Potential for Chemistry in Multidisciplinary, Interdisciplinary, and Transdisciplinary Teaching Activities in Higher Education

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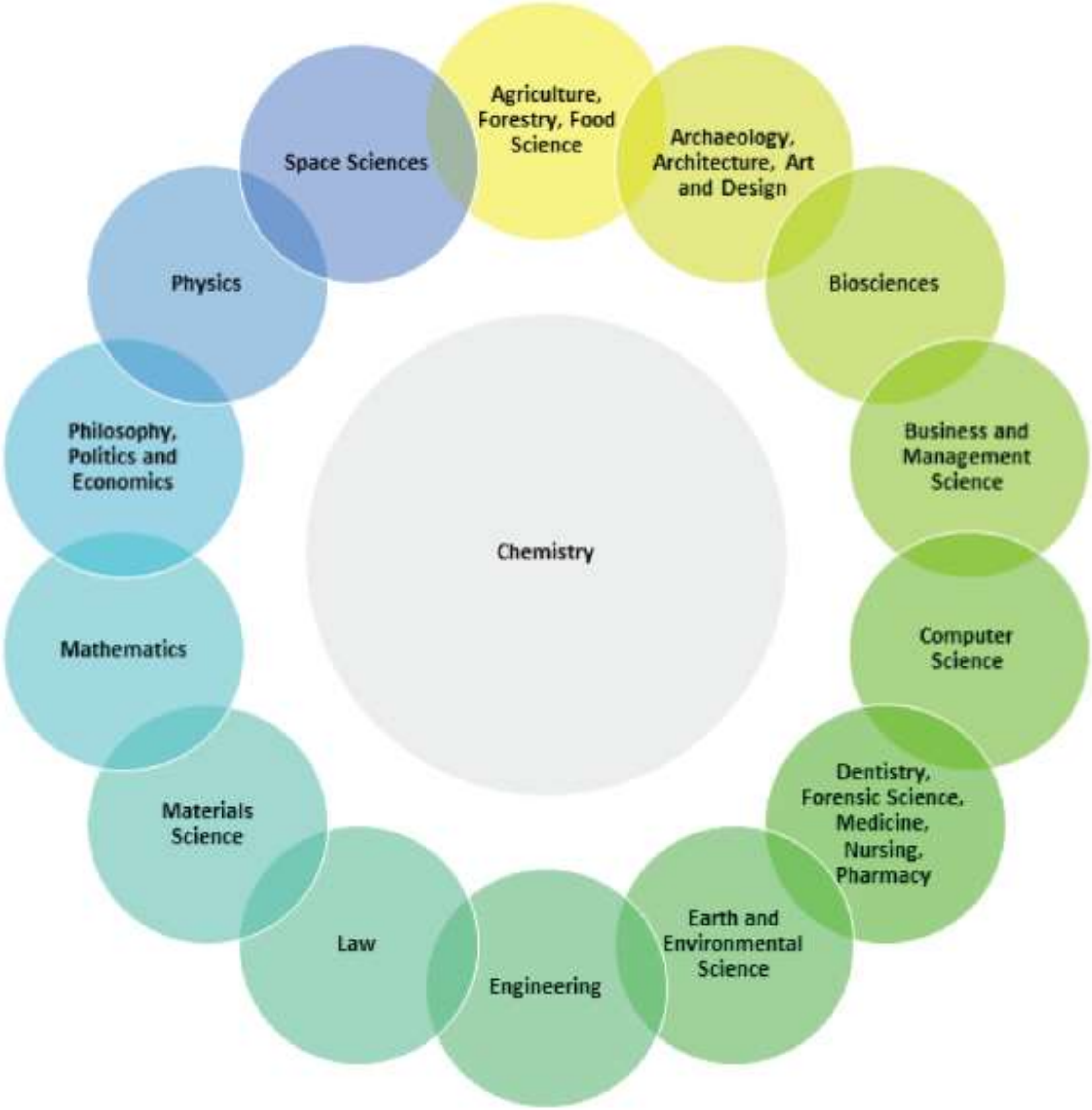
ABSTRACT

For some professionally-, vocationally-, or technically-oriented careers, curricula delivered in higher education establishments may focus on teaching material related to a single discipline. By contrast, multidisciplinary, interdisciplinary, and transdisciplinary teaching (MITT) results in improved affective and cognitive learning and critical thinking, offering learners/students the opportunity to obtain a broad general knowledge base. Chemistry is a discipline that sits at the interface of science, technology, engineering, mathematics, and medicine (STEMM) subjects (and those aligned with or informed by STEMM subjects). This article discusses the significant potential of inclusion of chemistry in MITT activities in higher education and the real-world importance in personal, organizational, national, and global contexts. It outlines the development and implementation challenges attributed to legacy higher education infrastructures (that call for creative visionary leadership with strong and supportive management and administrative functions), curriculum design that ensures inclusivity, collaboration, and is pitched and balanced appropriately. It concludes with future possibilities, notably highlighting that chemistry, as a discipline, underpins industries that have multibillion dollar turnovers and employ millions of people across the world.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate / General, Second-Year Undergraduate, Upper-Division Undergraduate, Curriculum, History/Philosophy, Interdisciplinary/Multidisciplinary, Laboratory Instruction, Problem Solving/Decision Making, Applications of Chemistry, Learning Theories

INTRODUCTION

National education systems vary in structure and curricula content, which renders it difficult to accurately benchmark performance and monitor progress towards national and international goals. The International Standard Classification of Education (ISCED) is the standard framework used to categorize and report internationally comparable education statistics. The ISCED 2011 classification was adopted by the United Nations Educational, Scientific and Cultural Organization (UNESCO),[1] spanning education at pre-school, primary, secondary, and tertiary levels (summarized in Table 1). Studies emphasize the importance of starting career-related education in the 3–11 age group (early and primary education)[2] to expose learners/students to a wide range of possible occupations (challenging diversity stereotypes, e.g., gendered perspectives of career prospects)[3–9] and gradually build on their knowledge by increasing the sophistication of the activities (e.g., role play at early stages, thereafter discussion of guardians' or family members' jobs, and at later stages other activities, including CV workshops, mentoring from external speakers (e.g., work experience of guardians, family members, others, etc.); such interventions broaden the aspirations of children, helping them develop social and non-cognitive skills.[2] As the workplace is ever evolving, many employers want children in the 3–11 age group to begin to develop science, technology, engineering, and mathematics (STEM) skills alongside high priority soft skills (e.g., listening, creativity, teamwork).[10] At a secondary level, the shift from a teacher-centered classroom to a learner/student-centered classroom facilitates collaboration and creativity; placing the emphasis on the teacher being the "facilitator" and potentially fusing some activities with other subjects (e.g., art, technology).

Table 1. International Standard Classification of Education Levels and Descriptions

Level	Description
0	Early childhood education (i.e., prior to primary education)
1	Primary education
2	Lower secondary education
3	Upper secondary education
4	Post-secondary non-tertiary education
5	Short-cycle tertiary education
6	Bachelor's or equivalent level
7	Master's or equivalent level
8	Doctoral or equivalent level
9	Not elsewhere classified

When introduced effectively, "integrated" STEMM curricula help learners/students contextualize the real world importance of STEMM subjects. The manifestation of such integrated curricula varies dependent on the school system, examples of which include the UK "integrated science" general certificate of secondary education awarded by many schools,[11] or the Montessori system found in many countries across the world that has been found to successfully integrate academic subjects in meaningful ways for the learners/students, better reflecting real-life situations and providing a more holistic education.[12–16] The general consensus among teachers of the effectiveness of teaching integrated curricula (particularly project-based tasks) is supported by increases in academic achievement. A great deal of interest emerged in integrated curriculums and many studies have been conducted dating back to the 1990s.[17,18] Most research on interdisciplinary programs is qualitative or anecdotal, the evidence collected is generally positive, highlighting the potential for increased student achievement and the development of an engaging, relevant curriculum.[19] More than 200 studies have been carried out to assess the effectiveness of the various forms of integrative curriculum and instruction,[20] and several authors have reported that students participating in interdisciplinary or integrated curriculums do as well as or better than, students in conventional program.[19,21,22] While there is an appreciation for obstacles to implementation, studies show that teachers believe in the effectiveness of integrated curriculums.[23,24] The benefits of integration are recognized internationally; a number of countries high in the PISA rankings are adopting policies for curriculum integration.[25,26] Application of these includes a shift toward project-based learning,[16] which combined with a real-world inquiry focus are naturally interdisciplinary in nature.[25] Although research has been undertaken into teacher perception and the implementation of integrated curriculums, Shriner et al. argue that the question of whether or not teachers' attitudes toward curriculum integration can be modified has not been addressed.[27] Other advantages of integrated science teaching approaches include: improved learner/student cooperation (concomitantly reducing disruptive behavior); improved learning and understanding; improved ability to apply concepts and engage in creative big picture thinking; improved reading, writing and mathematics skills; greater personal growth, self-confidence, motivation, and citizenship.[13,25,28–31]

An academic discipline is a branch of knowledge that can be taught throughout primary, secondary and tertiary/higher education, and researched in higher education establishments (however, researchers of higher education suggest that the concept of a discipline is nuanced).[32–37] The terms multidisciplinary, interdisciplinary and transdisciplinary are used in the literature, however, they can be ambiguously or interchangeably used (in part because of the ambiguity of the term “discipline” and evolution of new disciplines); nevertheless, disciplinary approaches were defined by Stember[38] as follows:

- Monodisciplinary or intradisciplinary: working within a single discipline.
- Cross-disciplinary: viewing one discipline from the perspective of another.
- Multidisciplinary: people from different disciplines working together, each drawing on their disciplinary knowledge.
- Interdisciplinary: integrating knowledge and methods from different disciplines, using a real synthesis of approaches.
- Transdisciplinary: understanding the unity of intellectual frameworks beyond the disciplinary perspectives.

Some curricula delivered in higher education establishments worldwide focus on monodisciplinary/intradisciplinary teaching, which enables the learners/students to demonstrate depth of knowledge and expertise in practice upon completion of their course. However, multidisciplinary,[39–41] interdisciplinary[33,35,42–44] and transdisciplinary[13,33,35,43,45–47] teaching (MITT) is reported to positively impact affective/cognitive learning and critical thinking,[12,13,15,48,49] enabling learners/students the opportunity to obtain a broad general knowledge base. Such broad based curricula are appealing to some employers because they demonstrate that the job candidate is well-rounded and capable of adapting to the changing workplace.[46,50–57]

McClaskey offers a clear distinction between students and learners: a student undertakes formal elements of teaching in an educational institution or affiliated industry partner workplace environment such as an industry laboratory or plant, with a specific course curriculum to be awarded a higher education qualification; whereas, a learner may not follow a prescribed curriculum nor seek the award of a qualification (Table 2),[58] and the continually changing workplace is motivation for students and graduates to transition to being learners at some point in their lives.[59] While all learners/students can benefit from MITT activities, the focus of this article is on the potential for inclusion of chemistry in MITT activities in a higher education context,[31] and therefore for the avoidance of ambiguity, the term “student” will be used for the remainder of the article.

Table 2. Examples Highlighting Differences between Students and Learners

A Student	A Learner
Learns in a classroom	Learns anytime, anywhere
Is directed by their teacher	Directs and supports their own learning
Works within a defined time	Works at their own pace
Is motivated by grades	Is motivated by the mastery of skills
Follows goals that are set and monitored by the teacher	Develops their own learning goals and monitors their own progress
Achieves by listening and following instruction	Achieves by active collaboration and feedback with others
Experiences teacher-designed activities and projects	Designs learning experiences based on passions and interests

Adapted with permission from an infographic designed by Kathleen McClaskey,[58] co-author of *Make Learning Personal*[60] and *How to Personalize Learning.*[61]

Educational research suggests that MITT promotes significant learning[62–64] through the engagement of students with classroom experiences that offer opportunities to develop a range of skills important for employability, including: communication, IT literacy, numeracy, project and time management, and scientific and technical knowledge.[31,51,52,65] MITT enables students to enhance their foundational knowledge of various disciplines through the acquisition and understanding of information and ideas. It also creates an opportunity for students to learn how and when to apply specific skills, to connect ideas and approaches from different disciplines, to integrate their knowledge base, and perhaps most importantly to learn how to learn, and thereby develop an appreciation of metacognition.[66] This enables the integration and application of knowledge as part of the bigger picture which leads to more critical thinking and fosters the development of foresight to consider potential consequences of an action, thereby leading to recognition of ethical concerns (e.g. potential environmental and health impacts if a chemical entity is released).[67,68] MITT involving academics from different disciplines offers students heterogeneous learning experiences and assessment strategies that mirror the heterogeneity of individual's learning styles, and are therefore more inclusive in terms of the backgrounds, experiences, interests and talents of the staff and students involved in MITT environments, which enhances student engagement and therefore learning.[37,69] MITT also offers opportunities for students to work as teams on multidisciplinary, interdisciplinary and transdisciplinary projects[12,56,69–74] (e.g., problem-based and research-based learning activities),[75] which is essential for many real-world applications of STEMM and other disciplines (e.g. development of chemicals [e.g., natural/synthetic drugs and/or polymers] for technical applications [e.g. computing, construction, engineering, textiles] and medical applications [e.g. pharmaceutical formulations, diagnosis and therapy]).[37,51,52,67,68,76] This is recognized by governments and learned/professional bodies as a key skill for graduates, as it underpins their employability in sectors that support economies.[47,51,52,77–81] MITT involving chemistry taught in combination with industry, product design (e.g., materials science and engineering), innovation, law and business/management science may facilitate the development of new technologies by reducing technical and market risk, thereby increasing the probability of success; such MITT offerings will help address the market need for people with scientific and technical skills, in addition to having business acumen, facilitating economies that employ graduates from the courses to become more competitive.[82] Furthermore, MITT training has the potential to help employers to build agile teams to solve problems, differentiate levels of instruction necessary for individual team members, and to evaluate performance more authentically; likewise, MITT could offer training that helps graduates in industry draw on their foundational knowledgebase to rotate between multiple teams, contribute ideas and contribute more broadly to the success of the employer and progress more swiftly in their careers.[83]

The skills required by new chemistry graduates[31,51,52,84] and their development in courses have been the subject of studies co-authored by academics and a variety of Professional, Statutory and Regulatory Bodies (PSRBs) including learned bodies (some of which approve, recognize and accredit higher education programmes).[84–90] Examples of such PSRBs include (but are not limited to): the American Chemical Society (ACS), the American Institute of Chemical Engineers (AIChe), Die Gesellschaft Deutscher Chemiker (GDCh), the Institution of Chemical Engineers (IChemE), the Institute of Materials, Minerals and Mining (IOM3), the International Union of Pure and Applied Chemistry (IUPAC), the Materials Research Society (MRS) and the Royal Society of Chemistry (RSC). This article discusses the potential for chemistry in MITT activities in higher education by illustrating their real-world importance in a variety of contexts (personal, organizational, national, and global), and some of the challenges of developing and implementing chemistry in MITT curricula that will deliver graduates to support economies across the world.

MITT GROUPS ARE NEEDED TO STUDY COMPLEX AUTHENTIC PROBLEMS WITH REAL-WORLD IMPORTANCE

A variety of complex problems currently encountered in the real-world need to be addressed carefully using the intervention of smart, creative and innovative solutions. Multidisciplinary, interdisciplinary and transdisciplinary perspectives offer opportunities to solve such complex problems when monodisciplinary/intradisciplinary approaches may be limited; particularly for globally important issues such as climate change, employment, health and medicine, migration, pollution, security, etc.[33,45,71,91–109] Multidisciplinary, interdisciplinary and transdisciplinary approaches are additive, interactive, and holistic, respectively. When the nature of involvement of multiple disciplines is unknown (or unspecified), multidisciplinary is the most appropriate term to use to avoid ambiguity.

The success of chemistry as a lens to understand the natural world has resulted in it being subsumed into a variety of biological subjects. Molecular biology,[110] biochemistry,[111,112] pharmacology and pharmacy[113–116] in particular draw heavily from chemistry but have long since moved to being independent disciplines in their own right. Their emphasis on observing biological processes as systems makes teaching every aspect from a detailed chemical viewpoint impractical. For example, gene expression in bacteria is largely dependent upon binding interactions of certain macromolecules and DNA, but it would simply take too long to teach and understand gene expression at this level of detail. The practical value of these chemistry related bioscience subjects has made them heavily integrated into other areas of biology, bioengineering and biomedicine curricula.[92,111,117,118]

The Sustainable Development Goals (SDGs, also known as Global Goals) have been adopted by all United Nations (UN) member states with the aim of ending poverty, protecting the planet and ensuring all people enjoy peace and prosperity by 2030.[119–124] There are 17 SDGs that, if acted upon in a knowledgeable and creative fashion, will enhance social, environmental and economic sustainability for the good of the world. The SDGs are complex real-world problems, and chemistry has the potential to play an important role in multidisciplinary, interdisciplinary and transdisciplinary solutions to these challenges, thereby improving the lives of millions of people across the world.[104,125,126] Table 3 displays the potential involvement of chemistry at the interface of other disciplines in solutions to address the SDGs.

Table 3. The United Nations Sustainable Development Goals with Some Corresponding Examples of the Potential Involvement of Chemistry at the Interface of Other Disciplines in Their Solution

Sustainable Development Goals		Potential Solutions Involving Chemistry
1	End poverty	Creation of jobs involving chemistry integrated with biology, engineering, mathematics, physics, etc.
2	Zero hunger	Improved agricultural processes employing novel agrochemicals and chemical biology techniques, resulting in higher crop yields, nutritional value, food security and lowering the cost of food production
3	Global health and well-being	Production of affordable medications and/or materials for medical interventions, education about principles of chemistry in an MITT health context
4	Quality education	Development and delivery of affordable, accessible and inclusive educational resources for lifelong learners/students involving chemistry in an MITT context, such as pharmacodynamics
5	Gender equality	Achieving equality of representation and salaries for all gender identities across the industries involving chemistry, as well as negation or reduction of labor intensive traditional gender roles, such as palm oil production, waste management, etc. and thereby improving opportunities
6	Clean water and sanitation	Development of green and affordable water filtration and purification processes capable of deployment in a variety of environments,[a,b] because only 3% of the world’s water is fresh water, and the fact that 2.4 billion people worldwide lack access to fresh and clean water,[c] has been identified as the most understated global security risk[d]
7	Affordable and clean energy	Development of affordable, reliable, and sustainable materials for energy harvesting and storage
8	Decent work and economic growth	Creation of jobs involving chemistry integrated with other disciplines across the globe
9	Industry, innovation and infrastructure	Supporting jobs involving chemistry integrated with other disciplines across the globe, particularly entrepreneurship, invention, innovation, leadership, management, etc.[e,f]
10	Reduced inequalities	Achieving equality of representation and salaries for all diversity groups across the industries involving chemistry and reduce inequality between countries (concomitantly supporting global security)
11	Sustainable cities and communities	Development of cities and communities utilizing sustainable sources of energy, food, housing, transport, water, etc. (all of which involve chemistry in some way)
12	Responsible consumption and production	Consumption and production of goods integrated within a circular economy[g,h,i,j]

13 Climate action	Comprehensive understanding of climate (biogeo)chemistry (combining theoretical and practical approaches) and development of sustainable materials and methods to combat climate change and its impacts
14 Life below water	Developing materials and methods to conserve oceans, seas and marine resources by minimizing or eradicating pollution from manufacturing and distribution, and the development of degradable polymers for packaging
15 Life on land	Development of chemicals, materials and methods to ensure the sustainability of terrestrial biodiversity and ecosystems
16 Peace, justice and strong institutions	Promotion of effective, equitable, inclusive and accountable institutions and societies involving chemistry at all levels, with specific, measurable, attainable, relevant and time-bound goals to address such issues and a transparent reporting mechanism for assessing progress against these goals on a regular basis
17 Partnership for the goals	Implementing and supporting global partnerships uniting researchers in the public sector (e.g., academia), private sector (e.g., industry) and third sector (e.g., community, non-profit, voluntary), thereby facilitating capacity building for sustainable development through knowledge transfer activities to advance innovation at global, regional, national, and local levels)

[a]See ref *127*. [b]See ref *128*. [c]See ref *129*. [d]See ref *130*. [e]See ref *82*. [f]See ref *131*. [g]See ref *68*. [h]See ref *119*. [i]See ref *120*. [j]See refs *132–135*.

Industries have evolved to address real-world problems, and chemistry (and its integration with biology, engineering, mathematics, physics, etc.) plays an important role in each of the different economic sectors which have multibillion-dollar turnovers and employ millions of people across the world (Table 4). Employability plays a role in league table rankings of universities (which has an impact on their financial viability), consequently imparting an appreciation of the complex real-world problems faced by industry and the application of multidisciplinary, interdisciplinary and transdisciplinary approaches to solving those problems (and their financial impact on the businesses) is fundamentally important.[136] It is therefore logical that recognized year-long industrial or professional placements are becoming increasingly common in chemistry related undergraduate degree programs.

Table 4. Chemistry Plays an Important Role in Each of the Different Economic Sectors

Economic Sector	Industries and Processes That Potentially Involve Chemistry
Primary	Involves the extraction and production of raw materials, including natural resources isolated from agricultural, marine or mining activities, with an increasing emphasis on ensuring the sustainability of supplies.
Secondary	The secondary economic sector involves manufacturing, including construction, electronics, plastics and textiles, all of which involve materials chemistry.
Tertiary	Services such as: distribution and transport (e.g., energy and fuel, packaging, security), healthcare (e.g., biomaterials, drugs, pharmacology), sustainable waste management and recycling (e.g., analysis, separation, purification, reformulation or repurposing).
Quaternary	Intellectual/knowledge services, including consultation, education, information technology, research, and development.
Quinary	Specialized services delivered by the highest level of decision or policy makers in government or industry.

The necessity of working in MITT groups involving chemistry to solve complex problems encountered in the real-world can also be viewed through the lens of Maslow's hierarchy of needs.[137,138] Problems related to our physiological needs involve chemistry at the interface of other disciplines (including biology, engineering, mathematics, physics, etc.) and the industries that provide the population with sustainable resources to satisfy our need for food, rest, water, and warmth (i.e., basic quality of life). Problems related to our safety and security needs involve MITT groups developing chemicals, materials and methods (including quantum technologies) for health (e.g., medication, personal protective equipment for clinic-, laboratory-, warfare-based activities) or counter terrorism (e.g., communication, sensors, etc.). Problems related to our belongingness and love needs involve

MITT groups developing chemicals, devices, materials, methods to facilitate or to enable intimate relationships (including contraceptives, fertility treatments, lubricants, perfumes, etc.) and/or platonic friendships (including food, drinks, drugs [alcohol, antidepressants, etc.]), being members of communities that potentially include membership of interdisciplinary learned and professional societies involving chemistry (including the American Chemical Society; American Institute of Chemical Engineers; Institution of Chemical Engineers; Institute of Materials Minerals and Mining; Materials Research Society; Royal Society of Chemistry; Society of Chemical Industry, etc.). Our esteem needs (prestige, status and feeling of accomplishment) for engagement in MITT activities can be met via awards, honors, prizes and other recognition of successful administration, leadership, management, research, and teaching; conference presentations, keynotes, named lectures and publications; editorial activity (journals, books, and other publications); engagement, partnership and collaboration nationally and internationally with other groups, institutions, industries and organizations; income from grants, teaching, commercialization; influence on industry, government, public policy, community and cultural organizations; membership of national and international committees (e.g. governmental, industrial, institutional or organizational); membership and fellowship of learned/professional academies and societies; publication of books, patents, registered designs, reports, research papers, reviews, etc. Our self-actualization needs (i.e., achieving one's full potential, including creative activities [which may concomitantly release dopamine, a neurotransmitter involved in thinking, planning and pleasure]) can be met by participation in activities with interdisciplinary and transdisciplinary teams and engagement in activities where our inherent disciplinary expertise can play a useful role in finding creative solutions to complex problems. Higher education institutions benefit from adopting this approach, providing students a holistic learning environment.

While an exhaustive listing of examples of MITT groups managing complex problems of real-world importance is outside the scope of this article, we hope that the summary presented here offers insights into their importance in a variety of contexts (global, national, organizational, and personal).

MITT CURRICULUM DEVELOPMENT AND IMPLEMENTATION IS A CHALLENGE

As highlighted above, individuals capable of working in multidisciplinary, interdisciplinary and transdisciplinary teams are needed to address real-world problems in all economic sectors (Table 3), helping to deliver the UN SDGs.[104,125,126] MITT offers individuals the opportunity to develop a range of skills necessary to work in such teams, including both hard skills (such as computer, instrumentation, operational skills; management skills; reporting and writing skills; monodisciplinary/intradisciplinary analytical and problem solving skills), and soft skills (cognitive flexibility and adaptability, collaboration, communication, critical thinking, curiosity, emotional intelligence, empathy, leadership, team working, time management), all of which are recognized and valued by industry. Those with MITT experience are well positioned for higher-skilled roles as one who has a more comprehensive perspective is more likely to efficiently identify and prioritize existing and future problems (however, extrapolation of this conclusion is not possible for all countries, due to the complexity of job markets).[86,139,140] The results of studies by PSRBs, learned bodies and consultation with industrial partners help inform policy developed by governments to ensure a pipeline of highly skilled workers to meet economy demands. For example, the UK government developed frameworks to assess the performance of universities, namely, the Research Excellence Framework (REF),[141] Knowledge Exchange Framework (KEF)[142] and Teaching Excellence and Student Outcomes Framework (TEF),[143] each of which have the potential to encourage higher education establishments to develop MITT activities (e.g., research-based learning activities, knowledge exchange activities with non-academic parties).[144,145] These frameworks are each assessed via metrics and accompanying narratives which help to describe their specific situation (geography, socioeconomics, etc.) and efforts towards meeting the goals of each assessment. The results of the assessments yield publicly accessible reports and league tables that potentially guide and mentor other departments and institutions to improve performances via reflective practice, interdisciplinarity is emphasized in these assessments, particularly the more established REF assessments.[146–148] Furthermore, the Times Higher Education Impact Rankings offer global performance tables assessing universities against the UN SDGs (comparing research, outreach and stewardship) which encourages the development of MITT activities within higher education establishments.

Integrative learning involves combining subject matter traditionally taught as separate curricula. This approach enables students to connect with and to apply theoretical/practical knowledge and skills developed in various settings (e.g., lecture theatres, tutorials, laboratories, and potentially industrial settings).[12,31,48,65,149–152] This approach benefits from problem-, question-, theme-based integrative learning experiences in a thoughtfully structured MITT curriculum with a number of core courses that include interdisciplinary and transdisciplinary concepts, methods and theories.[13,33,43,45,46,153] The development and delivery of coherent, effective and strongly MITT curricula offers a variety of challenges to higher education establishments.[33,37,56,63,72,140,150,154–161] The most obvious barriers to the development and delivery of MITT curricula are organizational, particularly the traditional structures of university departments and faculties and their teaching and training programs, which tend to be focused on the necessity to guarantee standards of training and to secure externally recognized accreditation for the program of study.[44,162] A direct consequence of this structure is that staff may not be encouraged to venture away from the safe ground of their disciplinary borders; which is mirrored by the historical scope of journals, and peer review models for research grants and outputs (books, conference proceedings, papers, reports, etc.). Other challenges include leadership (ideation, communication, championing change), management (change management, financial and human resource allocation for course development, staff support and training (e.g., practice sharing events)), administration (timetabling, credit-/finance-sharing between departments, etc.) and curriculum design (fundamental composition and balance of disciplinary content, accreditation, etc.).[109] Tellingly, high profile MITT activities, such as the increasingly popular and lauded International Genetically Engineered Machine (iGEM) competition,[163] take place over the summer months and out of term time, and are usually viewed as extra-curricular, added-value propositions for a limited numbers of students.

MITT Requires Effective Leadership, Management, and Administration

Leadership in the design and implementation of MITT offerings requires a combination of knowledge and creative vision (identifying an opportunity and having the confidence and interpersonal skills to develop a team to deliver that vision). In addition, effective management and administration skills, particularly planning and humility to acknowledge challenges and barriers and to develop mutually agreeable solutions, and effective communication skills are crucial in effective leadership of MITT offerings. Communication underpins the success of our daily lives, which is equally true regarding all aspects of curriculum design, implementation (leadership, management and administration), and delivery by staff. The staff may be experts in specific disciplines with a working knowledge of the language of different disciplines, including challenges presented by the same term being used with different meanings in distinct contexts.[33,164,165] Effective communication is the key to convincing faculty members and senior management of the benefits of MITT (e.g., relative advantage, compatibility, complexity, trialability [i.e. opportunity for the initiative to be implemented in steps], and observability [i.e., opportunity for the initiative to strengthen the identity of the departments involved]). Lacking evidence of the benefits is likely to result in the conclusion that the status quo is better (i.e., maintaining disciplinary silos). In addition, adoption of innovation in curricula[160] requires effective communication of:

- Knowledge of the educational innovation (e.g., evidence in the education research literature to suggest this change will be an improvement)
- Persuasiveness of the educational innovation (e.g., evidence to suggest feasibility and improvement for the institution).
- Evidence-informed decision to adopt or to reject the innovation (e.g., based on evidence from points 1 and 2).
- Evidence-informed implementation (i.e., adapt and adopt, communicating to staff and students why and how).
- Evidence-informed confirmation (i.e., determine the future use of the innovation based on improvements in assessments, outcomes and student satisfaction).

Management of the design and implementation of MITT offerings requires: the interpersonal skills necessary to build trust and strong working relationships within the team; forward/strategic planning; “commercial” awareness (i.e. strategic fit at an institutional, regional, national and/or international level, identification of unique selling points, key differentiators, etc.); stakeholder mapping at an institutional, regional, national and/or international level; understanding the strengths, weaknesses, opportunities and threats to the endeavor (SWOT analysis), etc.; decision-making regarding organization and delegation of responsibilities within the team (e.g., motivation of staff from various departments, faculties and/or institutes to contribute); availability and accessibility for individual and team meetings to ensure project progress; facilitating and contributing to discussions; problem solving (e.g. dealing with disagreements; acknowledgement of professional challenges/barriers and the development of mutually agreeable solutions); and mentoring (e.g., facilitation of staff development via training provision, recognition of effective contributions [potentially via encouragement of membership and fellowship of relevant education-oriented learned/professional academies and societies], etc.).

Financial and human resource allocation for course development (including staff support and training, e.g., practice sharing events) is a challenge for higher education establishments, particularly in resource constrained environments (e.g., institutions in developing and emerging economies). Such challenges/barriers within UN SDG 4 (quality education) may impact global economic inequality in years to come (i.e., UN SDG 10, reduce inequality). One potential solution is the collaborative development and delivery of MITT offerings involving staff and institutions in developed and developing and emerging economies, which has significant global impact, and is aligned with UN SDG 17 (partnership to achieve the goals). This highlights the complex interrelated nature of the UN SDGs.

Administration of the design and implementation of MITT offerings requires an appropriate mechanism for sharing credit and associated finances between contributors (i.e., departments, faculties, institutes) to ensure support from the various contributors and thereby success of the MITT activity. MITT activities involving chemistry within STEMM teaching must be underpinned by generic good teaching practice applicable to all teaching activities to ensure student, staff and employer satisfaction.[166,167] From an administrative perspective good teaching practice necessitates an effective mechanism for timetabling of synchronous and asynchronous elements of teaching in a face-to-face or online environment, often employing a course management system and online learning platform such as Moodle (popular because it is free and open source, thereby supporting UN SDG 4).[104,125,126] This requires staff training for academic and non-academic/support staff across the institution to ensure high quality teaching and subsequently achieve positive student outcomes and feedback.[160] Moreover, assessment of an individual university’s contribution to the UN SDGs based on metrics associated with research, outreach, and stewardship and compiled within the Times Higher Education Impact Rankings is available. Global level metrics compiled by the UN assess international progress towards the UN SDGs which may be of interest to students and staff alike. Clearly, initiatives to support diversity, equity and inclusion will play an increasingly important role in the economy and society in years to come, as will effective engagement with and delivery of the UN SDGs.[104,125,126,168–173]

MITT Curriculum Design in Higher/Tertiary Education

The development of MITT curricula requires attention to detail (appropriate assessments, disciplinary balance, encouraging creativity, involving external collaboration [e.g., industry, NGOs, etc.], real-world problems, societal trends, etc.)[174] to deliver a product that is appealing to students and supports economies across the world. While the individual PSRBs and learned societies may require elements of MITT embedded in curricula, there are some degrees that are accredited by more than one PSRB/learned society thereby ensuring the curricula do not “sacrifice” the original disciplinary content in the course (for a non-exhaustive list see Table 5). It is also noteworthy that qualification awarding higher education institutions are themselves subject to oversight by national and international higher education quality assurance agencies (examples in Table 6).

Table 5. Non-Exhaustive List of Examples of Dual Accredited MITT Degrees with Chemistry Content

University/Universities	Degree	Accrediting Bodies
Newcastle University (England)	Chemical Engineering (BEng)	Institution of Chemical Engineers and the Institute of Measurement and Control
Swansea University (Wales) and Trent University (Canada)	BEng Chemical Engineering and BSc Chemistry Dual Degree	Canadian Society for Chemistry and the Institution of Chemical Engineers
University of Bristol (England)	Chemical Physics (BSc and MSci)	Royal Society of Chemistry and the Institute of Physics
University of Edinburgh (Scotland)	Chemical Physics (BSc and MChemPhys)	Royal Society of Chemistry and the Institute of Physics
University of Strathclyde (Scotland)	Chemistry with Teaching (MChem)	Royal Society of Chemistry-accredited MChem course with professionally-accredited teacher training (Professional Graduate Diploma in Education, Secondary)

Table 6. Non-Exhaustive List of Examples of National or International Higher Education Quality Assurance Agencies.

Accrediting Agency	Focus: National or International
Egyptian National Authority for Quality Assurance and Accreditation of Education (NAQAAE)	National
Higher Education Accreditation and Evaluation Agency of Portugal	National
Higher Education Accreditation Commission (HEAC) of Jordan	National
Iranian Ministry of Science, Research and Technology (MSRT)	National
Italian Ministry of University and Research (MIUR)	National
Ministry of Education of the People's Republic of China	National
Ministry of Higher Education of Saudi Arabia	National
Russian Federal Service for Supervision in Education and Science (Rosobrnadzor)	National
Swiss Agency of Accreditation and Quality Assurance (AAQ)	National
UK Quality Assurance Agency for Higher Education (QAA)	National
US Council for Higher Education Accreditation (CHEA)	National
African Quality Assurance Network (AfriQAN)	International
Asia-Pacific Quality Network (APQN)	International
Association of QA Agencies of the Islamic World (IQA/AQAAIW)	International
European Association for Quality Assurance in Higher Education (ENQA)	International
European Quality Assurance Register for Higher Education (EQAR)	International
International Network for Quality Assurance Agencies in Higher Education (INQAAHE)	International

Higher education establishments should aim to ensure their programs meet societal needs and trends in terms of industrial requirements of graduates.[175–178] However, ensuring higher education curricula meet societal needs and trends requires a significant amount of foresight, and sometimes a willingness of the institution not to capture short term gains (via increased recruitment, and hence revenue) in response to short term trends. An example of this practice that negatively affected graduate employability in the UK, was the rapid implementation of forensic science degrees at some higher education institutions led by a surge in popularity due to the proliferation of TV shows focusing on crime scene investigation, which in turn led to an increase in the number of forensic science graduates that far exceeded the capacity of the forensic science sector. The drive to capitalize on this demand led to degrees that were not fit for purpose, having been formulated too quickly and not designed with an MITT approach, with graduates often requiring significant in-employment training, even within the specialism.[179,180] However, some trends are difficult to predict, but show that higher education establishments need to be able to adapt quickly, and to ensure graduates receive a sufficiently broad education that doesn't preclude them from pursuing a career away from their initially intended specialty. For instance, since the disaster at the Fukushima Daiichi Power Plant in 2011, Germany is undergoing a transition towards low-carbon energy production that no longer relies on nuclear power, which has a dramatic influence on the prospects of nuclear engineering graduates in Germany, who increasingly must look abroad for employment.[181] In contrast to these examples there are exciting successful examples of interdisciplinary innovation in the Higher Education sector, including: the Dyson Institute of Engineering and Technology (a private institution of higher education in England, founded in 2017 by James Dyson) with initial cohorts of students awarded Bachelor of Engineering (BEng) degrees in partnership with the University of Warwick, and it was recently awarded its own degree-awarding powers from 2021 onwards;[182] and the London Interdisciplinary School (a new university that aims to give students the knowledge and skills needed to address social and global problems in an increasingly interconnected world) with degree-awarding powers from 2021 onwards, initially offering a BASc degree in Interdisciplinary Problems & Methods.[183]

Changes in policies and societal trends can often be anticipated through consultation with governments and industrial partners. The use of industrial advisory boards is increasingly prevalent in the sciences, and commonplace within engineering disciplines. However, it is important to ensure diversity in the board membership (e.g., gender, ethnicity, etc., ideally in line with national census statistics, for example England and Wales[184] or the USA);[185] to attempt to ensure global geographical representation and reach of the board membership (i.e., avoiding over-representation of local employers that are most convenient to connect with); to remove bias towards any one industry, and to adhere to national and international accreditation requirements.

Academic and non-academic/support staff working in STEMM departments, faculties, institutes often have an element of chemical training (e.g. undergraduate/postgraduate study or postdoctoral experience), suggesting opportunities for institutions to deliver engaging MITT involving chemistry in inherently MITT STEMM curricula (e.g. biochemistry, engineering, forensic sciences, geology, liberal arts, materials science, natural sciences, etc.),[42,92,109,186–188] and potentially specialist elements of other curricula (e.g. arts and humanities [e.g. archaeology and architecture,[189,190] art and design,[191] patent law], business and management,[153] technician support, etc.). However, effective MITT curriculum design is a challenge, particularly achieving the appropriate balance of monodisciplinary/intradisciplinary content and integrated MITT options[192] that ensure students have the opportunity to develop both in-depth knowledge of monodisciplinary subject matter[193] and insight into different disciplinary approaches to problem solving.[57] A notable barrier to MITT curriculum design is ensuring curricular coherence and integration,[192] especially when there are disagreements between staff from different disciplines about the specific content and methodology of delivery.[194] A potential solution to issues of curricular coherence and integration is to ensure interactions between academics during all stages of curriculum design with regular meetings with module leaders presenting module plans to ensure awareness of the curriculum structure (potentially including modules taught by a multidisciplinary team of academics talking about a particular phenomenon, e.g. enzyme binding as a cross-cutting example of structure and function in biology, biochemistry and chemistry).[118] This broad awareness offers opportunities for constructive overlaps between modules, thereby ensuring the best eventual outcome for staff and students who may find it challenging to make a connection between their background knowledge and its relation to other topics, topic sequencing for students from different backgrounds, and effective communication in multidisciplinary teams.[195]

Another challenge is the development of robust, cross-disciplinary assessment criteria to ensure fair assessments are used to encourage student engagement.[174] Clearly at the highest level of MITT education (as the highest skill order) assessment in the traditional sense (e.g., exams) would be difficult, and assessment akin to postgraduate project evaluation would be more appropriate, however, project-based evaluation is time consuming, especially for courses with high student numbers. Project-based evaluation does offer opportunities for involvement of all department staff, and trains students to be assessors, which is good for employability. Moreover, depending on the structure of the curricula, particularly at the postgraduate level, there may be challenges teaching students from diverse disciplinary backgrounds and balancing the depth of material presented to ensure the appropriate assimilation of knowledge and skills. However, the presence of students with diverse disciplinary backgrounds also has advantages that can be manifested via peer-to-peer learning during interactive activities in which students work together in teams on problem solving activities.[196] It is noteworthy that the development of hard and soft skills (e.g., problem solving and team working) are some of the most important learning outcomes of courses at undergraduate and postgraduate levels, and MITT offers a variety of opportunities to enhance such learning experiences subject to what is possible at different higher education institutions (which may inadvertently introduce a bias/privilege gap based on the demographics of the students/staff and universality of adoption of MITT) and thereby employability.[37,174,197]

MITT offers students teaching activities that can encourage creativity and improve critical thinking.[48] Such activities enable students to learn to understand multiple viewpoints on a single topic (potential barriers to which include the communication skills of instructors and students) and to appreciate the differences between the techniques and/or data (factual information) and approaches (procedural knowledge) each discipline use to solve problems and draw informed conclusions; the complexity of such activities should develop over the duration of the course to ensure holistic understanding of concepts that transcend traditional disciplinary boundaries due to the holistic design of the curriculum.[198] An interesting example of an engaging learning experience called the "Chemistry Connections Challenge"[199] highlights the real-world applications of an introductory organic chemistry course via a combination of instructor-directed material in lectures and self-directed learning exercises (with students submitting work on the real-world application of organic chemistry to a variety of topics including: biological processes, botany, chemical warfare, cosmetics, gastronomy, materials, medical applications, natural products, pharmaceuticals and zoology). This engaging self-directed learning activity stimulates creative thinking and a personal connection with the subject matter, is adaptable to courses in other institutions and has overwhelmingly positive student feedback;[199] moreover, it helps students develop expertise in the discipline of choice and in the application of disciplinary expertise to other disciplines, thereby preparing them to work in MITT groups.

MITT curricula offer opportunities to present cross-cutting concepts[200] (e.g., energy for biology[201] and electronics[202]) in real-world scenarios (e.g., biology,[69,92,100,101,203] engineering[92,189,204,205]) that reinforce the relevance to students, via different methodologies (lectures,[188] tutorials/workhops,[206] and/or labs).[207,208] MITT curricula also permit an efficiency of resource by encouraging the reuse of multidisciplinary facilities (e.g., additive manufacturing[209,210] or computing for machine learning and augmented reality in chemistry and engineering),[211–213] making programmes more flexible and sustainable. Drennan and co-workers described the creation of an interdisciplinary introductory chemistry course without time-intensive curriculum changes (overcoming a significant barrier to development and implementation of new curricula).[188] The initiative equipped students with the skills to recognize underlying chemical principles in other disciplines and to solve interdisciplinary problems without "sacrificing" the original chemistry content in the course, using examples from biology and medicine to demonstrate applications of chemical principles in the lectures (see Table 7).[174,188,214] Examples that highlight the importance of the recognition of the underlying chemical principles in other disciplines include supramolecular interactions in biological processes (e.g., protein assembly, gene expression, etc.) that could be included in molecular biology and biochemistry curricula.[117,118,215–220] Drennan and co-workers' interdisciplinary introductory chemistry course resulted in increases in student assessment that the course instructors "inspired interest" in chemistry and "used good examples" (old curriculum: 5.50 ± 1.29, new curriculum: 6.36 ± 0.97) and increases in the overall course rating (old curriculum: 5.15 ± 1.29, new curriculum: 5.99 ± 1.22).[188] Frey and co-workers described interdisciplinary, application-oriented tutorials covering chemistry in the context of biology, engineering and environmental sciences, enhancing the students appreciation of chemistry in the world around them (with improvements in exam scores; old curriculum: ca. 69, new curriculum: ca. 74).[206] Baranger and co-workers described a green chemistry focused general chemistry laboratory curriculum incorporating over 30 new experiments that introduced students to green chemistry principles to explore and to solve real-world problems (summarized in Table 8), which resulted in measurable improvements in students' understanding of green chemistry principles in 6 out of 7 responses to the question "In your own words, define green chemistry",[207] and offers students an opportunity to learn the 12 principles of green chemistry[221–223] and to understand potential connections to the future courses and professions (another potential complementary/tangentially related topic include regulatory issues [e.g. environmental, health and safety, medical devices, etc.]).[82,207,224] Another exciting initiative is the Freshman Research Initiative (FRI)[225,226] wherein students participate in an interdisciplinary, inquiry-based research methods course, followed by two semesters of research; this integrates training in mandatory/accredited general chemistry skill sets with open-ended research experiences, and results in students who are trained in research methods and capable of contributing to peer-reviewed publications, presentation of research and winning awards at regional/national conferences. The success of this initiative was demonstrated by a number of variables with students with comparable grade point averages, with improvements in probability of graduating within 6 years (non-FRI curriculum: 66%, FRI curriculum: 83%), and with improvements in probability of graduating with a STEM degree (non-FRI curriculum: 71%, FRI curriculum: 94%).

Table 7. General Chemistry Lecture Topics and Corresponding In-Class Biology and Medicine-Related Examples[a]

Chemistry Lecture Topics	Biology-Related Examples
Introduction and course overview	Chemical principles in research at MIT
Wave-particle duality of light and matter	Quantum dot research at MIT
Periodic trends	Atomic size: sodium ion channels in neurons
Covalent bonds, Lewis structures	Cyanide ion in cassava plants, cigarettes. Thionyl chloride for the synthesis of novacaine
Exceptions to Lewis structure rules	Free radicals in biology: role in DNA damage and essential for life; Nitric oxide (NO) in vasodilation (and Viagra)
Polar covalent bonds, ionic bonds	Water-soluble versus fat-soluble vitamins: comparing folic acid and vitamin A
VSEPR theory	Molecular shape in enzyme-substrate complexes
Valence bond theory and hybridization	Restriction of rotation around double bonds: application to drug design; Hybridization example: ascorbic acid (vitamin C)
Determining hybridization in complex molecules	Identifying molecules that follow the "morphine rule"
Thermodynamics	Glucose oxidation: harnessing energy from plants
Free energy and control of spontaneity	ATP-coupled reactions in biology; Thermodynamics of H-bonding: DNA replication
Chemical equilibrium, Le Châtelier's principle	Maximizing the yield of nitrogen fixation: inspiration from bacteria; Le Châtelier's principle and blood-oxygen levels
Acid-base equilibrium, buffers, and titrations	pH and blood: effects from vitamin B_{12} deficiency
Balancing redox equations, electrochemical cells	Oxidative metabolism of drugs
Oxidation/reduction reactions	Reduction of vitamin B_{12} in the body
Transition metals	Metal chelation in the treatment of lead poisoning; Geometric isomers and the anticancer drug cisplatin
Crystal field theory, metals in biology	Inspiration from metalloenzymes for the reduction of greenhouse gases
Rate laws	Kinetics of glucose oxidation in the body
Nuclear chemistry and elementary reactions	Medical applications of radioactive decay (^{99}Tc)
Reaction mechanism	Reaction mechanism of ozone decomposition
Enzyme catalysis	Enzymes as the catalysts of life, inhibitors as drugs
Biochemistry	The methionine synthase case study

[a]Adapted with permission from ref *188*.

Table 8. Experimental Module, Chemistry Principles, and Green Chemistry Principles for Each Redesigned Experiment Used in the General Chemistry Laboratory Course at UC–Berkeley[a]

Module (Number of Weeks)	General Chemistry Principles	Green Chemistry Principles
How the Nose Knows (1)	Functional groups, physical properties, formal charges, bond-line notation, VSEPR	Designing safer chemicals, renewable feedstocks
Polymers: Properties and Applications (1)	Functional groups, density, solubility, structure–function relationship, dissolution, hydrolysis	Waste prevention, designing safer chemicals, design for degradation
Polymers: Cross-Linking and Toy Design (2)	Cross-linking reactions, intermolecular interactions, bonding, mass ratios in mixtures	Inherently safer chemistry, safer solvents, renewable feedstocks, atom economical
Polymers: Density of Liquids and Solids (2)	Precision and accuracy, systematic and random error, solubility, experimental design, polymer structure	Waste prevention, designing safer chemicals, and designing for degradation
Biofuels (3)	Transesterification, combustion and calorimetry, solubility, extraction, C_{cal} and ΔH_{comb}	Designing safer chemicals, renewable feedstocks, catalysis, safer solvent, atom economical, inherently safer chemistry, energy efficiency
Spectroscopy: Food Dyes and Riboflavin in Beverages (1)	UV–vis and fluorescence spectroscopy, Beer's law, extinction coefficients, calibration curves, error propagation	Inherently safer chemistry
Extraction of Curcumin and Spectroscopic Analysis (1)	Transmission, absorbance, extraction and separation, calibration curves, linearity of data	Safer solvent, energy efficiency, waste prevention
Equilibrium (1)	Solubility, acid/base equilibria, gases, Le Châtelier's principle, pH measurements	Renewable feedstocks, safe solvents and auxiliaries, designed for degradation
Depolymerization and Titration (2)	Ester hydrolysis, dimensional analysis, ICE tables, indicator and potentiometric titrations	Renewable feedstocks, designed for degradation
Acids in the Environment (3)	Solubility equilibria, acid/base titrations, gases and equilibrium, Le Châtelier's principle, buffers	Real-time analysis for pollution prevention, less hazardous chemical syntheses, waste prevention
Extraction from Thyme Leaves (2)	Extraction, IMFs, polarity, chromatography, diffusion, extraction, standard addition, uncertainty	Waste prevention, design for degradation, use of renewable feedstocks
Extraction and Analysis of Limonene (2)	Chromatography, boiling points, sublimation, triple point, polarity, mass spectrometry, standard calibration curves, uncertainty	Pollution prevention, safer solvents, energy efficiency, renewable feedstocks, design for degradation, safer chemistry and solvents
Methanol/Glucose Fuel Cells and Dye-Sensitized Solar Cells (2)	Electrochemistry, galvanic cells and batteries, catalysis and enzymes, cell potentials, net free energy calculations	Energy efficiency, catalysis, renewable feedstocks, design for degradation, inherently safer chemistry
Kinetics: Bleaching Organic Dyes and H_2O_2 Decomposition (2)	Catalysis, reaction rates, kinetics, reaction order, method of initial rates, visible spectroscopy, Beer's law	Catalysis, designing safer chemicals, inherently safer chemistry
Computational and Experimental Investigation of Pesticides (2)	MO theory, computer-based molecular modeling, solubility, UV–vis and fluorescence spectroscopy	Waste prevention, designing safer chemicals, real-time analysis for pollution prevention

[a] Adapted with permission from ref *207*.

Advancements in computer hardware and software over the last few decades have revolutionized our understanding of chemistry and developed new sub-fields offering opportunities for inclusion in curricula worldwide. The enhanced computer and technology literacy of students is reducing barriers to learning computational aspects of chemistry and its implementation in MITT,[227–232] also driven by the necessity to deliver increased levels of engaging online teaching.[233–238] Chemoinformatics[239–246] lies at the interface of chemistry and computer sciences, involving the: storage; classification and indexing; searching, mining, retrieving of information about chemical compounds (e.g. software developed for chemical analysis equipment, illustration of synthetic pathways, visualization of molecular docking of compounds with protein receptors, molecular dynamics simulations); and is particularly useful for dealing with large datasets (e.g. via data mining and statistical analysis) using mathematical techniques (e.g. machine learning [ML] and artificial intelligence [AI]).[247–251] In pharmaceutical R&D, advances in genetics and molecular biology have revealed potential new targets for developing medicines and deciding which target to pursue is challenging and an area in which there is opportunity to increase productivity. ML/AI approaches such as deep learning correlation analysis[252–257] can be used to accelerate identification of biological pathways and targets in disease biology, to find potential drug molecules, to understand the biological effects of the compound and help design clinical trials to ensure the best outcomes are achieved. Clearly a multitude of other opportunities exist for inclusion of computational studies in a variety of disciplinary contexts (e.g., agrochemical/drug delivery/design,[258,259] catalysis,[260] materials chemistry,[261] medical imaging and analysis,[262,263] etc.). Computational chemistry can help engage students learning about important concepts such as kinetics and thermodynamics, molecular descriptors (i.e. constitutional, electronic, physico-chemical, topological), stereochemistry and 3D structures in an interactive virtual learning environment; and moreover, provides various platforms to study intramolecular and intermolecular interactions that can be used for research and development in a safe and cost effective fashion (e.g. informing the selection of candidates to bind to biological receptors or pharmaceutical carriers for drug delivery, while minimizing resource utilization and exposure to chemicals).[264] Aspects of computational chemistry can be taught through inclusion of mathematics and computational skills (e.g. programming) in chemistry curricula, and computational chemistry for biologists, pharmacists, programmers, etc. in MITT curricula. This takes into account the student's background and ensures that the teaching is done at an appropriate level for the audience, thereby helping to facilitate communication of concepts underpinning computational chemistry to various audiences in preparation for real-life multidisciplinary teamwork in various economic sectors (i.e., better educational outcomes).

Research projects at various points throughout curricula (particularly Capstone projects) offer academics an opportunity to contribute to MITT activities in (potentially niche) topics of direct interest to themselves and/or the students (i.e. student-centered learning, which helps students to direct their learning of course material towards an outcome that is directly relevant to them [e.g. project management skills]).[265–278] Such MITT research projects embedded in curricula can deliver positive short and long term impacts, including: increased collaborative research,[42,56,57,73,77,191,279–287] increased research impact,[43,77,78,80,164,281,288–290] increased grant income,[80,279,280,291,292] increased student employability by training the next generation of research-active academics to comfortably work at disciplinary interfaces;[51,52,144] societal impact by delivering graduates comfortable in the changing workplace,[128,153,279,289,293] and economic impact by supporting the economies they contribute to (e.g., by generation of intellectual property).[12,51,52,72,78,278] Metrics associated with these factors have the potential to make the course and/or university more attractive to students and/or staff, which may have beneficial effects on the student and/or staff demographics, particularly when supported by mentoring initiatives (e.g. the US NSF Research Experience and Mentoring program).[80,288,289]

As noted above, industries have evolved to address complex real-world problems that are interdisciplinary in nature and support the employment of millions of people across the world. Industries are also engaged with learned/professional societies and PSRBs to offer guidance on the skills needed by graduates. There are a multitude of opportunities for the involvement of industrial partners in elements of MITT. These interactions vary depending on the scope of interaction between the higher education institution and industrial partner, including guest lectures about industrial/commercialization best practice,[131] opportunities for industry-based internships (during summer vacations or an entire academic year of study) and research projects in collaboration with industry partners ranging from short term projects such as consultancy. This can involve undergraduate and postgraduate researchers, to long term projects such as PhD studentships. These interactions offer students opportunities for research oriented individual or team-based learning activities such as students learning about research processes and methodologies, invention and innovation and project management. Of particular importance is how to align a technical academic solution to a problem or need early on, thereby enabling an early go/no go decision, and helping to deliver sustainable commercial success.[82,131]

However, there are many challenges to industry engagement. Perhaps the most obvious challenge is the resources required to foster relationships with potential industry partners (and vice versa), which may necessitate the appointment of dedicated staff in academia and industry to facilitate introductions, cultivate collaborative relationships, deal with any communication issues between industry partners and students/academics, setting expectations (of companies, students, supervisors, funding bodies and administrators), planning projects, negotiate contracts, deal with intellectual property, mitigate risks, manage reputation, etc. Nevertheless, the engagement of industrial partners in educational activities offers many benefits for students, staff, institutions and industry partners alike. This engagement and the direct/indirect involvement of industry partners in the delivery of MITT activities involving chemistry in many departments in STEMM faculties[42,92,186] (e.g., forensic science,[294] liberal arts, materials science, natural sciences, pharmacy, etc.) and beyond (e.g., arts and humanities [e.g., archaeology and architecture,[189] art and design,[191,295,296] patent law], business/management,[153] etc.) involving staff from other departments via experiential learning elements, problem-based and research-based learning activities related to real world problems.[128,145,279,297] The skills developed while undertaking MITT curricula offer enhanced engagement, learning, and employability, and ultimately beneficially impacts the economy and society across the developed, developing and emerging economies of the world, and enable us to deliver on the promises of the UN SDGs.[168–173]

ANALYSIS OF THE OUTCOMES OF MITT IN HIGHER/TERTIARY EDUCATION

The analysis of the outcomes of MITT in higher education institutions is often qualitative, however, examples of quantitative analysis offer educators insights into what to expect when contemplating new interdisciplinary undertakings (e.g., potential benefits, effect size, etc.). It can be challenging to quantify the outcomes of MITT initiatives,[174,298] and in some cases there may be little/no differences in quantitative outcomes,[299] however, a selection of initiatives reporting quantitative outcomes are summarized hereafter. An initiative to offer general chemistry in just one semester for life science majors resulted in significant improvements in exam scores (out of 200 points) for organic chemistry I (old curriculum: 155.75 ± 33.21, new curriculum: 170.69 ± 27.49) and II (old curriculum: 153.16 ± 31.17, new curriculum: 167.84 ± 27.31).[300] An adapted version at another institution offer general chemistry in just one semester for all majors resulted in increases in the percentage of successful completions (old curriculum: 71.7%, new curriculum: 87.7%), with students achieving similar scores on a full-year ACS general chemistry exam (out of 70 points; old curriculum: 41.6 ± 9.7, new curriculum: 39.8 ± 10.3); there was also a subsequent increase in the enrollment in organic chemistry (36% in Organic Chemistry I and 39% in Organic Chemistry II) and a 33% increase in the number of chemistry majors (old curriculum: 16.8 ± 1.0, new curriculum: 22.3 ± 4.6).[301] Another initiative to develop allied health courses with an entry level allied health chemistry course for non-majors showed enhanced student learning after 6 semesters (final exam score; old curriculum: 58.3 ± 16.1, new curriculum: 64.8 ± 14.2).[109] An interdisciplinary introductory chemistry course resulted in increases in student assessment that the course instructors “inspired interest” in chemistry and “used good examples” (old curriculum: 5.50 ± 1.29, new curriculum: 6.36 ± 0.97) and increases in the overall course rating (old curriculum: 5.15 ± 1.29, new curriculum: 5.99 ± 1.22).[188] Introducing an interdisciplinary guided-inquiry experience in chemistry and biology to the first year of a curriculum for forensic science students resulted in a significant decrease in fails and concomitant increase in distinctions and higher distinctions, and significant increases in the perception of the benefits in working in teams (old curriculum: 40%, new curriculum: >75%).[302] Replacing junior- and senior-level laboratory curriculum with 2, 2-semester long, student-led research projects as part of an ACS-accredited program was observed to enhance student perceptions of learning (old curriculum: ca. 5.8, new curriculum: ca. 6.4),[303] which is understood to improve overall academic achievement, skills acquisition/performance and motivation for learning.[304] The Freshman Research Initiative (FRI)[225,226] involving students in interdisciplinary research results in measurable improvements in their probability of graduating within 6 years (non-FRI curriculum: 66%, FRI curriculum: 83%), and their probability of graduating with a STEM degree (non-FRI curriculum: 71%, FRI curriculum: 94%).

The direct comparison of these quantitative analyses is itself challenging due to differences in curricula/innovation, socioeconomic factors of the student cohort and/or location of the higher education institution, however, it offers evidence to inform decision makers in higher education institutions of the costs/benefits of MITT initiatives enabling them to determine the future use of the innovation based on improvements in assessments, outcomes and student satisfaction. A few examples of the application of topics discussed in the paper (real world problems addressed, curriculum development and implementation, administration, and outcomes/feedback) to common elements of curricula (lectures/tutorials, instructed lab work and research) are highlighted in Table 9, with an interesting example of course design from scratch from McGill and coworkers also touching on these topics.[192] Engagement with MITT activities in well-designed curricula should equip students with a 21st-century skills set[28,72,305,306] that underpins their employability.

Table 9. Examples Highlighting the Application of Topics Discussed in This Work

Topics	Interdisciplinary Introductory Chemistry[a]	Green Chemistry Focused Laboratory[b]	Freshman Research Initiative[c,d]
Real-world problems addressed	Biology, health and medicine	Green chemistry, energy, environment, health/safety issues	Dependent on staff involvement, including health and medicine, sensing, catalysis/green chemistry, energy harvesting/storage, computational chemistry/biochemistry
Curriculum development and implementation	Lectures, problems and assessments use biological examples within a framework of chemistry	Labs use energy, environment, health/safety examples to integrate general chemistry and green chemistry principles	Interdisciplinary, inquiry-based research methods course, followed by two semesters of research
Administration	Financially supported by the institution	Financially supported by the institution	Initially financially supported by Howard Hughes Medical Institute and the National Science Foundation; thereafter, supported by the institution and research income Regular engagement with principal investigator (oversight and mentoring), a dedicated member of staff “research educator” (project design and management), peer mentor (peer to peer learning), initial training period (e.g., apparatus, health and safety), time management via Google Calendar/Forms
Outcomes/ feedback	Increase in the overall course rating; Increase in student assessment that the course instructors “Inspired interest” in chemistry and “used good examples”	Improvements in students’ understanding of green chemistry principles in 6 out of 7 responses to the question “In your own words, define green chemistry.”	Improved probability of graduating with a STEM degree Improved probability of graduating within 6 years Potential co-authorship of research papers; Potential to participate in research conferences and win awards

[a]See ref *188*. [b]See ref *207*. [c]See ref *225*. [d]See ref *226*.

CONCLUSION

Chemistry can serve as a bridge between various fields of knowledge offering students of MITT programs opportunities to develop hard and soft skills, and the ability to communicate ideas between these fields. Chemistry is therefore an important discipline to incorporate into MITT activities, because chemistry integrated with other fields of knowledge plays an important role in potential multidisciplinary, interdisciplinary and transdisciplinary solutions to the complex real-world problems encountered by each of the different economic sectors and in the UN SDGs.

Effectively establishing and delivering MITT at a higher education institution requires creative and visionary leadership, supportive management and administration that fosters an environment for creative curriculum design. The curriculum design itself requires collaboration (staff, students, externals [e.g., government, industry, etc.]), creativity, and a well balanced approach (balancing disciplinary input and other issues relevant to curriculum design, e.g., assessment). All of this is important because chemistry as a discipline underpins the global success by supplying employers with graduates, enriching the graduates experience (as they care about the world) and equipping them with a 21st-century skill set that underpins their employability.

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