology, chemistry, and physics topics by the teachers with relevant expertise. Teachers were also assigned to mentor two to three groups of four students each during the Experimentation and DBI phases, which were conducted in a standard school science laboratory. The teachers monitored and facilitated group planning, discussion, and conduct of experiments and prototype construction, mainly by answering students' queries and prompting them with questions, while avoiding directly influencing student actions or decisions. Immediately after each session, the teaching team and research team conducted a debrief, where mutual feedback on any instructional stints and learning points were shared, and where teachers had the opportunity to collect answers on "difficult" questions they or their students had. General administrative, lesson planning, and logistical matters for the next session were also discussed.

The MFC curriculum has been implemented with slight variations and allocations of time spent in each phase. In this study with Grade 8 students, each session averaged two hours each. The curriculum program consisted of a total of nine or ten sessions, typically once a week, though with interruptions for holidays or other activities. Consolidation of learning was originally conceived as a combination of group-based project reports and presentations to emulate the professional communication and sharing of findings that are a part of scientific and engineering practice. However, this was not always done due to a lack of time.

Table 1. Outline of the MFC Curriculum.

Phase	Learning Activities	Timeframe
Introduction	• Lessons on required prior knowledge ○ content/conceptual knowledge ○ practices, procedural skills, e.g., designing and conducting experimental investigations ○ introduction to the *MFC Challenge*	1–2 sessions
Experimentation	• Guided and open inquiry ○ conduct experimental investigations to determine effect of varying type and parameters of key MFC components/properties ○ sharing of experimental data as a class ○ analysis of each round of collective experimental data to formulate design of subsequent experimental investigation	3–4 sessions
Design-based Inquiry	• Iterative design and construction of MFC prototypes ○ engineering-design, 'making' and problem-solving ○ measurement of MFC prototype performance characteristics ○ intergroup observations of design ideas, construction techniques and success/failure outcomes	3–4 sessions
Consolidation	• MFC Challenge competition ○ Performance of MFC prototypes measured for each challenge criteria ○ Awarding of prizes ○ Consolidation of learning	1–2 sessions

2.3. Problem-Solving as a Measure of Scientific and Engineering Literacy Development

The aim of the MFC curriculum program was to contribute to the development of scientific and engineering literacy by engaging learners in inquiry-driven cross-disciplinary STEM tasks centered on a design-based challenge. The principal research task in evaluating the MFC curriculum was thus to examine the *development of scientific and engineering literacy* over the course of the program. To limit the scope of the research, *problem-solving* (PS) was chosen as the aspect of scientific and engineering literacy to be studied and to serve as a gauge for the development of it. Firstly, for a program pedagogically anchored in the problem-based learning paradigm, there was the inherent and ubiquitous need to *solve problems* that were posed and encountered throughout the program. This meant ample affordances and opportunities to observe PS as a central activity, and also one that is of value as a topic of research, with PS being a skill ubiquitously touted as an important competency in the present and future world. Secondly, there has been relatively little study of learning outcomes in integrated science curricula other than for science *content* knowledge [38], even where engineering design-based activities were conducted [39,40], which suggested an opportunity for research. Thirdly, the authors were interested in the ability of individuals to apply pre-existing knowledge, especially science knowledge learned in school and any nascent engineering skills, in the service of overcoming an encountered *problem*. The MFC curriculum was thus positioned as a means to expose learners to and exercise them in the applied use of the science and engineering knowledge they have, and perhaps then to seek the necessary knowledge they do not yet possess—that is to say, a means to engage in inquiry-based learning. To examine PS is thus to examine learners engaging in integrative cross-disciplinary, inquiry-based learning and, in the process, to develop aspects of scientific and engineering literacies.

Therefore, there is a selective focus here on the use and cultivation of PS skills for the development of these literacies, and in particular on the *overall* process of "finding a solution" to a problem—*not* in the underlying psychological constructs, task translation, or other cognitive processes in the development of the solution. The approach of Klahr and Dunbar [41] in framing PS as a "dual-space search" is particularly useful in this respect. In this model, PS is characterized as the application of *scientific reasoning* in a search process for answers in both a "hypothesis space" and an "experiment space". In the former, the learner scans their prior knowledge to generate explanations, while, in the latter, they may test ideas and seek results through experimentation in the real-world, ultimately to apply both these strategies towards finding or constructing a solution to the particular "problem". Both these aspects are important in this project, where it is hoped that students would apply their scientific knowledge to PS, as well as apply themselves to the conduct of suitable investigative practical work to derive answers and solutions to meet the design goals set, and similarly for the engineering design task of building MFC prototypes and thereby exercise themselves towards the desired scientific and engineering literacy goals. These two approaches to PS could be suitably described as fitting an *engineering model* or *science model* of experimentation, as framed by Schauble et al. [33]. Fundamentally, a science model of experimentation establishes as its goal to understand the "relations between cause and effect", whereas an engineering model seeks to "make a desired or interesting outcome occur or reoccur" [33] (p. 861). They further distinguish between the two models in the approaches that students adopt in practical work, where an "engineering" approach tends to focus on manipulating variables to produce a desired outcome, and when that outcome or some approximation of it is achieved, the experimentation stops—a try-and-see approach. On the other hand, a "scientific" approach attempts to systematically test all possible combinations of variables in order to derive the underlying principles and relationships of the system—a more theory-laden approach. Katehi et al. succinctly describe this distinction as "scientists investigate and engineers create" [31] (p. 41), while Apedoe and Schunn [42] usefully describe these as "science reasoning" and "design-focused" approaches.

2.4. Data Collection

Lessons were video- and audio-recorded, with audio recorders placed on each group's laboratory bench to capture group discussions. Typically, three video cameras were positioned around the science laboratory, each covering nearly the entire room in wide angle. An additional three video cameras were placed so as to focus on selected groups and/or provide additional views of the laboratory. Based on teachers' recommendations and the research team's observations during the initial lessons, two or three groups in each cohort were chosen for closer observation based on their potential for richer and more varied interactions. Video and audio recordings were assembled into synchronized multi-camera views using Final Cut Pro video editing software. Interactions and discussions could generally be followed by switching to the most appropriate camera view and audio track from the closest audio recorder. Notes of key events and noteworthy interactions mapped to the video timeline were made as a form of indexing of the data. Field notes from the direct observation of and interaction with students by the research team (primarily T.T.M.T.) of student actions and discourse were later cross-referenced and analyzed in conjunction with the lesson recordings in order to produce vignettes. In addition, group and individual worksheets (containing experimental data, design sketches, responses to guiding, assessment or survey questions) were collected, while still and video images of student prototypes were recorded. Video-recorded focus group discussions of about one hour with selected students (typically one from each group) were conducted within a week after each cohort concluded the program.

2.5. Analysis of Data

Our method of qualitative analysis followed Barton et al. [43], who themselves based their own analysis on ethnography and grounded theory. These authors first located individual episodes of interest within longer periods of field work in the science classroom. By so doing, they wished to understand how separate events contributed towards overall trends in the learning and engagement of students over time. Taking such a dual perspective of events and time therefore "worked in a complementary fashion to inform on the girls' contextually situated merging practices and identities" [43] (p. 81). While these authors represented their findings based on three specific practices, we decided to adopt a similar method of qualitative representation based on vignettes [44]. It was also because the MFC curriculum was a complex, multi-week intervention, that we have chosen to describe our findings through the use of three vignettes. Vignettes as qualitative representations are ideal here because they "restructure the complex dimensions of the subject for the purpose of capturing, in a brief portrayal, what has been learned over a period of time" [45] (p. 70). Employing a narrative format that is based on fact/evidence, they are "composites that encapsulate what the researcher finds through the fieldwork" [45] (p. 70). Furthermore, the analysis of vignettes serve as a strategy for contextualizing the data and as a means to find the relationships and connections therein [46]. These vignettes thus summarize and portray aspects of the lived experience of the participants in this program, their interactions with the semi-structured learning activities, and with each other, in order to illustrate the potential for learning afforded by this multifaceted intervention. Vignette analysis was supplemented by and triangulated against analyses of student artefacts (worksheet answers, design sketches) and focus-group discussions.

As earlier described, there was a particular focus on revealing instances of PS at the individual student as well as group levels, and the patterns of underlying conceptual and epistemic approaches (i.e., "scientific" or "engineering") adopted that apparently influence such PS. A set of descriptors for each approach was drafted in general alignment with Schauble et al. [33] and adapted for the context of this program, supplemented with exemplifying statements sampled from written artefacts and transcribed student discussions. These descriptors were used heuristically to determine the approaches adopted in particular instances on a best-fit and consensus basis between the authors.

Other qualitative and semi-quantitative evaluations of the curriculum package and its implementation, as well as its impact on student interest and engagement, were separately conducted and not presented here in order to focus on the key research question.

3. Results

To answer the research question, descriptions of three student groups, as well as selected pseudonymized students within each group, their actions, and discourse, are presented here for illustration. In general, it was observed that groups that were less successful (less robust prototypes and/or lower voltage, or even non-functional prototypes) tended to approach PS with a narrow focus. Either an overwhelming emphasis on the "science" or else that of being "practical" or on the "making" without appropriately establishing optimal or even just workable parameters. More successful groups tended to have heterogeneous opinions in their discussions and arguments, approaches to problem-solving, and generally had to compromise between opposing ideas; however, in so doing, seemed to give rise to more effective solutions. The first two vignettes are from groups that exhibited a bias towards either an overwhelmingly scientific (Group E) or engineering (Group G) approach.

3.1. Edwin and Group E

> A personable, smiling, and polite student, Edwin was obviously well-liked and respected by his group members. The teachers had very positive impressions of him and thought of him as intelligent and good at science. I remember him as being quick to offer thoughts and explanations using reasoned and scientific ideas. In the very first session of the DBI phase, Group E had made a prototype

that produced a very high voltage, the highest among the groups that completed a prototype that week and an impressive 0.832 V—on their first try! Part of this success came from their choice of reagents to use in this prototype, which they had decided upon based on their earlier excellent investigative experimentation using the Bennetto cells. This immediately gave Group E a certain reputation for "scientific" prowess within the class. In subsequent weeks, other students would "drop by" the group's bench to "check out" their progress. One obvious problem with their first prototype was that it leaked. This was a problem for nearly all groups; however, theirs was obvious. This "design flaw" may have been the major push factor for them to attempt a very different design approach with their next prototype. However, there were other reasons too. Edwin kept detailed notes in Group Worksheet 1 in his file. In it, he had reasoned that they could obtain even better performance if their next design had a larger surface area of the cellophane membrane; have a larger volume; and, to "shorten the distance" between the two chambers by removing the bridging tube, hence leading to the design of the second prototype (see Figure 2).

The second prototype had a maximum of only 0.632 V, lower than the first. Inter-chamber leaks were noted and reasoned to be the cause of the lower voltage. The next session, the design changed to reduce chamber volume (partly from the teachers' calls to consider and reduce volume where possible to save on the amount of chemicals used), with a focus on a larger ratio of membrane surface area to chamber volume. They also returned to the use of carbon-fiber for the electrodes, after it had been suggested (not clear by whom) that the use of rods in the second prototype reduced surface area and that the general consensus in the class was that fiber electrodes were "better". This third design achieved a high maximum of 0.845 V, which I pointed out was a "record" at the time. Group E was the odds-on favorite to win the MFC Challenge the following week. However, the same problem with leakage was plaguing this design. Regardless, it was decided to make more of the same for the Challenge. By the Challenge session, Group E had four nearly identical units of their third design. However, testing with water showed multiple leaks, and there was no easy way to reach the inner joins of the membrane and chambers due to its shape. They tried various ways to plug the leaks with epoxy glue, hot-glue, and tape, but nothing worked. They filled the prototypes anyway and put them forward for testing. The highest among the four tested at only 0.130 V at the time of the single-MFC challenge. By the time of the battery challenge, none had any appreciable voltage, and, in any case, most of the chemicals had leaked out. It was a huge disappointment, not just for the group, but it seemed even among the other groups, that Group E had not succeeded.

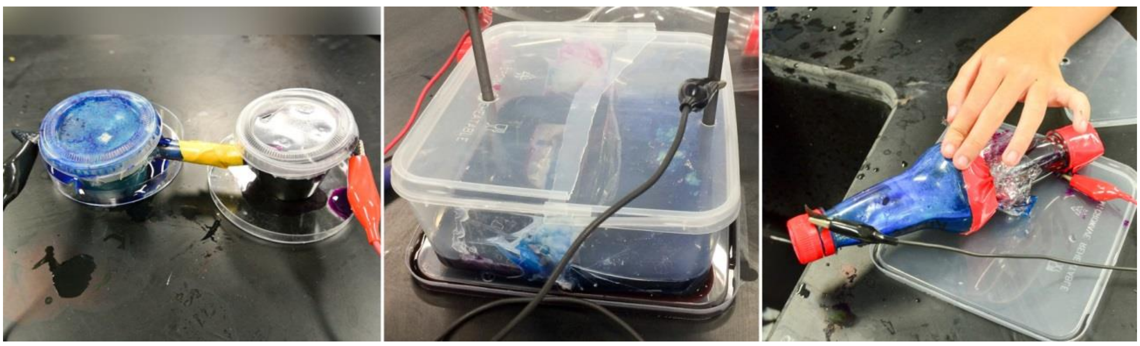

Figure 2. MFC Prototypes by Group E. From left to right: First, second and third prototypes. The third design was used for the MFC Challenge, where a total of four identical units were made.

3.2. Gerald and Group G

A quiet, soft-spoken student with a constant dour expression, Gerald had difficulty interacting with classmates and generally avoided having to do so. In his interactions with teachers and me, he seemed to be full of ideas, which he sometimes found difficult to express, but also seemed to be "resistant" to our explanations and answers to his questions, especially when they conflicted with the conceptions that he held. Group G was one of three groups that only had three members instead of four. According to the teachers, Gerald, Gloria, and Gwen were not on friendly terms with each other, and, in the MFC program, Gloria and Gwen were forced to be "friends" by their common dislike and distrust of Gerald. These circumstances largely explain the extremely dysfunctional dynamics of the group. Progress every week was slow, discussions were mostly between Gloria and Gwen only, but these were not particularly productive. During this first half of the program, Gerald would occasionally approach me directly to ask if he could see me "later". However, at the end of the lesson, he would quickly leave, claiming that he had "tuition" (lessons by private tutor). On one or two occasions, I managed to find the time to talk with Gerald about his questions. He was intensely interested in how the MFCs worked, and what use they could be put to. He had obviously read various material online and had somewhat convoluted ideas that he wanted to incorporate into "his" designs for the DBI phase. These ideas, however, were fundamental misapplications of misunderstood concepts. It was hard enough to know where to begin explaining why they were so, but even more so because Gerald seemed to become upset when I tried to do so.

At the first DBI session, Gerald brought along a plastic carrier bag from which he revealed a clear plastic "biscuit" container with a red screw cover (can be partly seen in Figure 3, indicated by arrow). It contained a brown slurry, and a pungent smell emanated from it. A teacher asked him what it was, and he explained that he had made it at home, based on information gleaned from the internet. He had filled it with leftover food the week before, and left it to "ferment". He showed that it registered a voltage. His groupmates and the teacher were revolted. When I was made aware of it, I too was shocked, but curious that it "worked", I asked him to explain how it did so. Rather than engage in talk, he showed me two sheets of paper with dense printed text describing a long protocol. It became evident that dissimilar metal electrodes had been used, and this accounted for the voltage, it was functioning as a galvanic cell, not as a fuel cell. I tried to explain this to Gerald, but as always, he did not accept what I said. I asked where the protocol came from, and, as best I could understand him, it seemed he had concocted it from at least two sources, essentially combining some instructions to build a conventional galvanic cell, with some (presumably) research article for a single-chamber sludge-based MFC. The former being a "modification", since he did not quite understand the way the latter had to be built. It was, however, very well-made. Neat, carefully-crafted parts. The teacher and I told the group that it was not an MFC, and hence they should proceed with construction of another. The two girls had brought some plastic bottles and all three students reluctantly got to work, though it was almost entirely the work of the two girls. Gerald spent a lot time just staring into space or aimlessly moving about. The prototype leaked badly and did not register a voltage, which may have been due to the poor design, resulting in the liquids not coming in contact across the small piece of membrane at one end of the bridging straw. Since that lesson, Gerald had repeatedly turned down all offers to have a chat or for me to answer his questions. He was polite, but the distinct impression was that he no longer wished to interact with me.

The following week, Gerald was unable to attend the lesson, but had a large plastic carrier bag delivered to class with another of his made-at-home MFCs.

> Made with the same type of plastic container as the first one, this was similar in design to the one made by Gloria and Gwen, but very sturdy, fully watertight, and most of all, really large. This led to problems with filling it. Both "chambers" were excessively large, perhaps a liter each. Gloria and Gwen were quite stunned at the size of the MFC and quickly realized that they would not have enough reagents to fill it. Even when all the chemicals were put in, they did not reach the level of the tube that bridged the chambers. The two girls debated, consulted their teacher, myself, and possibly asked friends from other groups. They were reluctant to build a new, smaller MFC (my suggestion). A seed of an idea to displace volume—just like in Aesop's Crow and the Pitcher—arose somehow, but they could not find suitable types and quantities of materials to put into the chambers. Eventually, they hit on the idea to inflate latex gloves to fill the chambers and hence raise the liquid level to fill the bridging tube. However, no record of the voltage obtained was made.
>
> For unknown reasons, Gerald did not bring an MFC prototype to the MFC Challenge session. Instead, the two girls were trying to make two MFCs, using plastic bottles and containers, some of which were apparently unneeded parts from other groups. Given the limited time to build during that session, they did not complete the MFCs in time to participate.

Both Groups E and G were unable to field properly functioning MFCs at the appointed time for the MFC Challenge. During earlier Experimentation sessions, Group E had shown great promise, achieving good performance characteristics in their prototypes through careful, systematic experimentation and analysis of findings to select reagents and conditions. Group G suffered from a dysfunctional group dynamic; however, all three members had demonstrated excellent practical engineering skills. Gerald had constructed well-made prototypes, while Gloria and Gwen were able to find ingenious ways to displace volume with the limited resources available. Both groups demonstrated notable strength in either scientific or engineering ability, but a concomitant weakness in the other area. Group E members excelled in conducting and analyzing controlled experiments but lacked the engineering skills to build watertight prototypes. Conversely, Group G had those skills but lacked the correct scientific conceptions, had persistently clung to beliefs in the face of contrary evidence or explanations, and had kept little to no record of their experimental data.

Figure 3. MFC prototypes by Group G. From left to right: first prototype, arrow indicates "fermentation MFC" made by Gerald at home and brought to class; second prototype made at home by Gerald, with inflated latex gloves and pebbles used to displace volume; incomplete third prototype made during final MFC Challenge session.

In comparison, Group N was one of the most successful groups. They attained a voltage of 0.847 V in the MFC Challenge and, although their final prototypes leaked, they were able to problem-solve quickly to staunch most of the leaks and managed to keep their MFCs functioning. An examination of their individual approaches to PS, their group dynamic, and how this resulted in a combinatorial approach to PS, suggests that their success can at least be partially attributed to the confluence and application of both scientific and engineering approaches.

3.3. Group N: Diverse but Effective

The four students of Group N have distinct approaches to encountered problems. Nigel tended to focus on data and evidence, just like Naomi, but he preferred to develop his own data empirically and formulate his own conclusions rather than rely on that of others, whereas Naomi would endlessly pore over the collective data from all the groups, comparing and trying to spot trends or some clue as to the best choice to make for the next experiment or design iteration. Both of them clearly foreground a scientific approach in both the experimentation and DBI phases. On the other hand, the other two members tended towards engineering-like methods, seeking options that were at least workable, and doing so either from gut-feel, or else copying and perhaps adapting from existing information or design ideas. Nellie tended to take the "easy" way out, namely the closest approximation or simplest approach. Noella was more circumspect and would consider data, and was willing to accept the data at face-value (unlike Naomi's deep deliberation). She primarily focused on using what was already "known" as a basis to "move on and try the next thing". The following exchange between group members illustrates this.

Group N is again trying to decide what chemicals to use in their first MFC prototype. The discussion is centered on whether they should use a mixture of the two oxidizing agents, potassium manganate (VII) and potassium hexacyanoferrate (III), as the catholyte in their prototype. The shared data from the previous session revealed that Group W had attempted that combination and obtained a significantly higher voltage compared to using either of the oxidizing agents alone. The three girls want to use the combined catholyte, but Nigel is opposed to it.

Nigel: It's proven one time only eh . . .

Nellie: Nigel! (in exasperation)

Noella: Trust the freakin' results! (in exasperation)

Naomi: Try it now? I mean we can try it now. So that next week can confirm. (calmly)

Noella argued that they could try it this one time, and if it did not work, they would not do it the following week. However, Nigel said that trying this combination of oxidizing agents would mean they were changing two variables, namely the prototype design and the catholyte chemistry. Noella argued that "the cell everybody changes! Everyone's still trying something . . . ", but Nigel insisted that they should stay with the catholyte parameters determined from their own experimentation and only vary the cell (prototype) designs henceforth, so that the prototype designs can be directly compared to see which developed the highest voltage, "these few weeks we are meant to upgrade the cell, not change the chemical. If we keep changing the chemicals, then we won't know how to improve the cell!". The three girls expressed frustration and jointly confronted Nigel: Naomi tried to reason with Nigel, "But you see, we can see whether this one is better or previous one is better."; Nellie pleaded, "Okay, just do this one?"; and Noella glared, "It's three versus one, majority wins!". Nigel, unfazed, just retorted, "but logic wins!"

Nigel was steadfast in his strict interpretation of the "fair test" methodology (that is, only one variable at a time is varied in any experiment). He was concerned with being able to compare the differences brought about by each iteration of their cell design. Noella and Nellie were more concerned about the limited time and opportunity to derive the best possible MFC design and chemistry. While Nellie wanted to "just do it" or "just do it this once" in the interests of expediency, Noella's argumentation involved references to "everyone else" doing the same, and decision-making by the "majority". However, it should be noted that their approach was not borne of a slipshod attitude. Indeed, the two were the most industrious and would do most of the 'making' during DBI. Naomi used reasoning and data to respond to Nigel's "logic"—that the current week's experiment could still be compared (or "confirmed") the following week, or against the previous iteration.

Later, while Noella and Nellie were trying to cut their carbon-tissue electrodes, there was a lot of discussion on the size and placement of the holes through which the electrodes would be inserted, and the size and shape of the electrodes themselves. Nigel wanted them "short" but "wide" to have a short electrical path, but maximum surface area in contact with the chemicals. Noella kept emphasizing the difficulties this presented in getting the electrodes inserted and may have been suggesting carbon rods to be easier to insert (albeit at the expense of electrode surface area). Eventually, Nigel suggested a compromise: to cut a slit instead of a drilled hole to fit the electrode, and this worked well from both prototype construction and effective design perspectives. The net result arose from the combined input of group members, each adopting contrasting approaches, both scientific and engineering.

It was interesting that most students were observed to persistently and consistently adopt their particular approaches to assessing, prioritizing, and addressing the multiple scientific and engineering problems encountered in the MFC curriculum. The four members of Group N were a microcosm of the general approaches seen. Some students such as Naomi and Nigel focused on "scientific" decision-making; however, where Nigel prized a logical and first-principles approach and trusted only empirical data from personally conducted experimentation, Naomi looked towards systematic analysis and a consideration of *all* available data in a search for trends to lend weight to the "correct" decision. On the other hand, Nellie and Noella adopted "engineering" approaches, as generally defined by Schauble and colleagues [33]; where Nellie preferred to seek the first functional solution that minimally suffices, Noella tended to reference known solutions and/or seek "a better way" to achieve something. These four approaches could be seen as distinct epistemic stances to PS, and we are developing a taxonomic framework to classify and describe these epistemic stances or approaches adopted by learners in problem-solving tasks encountered in integrated STEM problem-based learning activities [47].

The interpersonal interactions within Group N may have appeared slightly combative and heated at times, with members expressing frustration with each other's approaches to the tasks at hand. However, unlike the negative attitudes, lack of trust, and communication seen in Group G, Group N members were ultimately united in their goal to do well as a group in the MFC Challenge. Group N's within-group discussions were energetic and vociferous at times, but it seemed to be based on a mutual drive to *persuade* each other to their viewpoint, and a level of mutual respect to compromise and reach a tacit or even reluctant consensus for important decisions. The group's progress could thus be seen in part as a product of the push–pull between the individual members' approaches to PS. This ability to compromise was in sharp contrast to two other groups (P and V, not shown here) where the group dynamic was skewed by one domineering member insisting on doing things "their way". Both these groups fared poorly in the MFC Challenge.

4. Discussion

We now summarize the findings that support our claim that building improvised Microbial fuel cells are a model-integrated STEM curriculum for middle-school learners in

Singapore. Specifically, we discuss its affordances in terms of: the development of a STEM Curriculum Package (Section 4.1); problem solving and students' conceptual and epistemic knowledge gains (Section 4.2); group composition and performance (Section 4.3); before we describe some of its potential significance and impact (Section 4.4).

4.1. Development of a STEM Curriculum Package

The MFC curriculum presents a way to effectively integrate learning across STEM domains, especially in science and engineering. In engaging learners with a linked set of activities that progressively present a series of problems to be solved (what reagent to use, what concentration of reagent, what design features to incorporate, etc.), learners may learn concepts and skills, and, perhaps more importantly, are often forced to apply that newfound knowledge or skill in combination with prior knowledge as well as the ideas and opinions of their group members in the service of achieving the designated challenge goals. The vignettes presented above illustrate the how the MFC curriculum can engender and bring about such learning.

As described in Section 1, the MFC curriculum has certain disadvantages, primarily in the logistics/cost, and, perhaps more significantly, in its need for sufficient curriculum time, teacher readiness, and, in essence, a willingness by school leadership to embark on a curriculum program that is not focused on preparation for traditional academic achievement tests. Others are perhaps yet to be swayed to do so because further work lies ahead for this nascent and niche curriculum in order to produce evidentiary validation of our claimed merits. To that end, our future work will seek to further codify the learning that is possible, aided in part by a novel taxonomic framework in development, as well as to determine implementation success factors for the MFC curriculum and similar programs.

4.2. Problem Solving and Students' Conceptual and Epistemic Knowledge Gains

Problem solving was selected as a measure of the scientific and engineering literacies we were interested in since there are many opportunities to observe PS in the type of problem-based learning activities presented here. Were students able to solve the problems encountered through the application of conceptual knowledge and skills, either acquired prior to or during the MFC curriculum? This was clearly true when looking at PS in specific tasks by specific students. Students were able to find solutions to problems encountered as well as make design decisions, in terms of experimental design or engineering design, based on reference and/or empirical data. Were students able to demonstrate and apply different epistemic approaches to PS? Some students excelled at the designing of experimentation of physical prototypes, others at finding optimal conditions from detailed analyses of data or for optimal and efficient ways to construct some item. However, as might be expected, no individual student appeared to be broadly proficient in all areas. Nonetheless, it can be seen that Edwin, Naomi, and Nigel demonstrated proficient scientific abilities, while Gerald, Gloria, Gwen, Nellie, and Noella demonstrated impressive engineering prowess. While these were selected individual examples, they were not isolated cases. Other students (not shown here) had exhibited varying degrees of proficiencies and, indeed, in some instances, were possibly even more impressive.

At the individual level, these gains may be concentrated in either of, rather than both, domains of literacy. As earlier described, individual students tended to adopt relatively specific and consistent approaches to PS, being either distinctly "scientific" or "engineering" stances, as exemplified by each of the four students from Group N. Whether these epistemic stances represent existing aptitudes and/or were encouraged and developed by the activities presented by the MFC curriculum remains the subject of further study, as is the taxonomic framework we are developing for this purpose. Regardless, if the MFC curriculum is able to develop or at least proffer the opportunities for individual students to exercise their scientific *or* engineering knowledge and skills, then it should be able to do the same for all learners to some degree, whether they tend towards scientific or engineering stances. In other words, even if a student's tendency to adopt a "scientific" stance is somehow an innate inclination, they would still be exposed and have opportunities to develop *both* their scientific and engineering literacies in this integrative curriculum. It is perhaps of interest from a learning science perspective that the MFC program also affords a platform for the observation and further study of such epistemic approaches by learners.

The development of PS and other aspects of scientific and engineering literacies in science-based and/or engineering design-based inquiry learning activities have also been reported in other studies. These are summarized in Table 2 along with their relevance to this study. Our findings and those of these studies broadly agree with and complement each other.

Table 2. Comparison of Findings with Other Studies.

Study and Key Findings	Implications for MFC Curriculum
Wendell and Rogers (2013) [39] From an experimental study of an engineering DBI curriculum for elementary students, it was found that learners gained science content knowledge as well as engineering design skills that were independent of increases in attitudes towards science among learners which may arise due to the novelty of the curriculum.	Engineering DBI offers the potential to develop desirable science and engineering literacies, even if they often increase attitudes towards science for other reasons.
Fortus et al. (2004) [23] Science knowledge as well as problem-solving skills were significantly improved among 9th graders undergoing three cycles of DBI. Learning gains were assessed by pre-post written tests, and with models and posters to check application of knowledge to design problems.	Science-based DBI does also appear to support problem-solving skills.
Marulcu and Barnett (2015) [40] In a mixed-methods comparison of an engineering design-based curriculum with a FOSS inquiry program on simple machines for 5th graders, both approaches significantly improved their science content knowledge. However, learners in the DBI approach performed significantly better on the interview questions.	Engineering DBI is neither superior nor inferior to other forms of inquiry-based learning.
Li et al. (2016) [48] An engineering design-based modeling approach with LEGO helped 4th graders in their science content knowledge as much as those in the control group who learnt by inquiry. However, pupil gains in the experimental group were significantly higher for problem-solving ability ascertained through a survey questionnaire and evaluation of physical artifacts.	Engineering DBI does appear to support development of problem-solving skills and science content knowledge.
Shanta and Wells (2020) [49] Through an authentic engineering design-no-make challenge, high school students demonstrated significantly better critical thinking and problem-solving abilities compared to traditional classroom instruction.	Engineering DBI does again appear to support development of problem-solving skills.

4.3. Group Composition and Performance

Beyond the individual learner's development of scientific and engineering knowledge, skillsets, and overall literacies, it was apparent that success with DBI tasks at the *group* level somewhat depended upon group composition and the interactions between its members. Leaving aside the general dysfunction of group dynamics arising from interpersonal issues, and viewed through the perspective of this study's focus on PS, we found that groups that consisted entirely of students with the same overall conceptual and epistemic approach to PS (either "scientific" or "engineering") such as Groups E and G, or where one individual's will dominated (Groups P and V), were the most likely to fare poorly in the MFC Challenge. Conversely, groups with members with individual approaches to PS more evenly distributed between "scientific" and "engineering" stances (Group N and others) tended to do better, producing MFCs with higher performance metrics. This fits with the widely held view that group heterogeneity is important in cooperative and collaborative learning [50,51]. In addition, it is the *positive interdependence* among diverse group members that is the key to the success of the group as a whole and of its individual members [52]. Positive interdependence is where group members believe that working together collaboratively or cooperatively provides greater rewards or better outcomes for themselves and hence do so. In the context of the MFC curriculum, this suggests why groups with an even mix of students with "scientific" and "engineering" approaches to PS appear to fare better overall, and especially so if the group dynamic is positive and mutually supportive.

Success in problem-solving the multiple, complex, cross-disciplinary, and ill-structured tasks in this activity could perhaps also be simply dependent upon student groups bringing a variety of *skills* to bear on the problem. Single domain skillsets may only successfully solve the problems from that domain. Group heterogeneity in PS approach (and hence heterogeneity in preferred skillset for PS) alone may go some way in affecting success. Imagine if Group G's well-crafted prototypes were filled with Group E's systematically elucidated choices of reagents and conditions! Nonetheless, it should also be obvious that the MFC curriculum engages students in collaborative group work reminiscent of real-world, project-based workplace endeavors, and this affords rich opportunities for students to develop other transferable skills such as communication and working with others. Students also have the opportunity to experience success in such complex tasks that they would unlikely otherwise be able to on their own. However, as some cases demonstrated, careful grouping of students may be important to capitalize on this overall effect. Nonetheless, the MFC program affords students of different dispositions, with different conceptual and epistemic approaches to PS, and with varied overall abilities and the opportunity to apply their knowledge and skills to complex, ill-structured tasks, and thus has the potential to develop their scientific and engineering literacies.

4.4. Significance and Impact

It should be noted that the individual and overall performance of the students in the MFC curriculum had surpassed the expectations of their teachers and the research team. Middle-school level students were able to work collaboratively to design and make functional improvised MFCs that outperformed reference kit MFCs. This unfamiliar, complex, and ill-structured set of tasks required systematic investigation and deliberate evidence-based decision-making. This suggests that, with appropriate curriculum design and scaffolding, even complex STEM activities can be successfully implemented at this level. While there was no control group for a direct comparison, the informal subjective comparisons within the cohort and the surprising exceeding of expectations suggest to us that the MFC curriculum had indeed enabled the development of aspects of scientific and engineering literacies among the learners in this study. The school subsequently continued to conduct the MFC program annually. Teachers from several other schools have also expressed interest in the program, with one other school implementing a slightly modified MFC program at both Grade 8 and Grade 10 levels. At several schools, teachers were keen to implement the program and undertook the professional development and planning to do so; however, for various reasons, were ultimately unable to proceed.

5. Conclusions

The MFC curriculum is one of very few educational activities that combine the three natural sciences and engineering while providing authentic real-life contexts in alternative energy and sustainability issues. Unlike most DBI activities such as those in Table 2, where physical sciences and engineering tasks overwhelmingly predominate, the inclusion of biological and chemical subject matter, and their integration in the core of the MFC curriculum, is quite unique. This affords an intrinsically integrative approach to STEM learning. It is thus a successful proof of concept for integrated STEM for Singapore schools, which are only just opening up to such integrative programs. Furthermore, what might generally be considered to be material for undergraduate level learning has been redesigned and adapted for learners as young as Grade 8. This is an appropriate age to appreciate the science concepts and where students are also mature and skilled enough to design workable engineering products through DBI. On the other hand, aspects of the MFC curriculum have also been trialed with older students (Grade 10 and undergraduates) and even adult learners (especially as professional development and training for teachers involved in its implementation), and they appear to find it as engaging and challenging as the students in this study. Indeed, these other groups were better able to appreciate and articulate how novel and intellectually stimulating they found the MFC curriculum activities to be. Hence, we feel that the MFC curriculum has strong potential for use across a broad range of grade and ability levels.

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Appendix A

Appendix A.1. Key Parameters for Experimentation with the MFC

Two-chamber mediator-based MFCs are just one general class among many types of MFCs. There are discrete components and types of reagents that constitute such MFCs, and each of these can be relatively easily substituted and/or varied in some way on an experimental basis, and such variation may alter some performance characteristic of the MFC's electrical output. A small MFC in this type of design was developed for teaching purposes [8–10] and is commercially available in kit form from the National Centre for Biotechnology Education (NCBE), University of Reading, United Kingdom. We will refer to these as Bennetto MFCs.

Other forms of MFCs may be more prevalent in research, such as mediator-less, single-chamber MFCs, and, for educational purposes, there are soil-based MFC kits packaged for STEM learning such as the *MudWatt* from Magical Microbes [53]. However, these lack the breadth of affordances Bennetto MFCs provide for experimentation, as well as the flexibility of design choices in constructing improvised MFCs. The Bennetto MFC in NCBE kit form provides a standardized platform with which to conduct controlled experiments, with the general aim of determining optimal parameters for peak electrical output. The standard protocol, with the suggested type and concentration of reagents to be used with the NCBE kit, typically produce a voltage of about 0.5 volts. This can be used as a baseline reference MFC. Power output is generally limited to brief bursts of a few microwatts and sustained output in the range of nanowatts. Nonetheless, several such MFCs in series may be able to light up low-power LEDs or digital circuits (digital clock).

In the Experimentation phase of the MFC curriculum, students are provided with Bennetto MFCs with the standard set of reagents and protocol [9] with modifications. The key difference is the use of potassium manganate (VII) ($KMnO_4$, potassium permanganate) as the oxidizing agent used as the catholyte in the cathode chamber. $KMnO_4$ is generally safer for school use as it is a common antiseptic, whereas the reagent suggested in the standard protocol is potassium hexacyanoferrate (III), which is mildly toxic. An additional benefit of this change is an approximately 0.2 V increase in voltage over the reference cell, due to the greater difference in electronegativity between the chambers. This is an example of how changing one of the MFC's components can result in a change in its electrical output. Other such parameters that have been successfully tested are listed in Table A1. Note that not all parameters necessarily result in improved MFC performance. However, by providing some of these reagents or materials for experimentation, students will have to empirically determine the effect parameter has. Students in the MFC curriculum are usually not given the full list, with the intention of allowing for inquiry-driven and discovery-based elucidation of characteristics. Parameters for experimentation is typically distributed among the different student groups, with data shared in a common pool.

For the purposes of experimentation, measuring the voltage of the MFC over time, either open-circuit or with a relatively high resistance load to keep current draw to a minimum, serves as a simple measure of the effect of any changes made, as compared to the reference Bennetto MFC. The use of voltage sensors connected to a datalogger device is strongly encouraged. Tracking the voltage output curve over time is informative. The voltage profile over time is often characteristic of particular reagents used, and this temporal data represents a particular affordance not typical of most school science practical work, where end-point or spot measurements predominate.

Table A1. Properties of Microbial Fuel Cells for Inquiry Experimentation.

Property or Component	Parameters for Experimental Investigation and Design Decisions
Scientific Parameters [1]	
Microorganism (Species, source and quantity)	Yeast (various types of food-grade yeast) Algae (photosynthetic MFC) Bacteria (not ideal for school use) (for yeast, typically 0.05 g dried yeast per milliliter)
Food source (Type and Concentration)	Sugars: e.g., monosaccharides (glucose, fructose), disaccharides (maltose, sucrose) Other sources of food suitable for microorganism used, including mixtures (typically, ~0.3 M final concentration)
Electron mediator (Type and Concentration)	Laboratory stains and indicators: e.g., methylene blue, neutral red, phenol red, orange G, xylene cyanol, etc. Food dyes from natural extracts: anthocyanin dyes from red cabbage, butterfly pea flowers, etc. (typically, ~0.003 M final concentration and in 10-fold serial dilutions thereof)
Oxidizing agent (Type and Concentration)	Potassium hexacyanoferrate (III) Potassium manganate (VII) (typically, 0.02 M final concentration)
Temperature	Typically, room temperature, but may be varied using water-baths or incubator ovens

Table A1. *Cont.*

Property or Component	Parameters for Experimental Investigation and Design Decisions
pH	Typically, pH 7.0. All MFC reagents are prepared in phosphate buffer solution balanced to pH 7.0. Different pH may be selected, but all reagents need to be prepared in buffer solution of that pH
Engineering Design Parameters [2]	
Size and Layout of MFC	Overall size and form affects chamber volumes, surface areas of electrodes and proton-exchange membrane, and how non-motile microorganisms may settle within chamber, affecting their access to food, oxygen, electron mediator, etc.
Size and Type of Electrodes	Carbon fiber sheets, graphite rods/plates, or inert metals (gold, platinum) Carbon fiber has potential for high surface area, but tends to have lower conductivity than graphite rods (students can test for conductivity using a digital multimeter)
Chamber separation	Kit MFC uses bespoke proton-exchange membrane sandwiched between protective porous carrier films. Alternative materials: dialysis tubing/membrane or cellophane (these semi-permeable membranes lack specificity for cation-only exchange and hence allow electrons through, resulting in a slightly lower voltage). Alternative approach: salt-bridge for ion-exchange, e.g., paper strip soaked in conductive salt solution or tubing containing salt solution in agar gel
Anoxia	Limiting the microorganism's access to oxygen should allow more reducing power (electrons) to be captured by the electron mediator. Closed chamber designs with limited air space and only a small opening for loading or escape of carbon dioxide should help. Possibility of using oil layered on top of anolyte solution
Practical Design Considerations	Chamber that are easy to fill and/or have access to replace electrodes and reagents Watertight and leak-resistant design and construction methods Robust and durable for easy handling Ease of construction Availability and cost (e.g., resource limitations imposed)

[1] Scientific parameters are those that can be manipulated during the inquiry-driven experimental investigations, typically using the Bennetto kit MFCs under controlled conditions, but it is also possible to modify these during the DBI phase as students chase performance improvements. [2] Engineering design parameters are those that students typically only encounter during the DBI phase, when designing and constructing their prototypes, however these also feature opportunities for reasoning with scientific rationale.

Some parameters have greater effect on voltage output than others. Some changes may not apparently have any effect on voltage levels, but may affect other performance characteristics. For example, varying the concentration of oxidizing agent does not have a significant effect for short-term experiments; however, effects can be seen over several hours. As the oxidizing agent is consumed over time, lower concentrations limit the longevity of the MFC. Others parameters sometimes have peculiar correlations with MFC performance. For example, the voltage varies with the different concentrations of the electron mediator in a non-linear and complex way. This challenges students to make sense of the data they collect.

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