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Review

Seeking Genuine Vocations through Sustainability in Chemical Engineering

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Abstract: Sustainability in education is essential in raising awareness among pupils regarding the interconnected global challenges that we are facing and, at the same time, cultivating and transforming their mindsets to embrace and adopt sustainable lifestyles. In particular, college students who might briefly encounter sustainability issues during their courses of study would bring their values and attitudes regarding sustainability into their future workplace and beyond. In this article, we focus on sustainability in engineering education at the tertiary level, particularly in chemical engineering, and reveal how these potential engineers could seek genuine vocations when choosing their careers without compromising sustainability. The article begins with a description of what constitutes chemical engineering and its branches in plain language. It then outlines what to expect when one enrolls in a chemical engineering program as an undergraduate or graduate student. This includes the core subjects to obtain, skill sets to master, and other essential expertise that could be useful in the workplace. Since chemical engineering is one of the disciplines where the paradox of improving and impairing is conspicuous, it is also essential to delve deeper into the sustainability facet of the field, specifically in higher education. The discussion continues with career options for enthusiastic chemical engineers and how these young and early-career graduates could discover their reason for well-being and life purpose as aspiring chemical engineers, while at the same time maintaining and enhancing the sustainability in their vocations.

Keywords: sustainability; chemical engineering; engineering education; higher education; career; employment; vocation

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1. Introduction

Engineering remains one of the most popular majors among many college applicants, and engineering graduates continue to gain respect and dignity among professional employees, with handsome take-home salaries and high job-satisfaction reports [1,2]. On the one hand, according to the *City & Guilds Happiness Index* survey from the UK, chartered engineers are the happiest professionals around; they beat lawyers, scientists, architects, and accountants when it comes to job satisfaction [3]. What is particularly interesting, according to a survey by *Payscale.com* in 2010, is that a chemical engineering major was ranked number one in terms of job satisfaction, while psychology was ranked last among majors in the survey [4].

On the other hand, each of us faces global challenges that might affect our daily activities, including, but not limited to, working, employment, pursuing a career, obtaining an education, and even traveling from one place to another. Some of these global issues encompass the rise in the Earth's temperature, environmental pollution, and climate change. While progress in science, engineering, and technology has lifted millions from poverty and improved their quality of life through cutting-edge innovations, paradoxically, these advances also drive the pressure on the environment by depleting the Earth's resources and contaminating the ecosystem where living things coexist. Hence, it is essential to let the environment restore itself from the damage by adopting a sustainability approach.

In particular, this awareness should be expanded to the current and future engineers who toil at the forefront of innovation.

Although the field of engineering is a broad discipline, we focus our discussion on sustainability in chemical engineering since the field not only directly impacts but is also impacted by the environment through its chemical processes and products. Indeed, it is pressing for chemical engineers to address the paradox of improving well-being yet degrading the environment by developing and improving processes and products that appease the sustainable development criteria. All of us, not only chemical engineers, have a collective responsibility in taking care of future generations, an appropriate ethical concern emanating from our common sense and humanity.

Chemical engineering is a certain type, and one of the main branches, of engineering dealing with the study of the operation and design of chemical plants, as well as methods of improving production. It applies practices in mathematics and scientific principles for the design, development, and evaluation of operational systems. This includes employing the application of physics, chemistry, biology, and engineering principles harmoniously to successfully perform its operations. Chemical engineering contributes to the development of a wide range of new as well as improved products and processes. These comprise strong materials to resist extreme temperatures, new fuels for reactors and booster propulsion, medicines, vaccines, serum, and plasma for mass distribution, as well as numerous other examples [5].

Chemical engineering is both an art and a science, in addition to engineering itself. Chemical engineering as a science means that some parts of the field are thoroughly understood on a theoretical basis. As an art, there are other areas of chemical engineering that are only partially understood theoretically. Similar to other engineering fields, chemical engineering is an art to a certain extent since chemical engineers often conduct their work based on experience and judgment. The profession of chemical engineering deals with the technology of the chemical and processing industries. Chemical engineers must be able to develop, design, and engineer both the equipment and the process involved in their vocation. In addition to being able to operate plants efficiently, safely, and economically, chemical engineers must also understand the functions and characteristics of the product outputs [6].

Chemical engineers carry out chemical processes on a commercial scale by converting raw materials into useful products. They must be able to apply scientific and engineering principles when designing and operating plants for material production. Chemical engineers are also involved in various aspects of plant design and operation, process design and analysis, chemical reaction engineering, materials synthesis and processing, environmental aspects, as well as safety and hazard assessments. The areas that chemical engineers need to deal with encompass the manufacturing of commodity chemicals, specialty chemicals, petroleum refining, microfabrication, fermentation, synthetics and plastics, and biomolecule production.

Both chemical engineering practices and education have evolved from the field of industrial chemistry in the late 19th century, to the adoption of common unit operations and the implementation of mathematical tools in the 20th century, and subsequently to consolidating and improving awareness of sustainability in the 21st century. While in the past each discipline only worked and interacted within their specific area of expertise, collaboration with other disciplines is inevitable when embracing sustainability education, not only in the field of chemical engineering but also in other engineering disciplines.

The body of published literature offers rich and diverse coverage of the sustainable aspects of chemical engineering. Although our discussion is far from exhaustive, we anticipate that it still provides a better understanding of the recent progress not only in sustainable development in chemical engineering education but also on how aspiring chemical engineers might pursue a sustainable career that aligns with more general sustainable development issues. We encourage all interested readers to examine the bibliography listed at the end of this article and consult the references therein.

Kim (2002) and Perkins (2003) covered chemical engineering from a historical point of view [7,8]. By focusing on mass and energy balances in liquid-phase processes, Denn (2012) introduced chemical engineering through various activities in which contemporary chemical engineers are engaged in [9]. Hipple (2017) discussed basic concepts of chemical engineering in an easy-to-understand way that enabled non-chemical engineers to understand fundamental concepts of chemical processing, design, and operation effortlessly [10]. Nnaji (2019) offered a comprehensive overview of the evolution, essence, concept, principles, functions, and applications of chemical engineering [11]. Ogawa (2007) attempted to enlighten the usefulness of information entropy for many phenomena that appear in chemical engineering [12]. Recently, Pushpavanam (2021) introduced new chemical engineering students to their potential future roles in society when they become engineers themselves [13].

In particular, for high school students who are considering majoring in chemical engineering, Stimus (2013) provided a basic and non-technical introduction to chemical engineering [14]. The book was specifically written for readers who have no background or experience in the field. Additionally, also written with high school students and recent graduates in mind, Ridder (2016) arranged a gentle tour through the work of chemical engineers in practice, how they would accomplish it, what kinds of employment and careers are open to them, and how much salary they can expect [15].

Thanks to the multidisciplinary nature of chemical engineering, it could indeed play a major role in promoting and enhancing sustainable development. When addressing the topic of chemical engineering and society, Batterham (2003) proposed a more proactive role from the profession regarding sustainability in its interaction with the community [16]. Another review by Batterham (2006) suggests effective and reliable indicators to assist companies in chemical industries when implementing sustainability [17]. For the sustainability aspect of chemical engineering, we may examine what the American Institute of Chemical Engineers (AIChE) has disclosed and publicized. Most notably, the AIChE Institute of Sustainability has developed an index that can be utilized to assess the sustainability performance of companies in the chemical industry with respect to their commitments toward sustainable development. Unlike other sustainability indices, the AIChE Sustainability Index outlines essential components in those chemical process industries. It consists of seven factors with well-defined metrics and practical benchmarks: strategic commitment to sustainability, sustainability innovation, environmental performance, safety performance, product stewardship, social responsibility, and value-chain management [18,19].

There also exist new trends in chemical engineering design that cater to sustainability, including biomimicry, cradle-to-cradle, cradle-to-grave, the natural step, green chemistry, green engineering, ecological design, approaching zero waste, resilience engineering, self-assembly, and inherently safer design, among others [20–26]. In his commentary article, Charpentier (2007) proposed four simultaneous research directions that chemical engineers could embark upon in their journey toward a more sustainable discipline. These are: the thorough multiscale control of processes, process intensification through the design of state-of-the-art apparatuses, structured product synthesis, and the implementation of multiscale modeling and simulations of real-life situations [27].

Since both chemistry and chemical engineering are closely related to the use and generation of energy, sustainability in chemical engineering has an essential role in tackling any challenges associated with energy, as well as an imperative task to shift to and develop renewable and alternative energy sources in chemical processes and productions [28,29]. Using quantitative evidence, MacKay (2009) demonstrated in his monograph on energy matters that our addiction to fossil fuels is unsustainable, and via "tour de force and energy", outlined some adjustments that society must undergo if we would like to attain sustainable living [30]. Some products of chemical engineering include materials such as metal, cement, plastic, and paper. Aiming to use less amount of materials when accomplishing identical goals will open wide the door of innovation opportunities in the sustainable development of chemical engineering. Looking forward and "with both eyes open", Allwood et al. (2012)

have composed an excellent work presenting various options for the future of sustainable materials. They are optimistic about future sustainability when the trinity of businesses, government, and individuals each play their own role in contributing constructively to sustainable development [31].

Argoti et al. (2019) summarized recent developments with regard to the challenges and opportunities when assessing sustainability during chemical process design and classified the associated sustainability metrics according to the stages of the design in which they could be implemented [32]. A review by Bakshi (2019) specifically highlighted the role of process system engineering, a subdiscipline of chemical engineering, in advancing toward sustainability. Rather than adopting the popular understanding of sustainability as an intersection between the economy, society, and the environment, i.e., the triple bottom line model, all involved parties should alter their view to the triple value model, where the three aforementioned components are depicted as a nested system instead of a Venn diagram [33], cf. [34,35]. Nnaji (2019) described a model for sustainable chemical engineering processes from a progress-flow perspective, within which sustainable raw materials, utilities, designs, and syntheses assemble sustainable manufacturing processes that produce sustainable products and compel sustainable consumption behaviors [11].

The focus of this article is not only on the sustainable aspects of chemical engineering education but also on the psychological aspects of employment for potential chemical engineers, particularly those who are interested in marrying up their genuine vocations with sustainability. The purpose of this article is to provide outreach to potential students who are interested in majoring in chemical engineering, as well as to teachers and academic counselors at the secondary school level who might advise their students as to whether selecting this study program is a feasible career pathway. In particular, one may also want to contemplate issues beyond merely talents and interests when deciding on a specific major to pursue or choosing an employment and career, i.e., sustainability and vocation. The theoretical framework for our discussion is an intersection of the sustainable aspect of chemical engineering, sustainability in chemical engineering education, and the psychological aspect of careers, sustainability, and vocations, as can be seen in Figure 1.

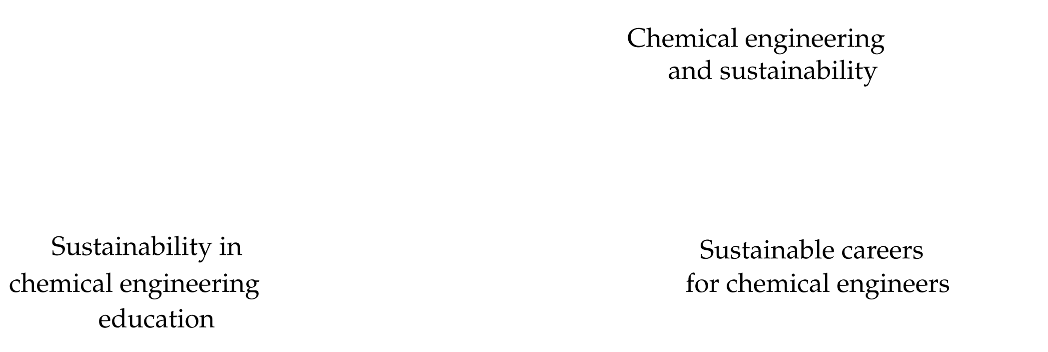

Figure 1. A theoretical framework for aspiring chemical engineers who desire to find sustainable, meaningful, and satisfying careers while adopting, cultivating, and progressing in sustainable development.

After this introduction, the article is organized as follows. Section 2 covers the educational aspect of chemical engineering, which includes a general list of courses and plausible progression pathways, integrating sustainability into the curricula, the ubiquity of mathematics and physics in chemical engineering, and the mathematical features of sustainability written in the context of chemical engineering. Section 3 discusses possible career options for aspiring chemical engineers who not only want to seek their true vocations in life but also to adopt, develop, and enhance sustainability in all aspects of their lives. Finally, Section 4 concludes our discussion.

2. Chemical Engineering Education

2.1. General Curriculum

According to Thompson and Ceckler (1977), students who take their first course in an introduction to chemical engineering should understand the nature and scope of the chemical process industry, comprehend certain physical and chemical principles as they relate to the analysis of chemical processes, and be proficient in a systematic approach to organizing information and solving problems [36].

In order to become a chemical engineering graduate, one needs to obtain competent credentials. Pursuing a bachelor's degree in chemical engineering is the most common path to follow, which usually takes four years to complete. One may continue on to graduate schools to obtain a master's and/or PhD degree to delve further on an academic level. The former commonly requires two years of study, while the latter may range from three to six years to complete, depending on various factors. In addition to acquiring important skills, adequate experiences, and necessary credentials, these degrees open the door to a wide array of exciting academic and career opportunities, as we will discuss in Section 3.

In addition to enrolling in the required core subjects, students enrolled in an undergraduate program in chemical engineering also need to take general courses in mathematics and sciences, which may include modules in mathematics, physics, chemistry, and biology. The mathematics modules cover differential and integral calculus, multivariable and vector calculus, linear algebra, and differential equations. The physics modules include classical mechanics, thermodynamics, electricity, magnetism, and special relativity. It should not be surprising that in addition to two-semester of general chemistry courses covering atomic and molecular theory, chemical periodicity, stoichiometry, chemical reactions, chemical kinetics, and chemical equilibrium, students also need to take a sequence of courses in organic chemistry. Some institutions also require their students to complete a set of elective social science and humanities courses.

Common themes covered in chemical engineering programs include physics, chemistry, kinetics, chemical reactions, separation processes, electrochemical systems, fluid mechanics, transport phenomena, energy conservation, and so forth. A substantial number of these subjects are often accompanied by laboratory activities and/or computer applications. Table 1 displays an example of a curriculum listing course names and a typical progression pattern plan for an undergraduate program in chemical engineering. It turns out that the undergraduate curricula for chemical engineering majors are rarely uniform. There are ample variations from one university to another. Even within an engineering program at one specific university, obtaining a degree in chemical engineering is often customizable. As the excerpted example from the University of Virginia has revealed, the program acknowledges several concentrations and multiple paths to obtaining a degree, tailored to the students' interests and needs. Although the displayed sample is by no means fixed or rigid, it could provide a general idea of possible progression paths for potential students who wish to study chemical engineering.

It is a common misconception among prospective undergraduate and high school students that they can learn more about and specialize in chemistry once they take a chemical engineering program. While the notion is not entirely wrong, it turns out that only around 20% of the courses are related to chemistry, particularly physical and organic chemistry, as we observe in Table 1. Similar to other engineering degrees, mathematics and physics are ultimately the most important elements of the program. There are also some courses related to biology, but these would typically be for more specialized tracks, see Figure 2.

Table 1. An example of a curriculum for an undergraduate program in chemical engineering. Course names and the progression pattern plan are adapted from those of the University of Virginia (Charlottesville, Virginia, United States).

	Freshman		
Fall	**Credits**	**Spring**	**Credits**
Calculus 1	4	Calculus 2	4
General Physics 1	4	General Physics 2	4
General Chemistry 1	4	General Chemistry 2	4
Introduction to Engineering	3	Biology for Engineers	3
Engineering, Technology, and Society	3	Introduction to Programming	3
	18		18
	Sophomore		
Fall	**Credits**	**Spring**	**Credits**
Calculus 3	4	Differential Equations and Linear Algebra	4
Principles of Chemical Engineering	4	Fluid Mechanics	3
Organic Chemistry 1	4	Organic Chemistry 2	4
Materials and Energy Balance	3	Applied Probability and Statistics	3
HSS Elective	3	Thermodynamics	3
	18		17
	Junior		
Fall	**Credits**	**Spring**	**Credits**
Transport Processes 1	3	Transport Processes 2	3
Physical Chemistry	3	Chemical Reaction Engineering	3
Separation Process	3	Chemical Engineering Analysis	3
Chemical Thermodynamics and Unit Operations	3	Engineering Materials	3
Major Elective	3	Kinetics	3
	15		15
	Senior		
Fall	**Credits**	**Spring**	**Credits**
Process Synthesis, Modeling, and Control	3	Process Design and Simulation	3
Engineering Practice	3	Chemical Engineering Lab	3
Introduction to Process Safety	3	Bioprocess Engineering	3
Major Elective	3	Major Elective	3
Unrestricted Elective	3	Unrestricted Elective	3
	15		15

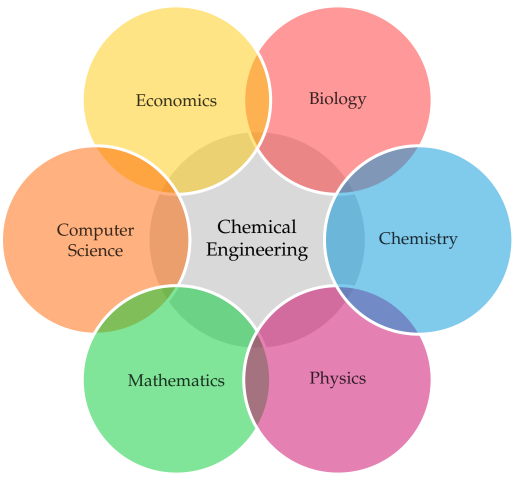

Figure 2. Chemical engineering consists of the application of mathematics, physics, chemistry, biology, computer science, and economics.

To see the difference between chemistry and chemical engineering, it is worth understanding the difference between science and engineering itself. Although they are different, both subjects are closely related and have existed since the dawn of history. Science involves expanding a body of knowledge about a particular topic by conducting a sequence of simulations or experiments. In contrast, engineering applies those scientific ideas to real life. While scientists use scientific methods in their research, engineers employ scientific principles to design equipment, construct tools, and realize products [14].

By examining the curricula closely, there are significant differences between chemistry and chemical engineering programs. Studying and majoring in chemistry means exploring large repositories of chemical reactions and investigating the fundamental theories behind their existence. In addition to learning in great detail the theory behind the numerous instruments used for chemical analysis, chemistry majors also spend some time studying and experimenting with chemical synthesis, i.e., the construction of complex chemical compounds from simpler ones. On the other hand, majoring in chemical engineering focuses on the practical implementation of various reaction patterns and relates to how different transport phenomena affect the outcomes of those reactions [15].

2.2. Sustainability in Chemical Engineering Education

At the dawn of the 21st century, research works that discussed sustainability in education began to emerge. Mitchell (2000) argued that sustainability should be an essential principle in chemical engineering education and chemical engineers have a crucial role in promoting sustainable development [37]. Furthermore, by proposing a revised concentric model on sustainability, she suggested that a paradigm shift in chemical engineering curricula is inevitable, whereby sustainability integration throughout the courses should be a novel mindset. While demonstrating that the engineering accreditation practices in the UK lag behind their counterparts in the US and Australia, Mitchell (2000) and readers might want to investigate other similar initiatives among institutions in mainland European countries where they usually act as pioneers in the forefront of promoting sustainability.

In the broader context of the chemical engineering profession, Batterham (2003) proposed assimilating a strategic framework of sustainability into chemical engineering curricula and encouraged educators to emphasize sustainability and life-cycle analysis in all their courses [16]. While suggesting accreditation requirements for courses and study programs, based on whether a particular institution has adopted the strategic framework of sustainability, Batterham (2003) should have included a proposal for rewarding teachers and college instructors who strive to promote sustainability in their teaching.

A study from Finland by Tikka et al. (2000) revealed that engineering students exhibit more negative attitudes toward the environment and participate in fewer nature-related activities than students majoring in biology [38]. Although their findings were only limited to the Finnish context, it would not be too surprising if similar outcomes are also duplicated in other neighboring Scandinavian or mainland European countries, where the awareness of sustainability starts early, at home. Across the Atlantic and nearly a decade later, Allen et al. (2009) benchmarked the data from American universities that offer a program in chemical engineering with the inclusion of sustainability-engineering concepts and discovered that multi-objective designs, system approaches, and multiple-scale design considerations are constructive pedagogical resolutions in sustainability education [39]. While Mitchell (2000) proposed embedding sustainability elements into engineering courses, the findings of Allen et al. (2009) revealed that courses dedicated to sustainable engineering (48%) triumph over three other course categories in this respect by more than double or triple, i.e., the integration- (23%), technological development- (14%), and cross-interdisciplinary (15%) types of courses.

In their separate report, Murphy et al. (2009) documented various activities in research and teaching that are related to sustainable engineering among American higher education institutions, albeit discerning minimal organization at the national level [40]. In both articles, they adopted four distinct levels of decision-making, which are grouped according to the system scales, i.e., gate-to-gate, cradle-to-grave, inter-industry, and extra-industry. Together with the associated green engineering principles and sustainability topics covered in engineering courses, many of them are closely related to chemical engineering, such as process and product design, material and chemical selections, material flow and nested life-cycle analyses, and by-product energy, among others. However, it would be more interesting to perceive the next step of sustainability, e.g., cradle-to-cradle instead of cradle-to-grave.

Allen and Shonnard (2012) argued that in order to achieve sustainable chemical engineering design, it is necessary for chemical engineers to not only acquire knowledge outside their discipline but to also collaborate with experts from different fields [41]. This persuasive mindset compels chemical engineers and chemical engineering educators to promptly implement three elements of sustainability in chemical engineering education, i.e., framing the challenge, conducting design and assessment, and establishing system perspectives. In practice, however, consolidating these ingredients into already cramped chemical engineering curricula is a mammoth task, let alone making sure that students will eventually adopt and practice sustainability once they graduate from college.

Montañés et al. (2012) discussed a practical example of incorporating sustainability in chemical engineering education through environmental management system laboratory work [42]. Glassey and Haile (2012) described a concentrated strategy to embed sustainability teaching into a chemical engineering undergraduate curriculum in the UK and received a positive response from the students [43]. Recently, from their review on sustainability in engineering education in general, which was not specifically limited to chemical engineering education, Gutierrez-Bucheli et al. (2022) suggested that universities should adopt an education paradigm change in integrating contextual-based sustainability initiatives in their curricula [44].

From this incomplete literature review, we observe that there exists a paradigm shift in chemical engineering education and curricula all over the world, but this is mainly led by institutions in the West. There are various efforts in terms of embedding sustainability elements into chemical engineering modules and raising awareness among the younger generations to adopt a sustainable way of thinking. We also hope that other universities in the East and South will follow this path toward a better sustainable education.

2.3. Mathematics and Physics in Chemical Engineering

This subsection demonstrates that a multidisciplinary course in chemical engineering is inevitable. While potential students would anticipate taking a sequence of courses related to chemistry, it turns out that the number is illuminating when it comes to mathematics and physics contents in any given chemical engineering program. In addition to completing a sequence of calculus courses, linear algebra, differential equations, and statistical methods, prospective chemical engineers must also study mathematically intensive physics modules, including chemical thermodynamics, fluid mechanics, mass transfer, transport phenomena, and reaction engineering. The father of modern chemical engineering, Neal Amundson (1916–2011), left behind a long-lasting legacy in amalgamating progress in science and engineering with elegant yet practical mathematical methods, from which the contemporary education and research in chemical engineering cannot be dismantled. In Appendix A, we provide one example from fluid mechanics, with applications in chemical engineering, where an interplay between mathematics and physics is vividly animating, i.e., the classical Graetz problem [45,46].

As always, the body of literature will never be exhaustive, and we are barely scratching its surface in this article. Mickley et al. (1957) wrote a classic work on applied mathematics in chemical engineering, and it is still regarded as an excellent textbook for chemical engineers who are willing to perform their own modeling procedures [47]. Rice and Do (2012) demonstrated how classical mathematics solves a broad range of new application problems in chemical engineering in their book's second edition [48]. Focusing on mathematics application in chemical engineering, Loney (2016) also addressed the setup and verification of mathematical models using experimental data in his expanded and revised monograph [49].

Some early papers on mathematical aspects in chemical engineering were contributed by Neal Amundson and his key collaborators, such as Leon Lapidus and Paul Kasten, with a sequence of papers discussing the mathematics of adsorption in beds that appeared more than seven decades ago in the late 1940s and early 1950s [50–55]. In the years and decades after that, his high-impact publications continued to flourish in the body of literature on chemistry and chemical engineering, written with other distinguished collaborators, including Andreas Acrivos, Rutherford Aris, Olegh Bilous, Hugo Caram, Dan Luss, Fred Newbold, Kenneth Valentas, and Arvind Varma, among others [56–70]. The following provides a brief description of some of his works and more recent articles from other authors as well.

Acrivos and Amundson (1955) published a brief survey on the applications of matrix algebra and calculus in chemical engineering problems [71]. Sweeny et al. (1964) reviewed mathematics applications in chemical engineering, particularly in statistics, basic and industrial operations research, and optimization [72]. Elnashaie et al. (1993) have argued that since the field of chemical engineering is progressing rapidly, mathematical modeling is necessary for its curriculum to prepare future engineers for the diverse industries in which they might participate [73]. Ramkrishna and Amundson (2004) provided an overview of mathematics in chemical engineering during the second half of the past century and concluded that mathematics is the principal instrument not only for chemical engineering processes but also for interceding about materials and products [74]. Wang et al. (2013) observed a common mathematical feature of geometric and parametric singularities in their chemical engineering research [75]. Finlayson et al. (2015) comprehensively covered mathematical topics useful for chemical engineering [76].

2.4. Mathematical Aspect of Sustainability in Chemical Engineering

Mathematics is undoubtedly advantageous, not only for modeling and solving many problems arising in engineering but also as an indispensable tool in understanding issues in sustainable development. Even though some people might consider that mathematics and sustainability are unrelated, a closer look at both topics reveals that they entail each other. Mathematics does need sustainable development. As we have covered earlier, mathematics and its related products in science, engineering, and technology have contributed to positive outcomes toward mankind's welfare but at the same time have also caused many global problems, from climate change to declining biodiversity. Mathematics, together with science, engineering, and technology, ought to engage with these paradoxical issues so that they do not to lose their legitimacy.

Conversely, sustainability also requires mathematics. Since many of the actions in sustainability call for a significant level of global consensus that can be supported by solid evidence, mathematics has a vital role in generating these clear and coherent facts. In the absence of mathematics, anthropogenic global warming and climate change would not have been distinctly identified, in the same manner that ecosystem dynamics would be unfathomable. We are again pleased to discover that the body of literature has something to offer on the mathematical aspect of sustainable development, even though it does not cover a specific topic on chemical engineering per se [77].

Although mathematical theories are historically developed around problems emanating from physics and engineering, recent advances in sustainability also call for more contributions from mathematics. For instance, Hersh (2006) provided a fine basic introduction and advanced mathematical techniques for sustainable development; although the presented case studies are wide-ranging in nature, some of them are closely related and have some relevance to chemical engineering, e.g., optimization and decision-making in coal-fired power plants [78].

In a work designed for developing quantitative and critical thinking skills, Roe et al. (2018) have written an excellent undergraduate textbook that focuses on mathematical reasoning and the quantitative aspect of sustainability. Several of the case studies are compatible with topics in chemical engineering, such as polymer recycling, genetically modified crops, and energy return and investment [79]. When defining sustainability, the authors resolved on the 1987 definition of the Brundtland Report, and instead of locating it in the main part of the textbook, they obscured it in the note for students [80]. Some readers might not completely agree with adopting this particular and rather vague definition of sustainability for a textbook, as there are other definitions with more clarity and specific goals to avoid potential misconceptions, e.g., the definition from the United Nations' Sustainable Development Goals includes improving the quality of education, eradicating poverty, and global transformations to affordable and clean energy, among others [81].

In his opinion piece on the mathematics of sustainability, Levin (2013) focused on the ecosystem's services to humanity, which may be through either the direct or indirect products of chemical engineering processes, such as food, fiber, fuel, pharmaceuticals, and the sequestration of toxic materials. He further identified that developing statistical mechanics and schemes for robust governance are among some of the mathematical challenges in achieving a sustainable future [82]. While perturbation theory and multiple-scale analysis have been successfully implemented in handling various problems in mathematical physics as well as in engineering, Rossberg (2018) argued that we require a different kind of mathematics toolbox to address research in sustainability, thanks to its dynamical structures that encompass a wider range of scales than the former [83].

Supplemented with numerous features, such as "fun with numbers", Sankey diagrams, pie charts, tables, graphs, and material catalogs, Alwood et al. (2012) provided an excellent opportunity for incorporating mathematical and statistical analysis to attain a better understanding of profuse options yet arduously implemented in the future of sustainable materials [31]. Although renewable energy sources have been discussed more comprehensively than enhanced end-use efficiency types of technology, MacKay (2009) invited an excursion into those energy alternatives quantitatively, using numbers and arithmetic, which makes it suitable for further discussion on the mathematical aspect of energy sustainability, alongside potential contributions from chemical engineering [30].

Coppens (2004) discussed an excellent connection between sustainability, chemical engineering, and the mathematics of Mandelbrot's fractal geometry by reasoning that sustainability in chemical engineering processes and products involves structural optimization from the molecular to macroscopic scales. He further argued that chemical engineering could learn from nature, in terms of hierarchical networks and structured patterns, by adopting similarly structured environments on various spatial and temporal scales since fractal geometry imparts effectiveness and efficiency to modeling and controls in chemical engineering [84].

Even though they are not directly related to chemical engineering, there are also some examples of sustainability in mathematics and the mathematics for sustainability. Petocz and Reid (2003) examined the problems of integrating issues of sustainability within the mainstream curriculum of university mathematics and suggested some ideas to educators that they should include some knowledge of sustainability within the context without compromising the mathematical content itself [85]. Singh (2014) described exponential and logistic models and their applications in understanding certain issues related to sustainability, such as population growth, lake water quality, fishery management, and economic growth, as well as the gross domestic product [86]. Meyer and co-workers (2018) applied a mathematical tool of dynamical system theory in quantifying and strengthening resilience in response to shifting ecosystem disturbance patterns due to either climate change or direct human interference [87].

From this brief survey, we observe that mathematical facets of sustainability encompass a wide-ranging branch of mathematics, from statistics and data analysis to differential equations and dynamical systems. The relationship between components of the sustainable development process, such as environmental and social dimensions, may exhibit similar behavior and possess a corresponding analogy with the physical and chemical engineering balance laws, such as mass, momentum, and energy [88]. We also recognize that the mathematical aspect of sustainability in chemical engineering is still an open problem, and with this opportunity, we invite experts for further discussion, commentary, and debate on this particular topic.

3. Careers in Chemical Engineering

In this section, we explore various employment and career possibilities for competent chemical engineers. Even though it is important to identify employers who treat their employees with respect and dignity, aspiring potential chemical engineers might want to work in a sector that strives vigorously in promoting sustainability while seeking their genuine vocations in life when it comes to achieving long-term careers and professions.

3.1. Career and Employment

A degree in chemical engineering is a path to making a positive difference in this world. There are numerous facts and inspiring stories about how chemical engineers have shaped our world over the years. Today, chemical engineers have benefited from systematic subjects and satisfying careers thanks to the early pioneers in the field; thus, they are standing on the shoulders of giants, so to speak.

For example, the British chemist George Edward Davis (1850–1907) is regarded as the founding father of chemical engineering. In addition to identifying extensive characteristics that are commonly found in the chemical industry, Davis published a lecture series wherein he defined chemical engineering as a discipline and wrote an influential handbook on chemical engineering [89–92]. An American chemist, Arthur Dehon Little (1863–1935), introduced and developed the concept of unit operations used in physical and chemical changes and promoted the sets of activities of industrial research and technological development [93–95]. The first woman to earn a PhD in chemical engineering and the first female member of the American Institute of Chemical Engineers, Margaret Hutchinson Rousseau (1910–2000), designed the first commercial penicillin production plant [96–98]. Although polyethylene was discovered twice, it was a chemical engineer from England, Dermot Manning, who built high-pressure research reactors that made experiments and full-scale production possible [99–101].

While not every chemical engineering graduate will make the significant breakthroughs achieved by these people, many graduates still have numerous opportunities to work in and contribute to a wide range of fields and industries. Their roles involve not only developing and improving existing processes but also discovering and creating new techniques for altering materials and producing useful products. Other equally meaningful sectors that utilize the skills developed in a chemical engineering degree include quality assurance, consultancy, and manufacturing. A few popular examples of industries where chemical engineers work and progress in their careers are petroleum and natural gas; pharmaceuticals; processed food; pulp and paper; metallurgy, mining, and metal extraction; household products; polymers; and medical devices [15].

Any potential chemical engineers and many readers might be pleased to understand that skillful graduates with a degree in chemical engineering earn handsome salaries and enjoy generous benefits. If money is not the main concern, a lofty salary may also mean that chemical engineers deserve respect and dignity for their qualified skill sets and credentials [102]. In the United States, the starting salaries for chemical engineers rank among the highest, approaching USD 70,000 per annum, just below the salaries of petroleum and computer engineers [103]. A more recent report from the US Bureau of Labor Statistics suggests that the median annual salary for chemical engineers stood at USD 108,540 [104]. Depending on industries, the wage may vary significantly, with the top rate earning more than USD 150,000 annually. The top-paying industries for chemical engineers among others are oil and gas extraction, the management of companies and enterprises, petroleum and coal products manufacturing, computer and peripheral equipment manufacturing, and local government, albeit excluding schools and hospitals [105].

Figure 3 displays several career options and possible job titles for chemical engineering graduates. The list is far from exhaustive, and the occupational prospects are wide-ranging. Many chemical engineers follow a particular path in their careers by expanding and delving deeper into a particular area of expertise, whereas other graduates collaborate with or switch over to other fields where chemical engineering expertise is in high demand. Those engineers who specialize might also encounter multiple options to focus on, such as design, process, and plant management, project engineering, environmental engineering, safety engineering, automation and process control, quality, validation, and so on [11]. Due to the interdisciplinary nature of chemical engineering, many graduates also work in emerging fields of multidisciplinary chemical engineering, such as biotechnology and biomedical engineering, computer-assisted processes, software programming, chemical-process patent work in legal firms, sales and marketing, teaching and research at universities, or even the less-traveled paths of enrolling in a medical school or becoming entrepreneurs [15,73].

Figure 3. Chemical engineering career options and job titles are diverse, ranging from research and development to sales and marketing.

3.2. *Seeking Purpose in Life as a Chemical Engineer*

In their job-hunting guidebook, Bolles and Brooks (2021) famously outlined their well-known flower exercise for a personal self-inventory to assist readers in planning their careers around their key passions, transferable skills, and other useful traits [106]. The flower diagram consists of seven petals that represent seven descriptions of one's mindset using the language of the workplace. These are our descriptions in terms of the types of people we most prefer to work with or assist at, our favored workplace or working conditions, transferable skills, sense of mission and purpose in life, knowledge and interests, preferred salary and level of responsibility, and geographical or environmental preference.

While Bolles and Brooks' (2021) flower diagram of this self-inventory might not directly relate to sustainability or sustainable development goals, we could adjust their theoretical framework to and endow with sustainability, by keeping in mind that there are various facets of sustainability in its most general context, e.g., using the United Nations Sustainable Development Goals, then implementing them at the lowest—individual—

level [81]. Figure 4 depicts a modified version of Bolles and Brooks' self-inventory flower diagram wherein each petal is now endowed with the adjective "sustainable". Whilst we could cover all petals from this modified Bolles and Brooks' flower diagram of self-inventory, in this subsection, we only focus on the central petal of seeking a sustainable yet meaningful mission in life. This is particularly essential for potential and aspiring chemical engineers who want to find their purpose, given their knowledge, skillset, and other factors at the tap of their fingertips. This subsection will also be particularly useful for guidance teachers, career counselors, and academic advisors.

Figure 4. Modified Bolles and Brooks' self-inventory flower diagram endowed with sustainability. The focus of this subsection is the middle petal, where aspiring and potential chemical engineers attempt to seek meaningful career goals in their lives.

It is a common perception that salary very often becomes one of the most important factors, if not the only one, when accepting a job offer. According to Bolles and Brooks' theory of self-inventory, it turns out that salary is only a portion of one petal of the flower diagram when one perceives it in the context of the workplace (the farthest left-hand side petal in Figure 4). While working in a particular industry might attract particularly high salaries, and there is nothing wrong with that, many new and young chemical engineering graduates might also want to seek their meaning and purpose in life while they pursue a career in chemical engineering. The body of literature consistently reveals that wealthier people not only feel happier and more satisfied with their lives but are also healthier and live longer than their less fortunate counterparts [107–115].

At the composite level, engineers—including chemical engineers—are often perceived as intelligent and creative individuals who attempt to change the world into a better and more sustainable place. They identify problems around them and tackle those using logical, analytical, and innovative thinking. Hence, encouraging them to seek goals and missions might seem superfluous as they are already on a noble mission to reinvent the planet as a better place to live. However, at the individual level, the significance cannot be overemphasized. Although finding a mission or vocation in life can be a challenging task, its success may lead to lifetime satisfaction, self-efficacy, and self-esteem. Whithin a shorter time frame, higher levels of competence, commitment, and productivity are also reported [116–125].

According to Super's theory of career development, the teenagers and young adults (age 15–24), at whom this article is primarily targeted, are in the exploratory stage. This stage is characterized by trying out and exploring different things, such as pursuing hobbies, participating in extracurricular activities, signing up for classes, enrolling in various elective courses, volunteering, obtaining work experiences through part-time employment and internships, going to graduate school, getting jobs, changing jobs, moving houses, et cetera. Through role tryouts and exploration, this group of youths realizes their vocational preferences and embraces a realistic self-concept. A piecemeal narrowing of choices leads to preferences. In turn, these predilections become choices when they are acted upon. Therefore, coaching them not only about choosing a particular major, such as chemical engineering, but also about what they are going to do after that teaching them that being inclusive, yet seeking a meaningful vocation and goal in life, may have a tremendous positive impact on their psychological and career developmental well-being [126–133].

Finding goals in work and life is frequently associated with the words *purpose*, *mission*, *vision*, *calling*, and *vocation*. *Mission* is always used in a religious context and can be defined as "a continuing task or responsibility that one is destined or fitted to do or specially called upon to undertake" [134,135]. Historically, mission is often synonymized with calling and vocation. Both terms are derived from the identical Latin word *vocatio* or *vocare*, which means "to call" or "to summon". One dictionary defines them as "life's work", "a trade or profession", "a person's employment or main occupation, especially regarded as particularly worthy and requiring great dedication", and "a strong feeling of suitability for a particular career or occupation" [136] (see also [137–139]). Indeed, both calling and vocation have a significant overlap, as both definitions contain "an approach to a particular life role that is oriented toward demonstrating or deriving a sense of purpose or meaningfulness and that holds other-oriented values and goals as primary sources of motivation" [140]. However, Dik and Duffy (2009) also attempted to construct a distinction between these two terms from the perspective of the origins of motivation. The perceived roots of a calling are external, whereas the conceptual construct of vocation is inclusively internal.

Whether the sources of origin are internal or external, aspiring and potential chemical engineers would like to, and should, find their purpose in life. It would be better were this purpose or vocation not only meaningful at the smaller, individual stratum but also sustainable, and that it holds sustainability at a larger, collective level. Similar to developing a career and embracing sustainability, seeking genuine goals in life is a journey, not merely a destination. Each of us must work toward attaining that particular goal every single day. Since challenges are inevitable and obstacles are present on multiple levels, we need to be committed and keep on improving. Returning to Super's theory of development tasks, we also might experience various other development stages within each of the life stages during this progress, i.e., growth, exploration, establishment, maintenance, and decline.

Another equally formidable task when connecting our daily activities (such as going to school or work) to a higher purpose of life and vocation is very often just a matter of communication. The work that chemical engineers perform has a real and positive impact on society, helps people to improve their lives, and can shape the world around us for the better. However, these engineers are often astounding experts at narrating "what" they do but not in explaining "why" they do it. When we tell stories by starting with the why, or even better, by combining both the what and the why, we not only clarify our purpose-driven work and find satisfaction in our vocation, which are ingredients for a genuine life purpose, but also inspire others, better understand what the community needs, and deliver better value customer service [141].

Chemical engineers might talk about a spreadsheet application or new plant facilities. However, the data they analyze and the complex distillation calculations they perform might, for instance, be part of the work needed to distribute clean water to many people in developing countries, cf. [10,142–147]. Instead of detailing artificial photosynthesis, chemical engineers could explain that the project they are involved in is part of building a sustainable and smart city, cf. [11,147–153]. In addition to describing mathematical modeling and Python computer coding, chemical engineers might elaborate that their programming algorithm will be used for harvesting alternative solar and wind energy, cf. [142,154–161]. These are some illustrations where chemical engineers could talk about both the what and the why, and simultaneously connect their contributions with their vision and mission in life, to promote sustainability, to make the world a better place, and so forth. The body of literature is saturated with other noble examples, and it is the engineer's task to connect those examples, or even to come up with some novel and innovative ones, with genuine vocations that are aligned with sustainability.

4. Conclusions

In this review article, we have introduced chemical engineering and its sustainability facet to general readers. Our discussion encompasses the definition and scope of chemical engineering, its general curriculum at the undergraduate level, sustainability in chemical engineering, the mathematical aspect of it, potential career options, and how aspiring chemical engineers could seek genuine purpose in their work and vocation in the context of sustainability. For each topic, we have provided selective yet important literature to support the argument. We aspire that this article will illuminate not only many high school students who contemplate applying to an engineering program but also parents, teachers, and academic counselors who desire their children, pupils, and advisees to uncover their fine but perhaps hidden academic potential.

As we have observed from the educational element, the curriculum of a chemical engineering undergraduate program is a balanced combination between mathematics, physics, and chemistry. Hence, anyone who is good at these subjects and is interested in delving further into the application aspects of these fields might want to consider majoring in chemical engineering. A classic example of the Graetz problem, which marries fluid flow and heat/mass transfer, demonstrates this feature (see Appendix A). Those who are interested in specializing further, possibly at an advanced undergraduate or graduate level, may discover multidisciplinary aspects of the subject, with biology, computer science, and economics, among others, appearing to become significantly important.

Our literature survey also suggests that there exists a paradigm shift in embedding sustainability into the chemical engineering curriculum across many universities, particularly in the Western world, where they have historically also pioneered and taken the lead in sustainable development practices. Since chemical engineering is multidisciplinary by nature and dynamically evolving in tandem with modern technological tools, efforts in blending sustainability into the already-crowded existing curricula remain a substantial challenge. Furthermore, although the literature on the mathematical aspect of sustainability with applications in chemical engineering is still relatively scarce, we hope that this review will expedite further discussion in unlocking the adjacent possibilities with other—interdisciplinary—topics, while concurrently stimulating collaborative efforts in this research direction.

When it comes to careers and employment, graduates of chemical engineering work in various industries and sectors, including production and services, both public and private. Chemical engineers solve diverse and challenging yet interesting problems under various technical, economic, and environmental constraints. They earn respect and dignity thanks to their professional skill sets and credentials, as shown by their attractive remuneration offers and packages. With future global challenges in healthcare, sustainability, and security, current and future chemical engineers have plenty of opportunities to contribute to the world and a better society. Potential and aspiring chemical engineers could also contemplate pursuing a genuine purpose in their life through their work and vocation. By communicating effectively with other people, especially younger ones, their enthusiasm, engagement, and service will not only inspire but also attract the next generation of chemical engineers into the profession.

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Appendix A. The Classical Graetz Problem

The classical Graetz problem is a fundamental tube flow problem that couples fluid flow with heat and/or mass transfer. It considers the thermal entry of an incompressible fluid in a circular pipe with a fixed velocity profile. In this problem, there exists a sudden jump in the tube temperature, with lower and higher temperatures at the downstream and upstream positions, respectively. The fluid enters the tube at a particular temperature in the upstream position, which can be higher or lower than the wall temperature (see Figure A1). The objective is to determine the behavior of the temperature profile as it travels along the tube downstream. Since the flow is incompressible, the velocity distribution does not depend on the varying temperatures. In particular, for laminar flow in a circular pipe, the velocity profile is parabolic [162,163]. The Graetz problem finds applications in chemical reactors, heat exchangers, blood flow, and other fluid transport phenomena.

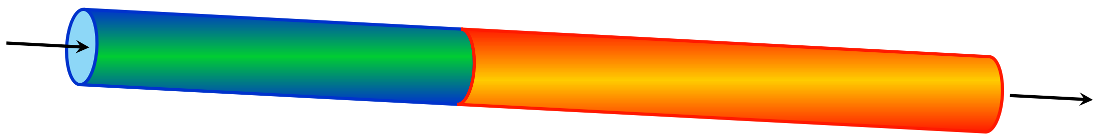

Figure A1. A schematic diagram for the classical Graetz problem. Fluid enters upstream from the left-hand side of a cylindrical tube and encounters a low-temperature wall. While it travels downstream in the tube, the fluid experiences a sudden jump in heat as the surrounding tube possesses a higher temperature surface.

By adopting the boundary-layer assumption, we regard that the axial diffusion is negligible compared to the axial convection. Furthermore, by employing the parabolic velocity profile, the governing equation for the fluid temperature profile $T(r,z)$ can be expressed as the following partial differential equation (PDE) in non-dimensional quantities:

$$\frac{\partial T}{\partial z} = \frac{1}{(1-r^2)} \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right),$$

with the following boundary conditions:

$$T(r=0,z)=1, \qquad T(r=1,z)=0, \qquad \text{and} \qquad \frac{\partial T}{\partial r}(r=0,z)=0,$$

where the spatial coordinates r and z denote the tube variables in the radial and axial directions, respectively. By implementing the method of the separation of variables, i.e., writing $T(r,z) = R(r)Z(z)$, the PDE is decomposed into two ordinary differential equations (ODEs). In particular, $R(r)$ satisfies the following Sturm–Liouville boundary value problem (BVP):

$$-\frac{1}{r}\frac{d}{dr}\left(r\frac{dR}{dr}\right) = \lambda^2(1-r^2)R$$

$$R(1)=0, \qquad \text{and} \qquad \frac{dR}{dr}=0.$$

Performing another set of transformations of both dependent and independent variables, i.e., $x = -\lambda r^2$ and $R = e^{-x/2}y(x)$, we obtain the well-known Kummer's differential equation [164]:

$$x\frac{d^2y}{dx^2} + (1-x)\frac{dy}{dx} - \left(\frac{1}{2}+\frac{\lambda}{4}\right)y = 0.$$

This Kummer's ODE belongs to a class of confluent hypergeometric equations, a degenerate form of hypergeometric ODE, where two of the three regular singularities merge into an irregular singularity [165,166]. Although a second-order ODE yields two linearly independent solutions, it is only one that is bounded at $x = 0$. By requiring that both $R(0)$ and $y(0)$ must remain finite, we rule out the singular solution, and hence, we acquire only the first kind of Kummer's function. Up to a multiple of constant, this regular solution can be expressed in the following form:

$$y(x) = M\left(\frac{1}{2} - \frac{\lambda}{4}, 1, x\right) = {}_1F_1\left(\frac{1}{2} - \frac{\lambda}{4}; 1; x\right) = \sum_{n=0}^{\infty} \left(\frac{1}{2} - \frac{\lambda}{4}\right)^{(n)} \frac{x^n}{1^{(n)} n!},$$

where the Pochhammer function $\xi^{(n)}$, $n \in \mathbb{N}_0$ (also known as the rising or ascending factorial) is defined as:

$$\xi^{(0)} = 1,$$
$$\xi^{(n)} = \prod_{k=0}^{n-1} (\xi + k) = \xi(\xi+1)(\xi+2)\cdots(\xi+n-1).$$

By applying the boundary condition at the tube wall, i.e., $R(1) = 0$ or $y(1) = 0$, we obtain the following transcendental equation for the eigenvalues, or rather, the square root of eigenvalues:

$$M\left(\frac{1}{2} - \frac{\lambda_n}{4}, 1, -\lambda_n\right) = 0, \qquad n \in \mathbb{N}_0.$$

For each value λ_n, there exists an associated eigenfunction $R_n(r)$ given by:

$$R_n(r) = e^{-\frac{1}{2}\lambda_n r^2} y_n(-\lambda_n r^2).$$

A general solution to the classical Graetz problem can then be obtained by applying the linear superposition principle. Furthermore, the unknown coefficients can be retrieved by utilizing the orthogonality properties of the Sturm–Liouville problem after employing the initial condition accordingly [164]. Those readers who are interested in delving more into the Graetz problem may consult [167–171]; for confluent geometric Kummer's function and equation, review [166,172–175]. For more information on the Sturm–Liouville problem, see the listed monographs and the references therein, see [176–183].

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