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综 述

Industrial Biosystems Engineering and Biorefinery Systems

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Abstract: The concept of Industrial Biosystems Engineering (IBsE) was suggested as a new engineering branch to be developed for meeting the needs for science, technology and professionals by the upcoming bioeconomy. With emphasis on systems, IBsE builds upon the interfaces between systems biology, bioprocessing, and systems engineering. This paper discussed the background, the suggested definition, the theoretical framework and methodologies of this new discipline as well as its challenges and future development.

Keywords: biosystems engineering, biorefinery, industrial biotechnology

1 The needs for a new engineering discipline-Industrial Biosystems Engineering

The recent developments in bioenergy and bioproducts have shown several major characteristics that demonstrate unprecedented challenges to the scientific community as well as to society: (1) the topic has enormous importance to sustainable development and the future wellbeing of human societies; (2) the complexity of the problems is beyond the scope of any existing single scientific discipline; (3) the major technical barriers presented must be overcome with a new way of thinking and with a new set of tools; and (4) none of the branches of science and engineering in the current education system are suited to, by themselves, train these future scientists and engineers. These characteristics indicate the necessity of new integrated disciplines for more effectively addressing the needs of the upcoming bioeconomy. A new integrated engineering discipline called Industrial Biosystems Engineering (IBsE) was identified as one of these needs[1] since bioenergy and bioproducts will be ultimately produced via a series of structures, machines, operations, or conversion processes that are organized or operated in a cohesive, yet well coordinated system, many of which are biological in nature. There are five major indications that support the need for not only new knowledge but new disciplines. The first indication for the need for a new engineering discipline is the significance of the problems. The topic of bioenergy and bioproducts has great societal significance since it connects four major cornerstones of our modern society: (1) energy security, as it offers an alternative to the limited fossil fuel supply; (2) environmental protection, specifically for combating climate change by reducing greenhouse gas emissions; (3) economic development, as it creates new opportunities for agriculture and energy industry as well as brings about fundamental change to the future economy; and (4) allocation of natural resources such as land and water, as bioenergy and bioproducts may compete with human food supply for the production of feedstocks. The second indication is the fact that the increasing interests in bioenergy and bioproducts are a result of a new demand created by societal developments, and not a new demand created by science and technology developments. For instance, the notion of the "third wave of biotechnology," i.e., the application of biotechnology principles and tools for producing bioenergy and bioproducts from biomass arrives in response to society's demand for renewable energy, and not in response to the development of biotechnology, has created a new demand for society. Moreover, the societal demand for developing biofuels and bioproducts has come faster than anyone could have predicted. Consequently, the biofuel and bioproduct market demand is ahead of the science and technology. The third indication of the need for one or more new disciplines is that bioenergy and bioproducts related scientific issues are so complex that not one of the existing disciplines alone offers full coverage for the needs. There is little argument that one of the most rapidly developing fields is industrial biotechnology, which uses biomass to produce industrial materials and

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products. However, successful implementation of industrial biotechnology must be done in a much broader context, that is, a system where biotechnologically designed process can be fully functional and effective, since a successful biorefinery involves more than just biotechnology. For example, it has become clear that the ultimate limit of the potential of a biorefinery is not the technology needed to convert the biomass materials to various products, but rather the amount of biomass materials that are available as feedstock. Therefore, feedstock supply must be considered as a major part of a biorefinery system. Other considerations for developing a successful biorefinery include additional resources for a sustainable feedstock supply (land, water, etc), net energy gains, and environmental impacts such as waste disposal and emissions. The fourth indication showing need for a new discipline is that the existing disciplines in higher educational institutions do not adequately provide the core competencies or the associated knowledge bases and skill sets required to effectively address technical challenges related to biorefinery. The new IBsE discipline, which will more effectively integrate and connect to other disciplines, is more desirable than the existing ones, even considering the multidisciplinary approach currently recognized and encouraged. Presently, both industry and research and development organizations are seeking a new generation of professionals who are specifically trained with the comprehensive background for developing the bioeconomy. The fifth indication of a need for new disciplines is that, while various new concepts have been advanced and methods from existing disciplines have been used for solving biorefinery related problems with promising results, these attempts have also demonstrated limitations, since different disciplines are lacking 'overlap' knowledge necessary for the conceptual interface.

Clearly, the upcoming bioeconomy and the concept of biorefinery provide opportunities for new applications of existing science and engineering principles. However, such applications require a new theoretical framework, a new integrated knowledge base, and new approaches for solving these complex problems. IBsE was proposed for the application of biological processes for the production of fuel, chemicals and other products at industrial scale in a manufacturing/refinery system setting. It is hoped that, with further development, IBsE serves as the premier engineering discipline that provides the scientific and engineering principles as well as unique approaches to problem solving for addressing scientific and technological challenges related to biochemical biorefinery platform. The purpose of the current paper is to present some additional thoughts on theoretical framework and further development needs regarding this discipline, and to stimulate more discussions on and contributions to this concept.

2 Industrial Biosystems Engineering concept development and definition

Based on the above discussion, IBsE was proposed as a new engineering branch that applies science and engineering principles to design, analysis, and operation of complex systems that consist of biological, physical and chemical subsystems for the production of industrial products such as fuels, chemicals and others, from biomass through bioprocessing, via principally biological processes. This definition includes four major points. First, it is an engineering discipline since it involves creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes for the production of bioenergy and bioproducts, all as respects an intended function, economics of operation and safety to life and property. Second, major limiting process in a biochemical biorefinery platform is biological in nature, employing biological systems to accomplish the most critical functions, from feedstock supply to conversion of raw materials to final products. These engineering goals cannot be achieved without proper function of biological systems that are designed and optimized with biotechnology. Third, it is systems engineering as (1) the subject deals with complex biological, chemical and physical systems and subsystems, (2) the design has multi-objective functions—i.e., to maximize the overall performance of the system and minimize greenhouse gas emissions within the life cycle under various sustainability constraints, and (3) the optimization of the overall system is the most critical, although improved performance of subsystems is important. Fourth, the system that the IBsE discipline studies is of industrial scale, meaning the system produces commodity industrial products that have large market, and the system must operate on a large scale with low production cost, and high productivity and reliability.

IBsE as a new engineering discipline has its own merit because it can build upon yet be different from the existing disciplines. The interface of multi-disciplines, especially systems biology[2,3], bioprocess engineering[4], and systems engineering[5], can provide a unique theoretical base for IBsE. With such a multidisciplinary structure, IBsE interfaces biological systems with engineering systems for design and management of complex biorefinery systems in which the biological systems will be modified and incorporated into engineering processes for the production of products that otherwise are not going be produced in the same way through a natural process. Unlike other biological systems, the functions of these biological systems are specifically designed for the production of industrial products. Due to the complexity of a biorefinery system, a major feature of IBsE is the appreciation of subsystems with vertical (different levels), horizontal (among sequential steps), and temporal (different time scale) connections. Interactions among the subsystems must be recognized and utilized to achieve the overall optimal system performance through integration. Therefore, IBsE particularly emphasizes the requirements of a systems engineering approach as part of its core methodology framework. Such systems produce large quantities of product, which is extremely cost sensitive since the products are closely related to people's daily life. The systems must be very efficient in terms of energy consumption and materials utilization. Additionally, the scale of the operation is substantial. Therefore, success of such systems has great impact upon the ecosystem and the environment, as it requires significant amounts of feedstock that competes with water and land resources and other functions, and has great amounts of output that can benefit the environment in terms of greenhouse gas reduction and fossil fuel displacement. Consequently, the development of this IBsE engineering branch has a fundamental impact on society as it concerns in large part the future economy. The above discussion on IBsE can be summarized in an illustration as Fig. 1 which demonstrates the complexity of biorefinery and the comprehensiveness of the broad IBsE concept.

3 Theoretical framework of IBsE

A biorefinery is a system that has many attributes, dimensions, subsystems, and various processes within these subsystems. For the purpose of simplifying discussions, a biorefinery system (BrS) described in this paper would include the following subsystems: plant as the raw material, harvesting and transport (HT), pretreatment and hydrolysis (PH) of the feedstock, conversion (CV), product separation (PS), and by-product disposal (BPD). Within a larger scope, a biorefinery system is a subsystem that will interact with other subsystems within the ecosystem (ES).

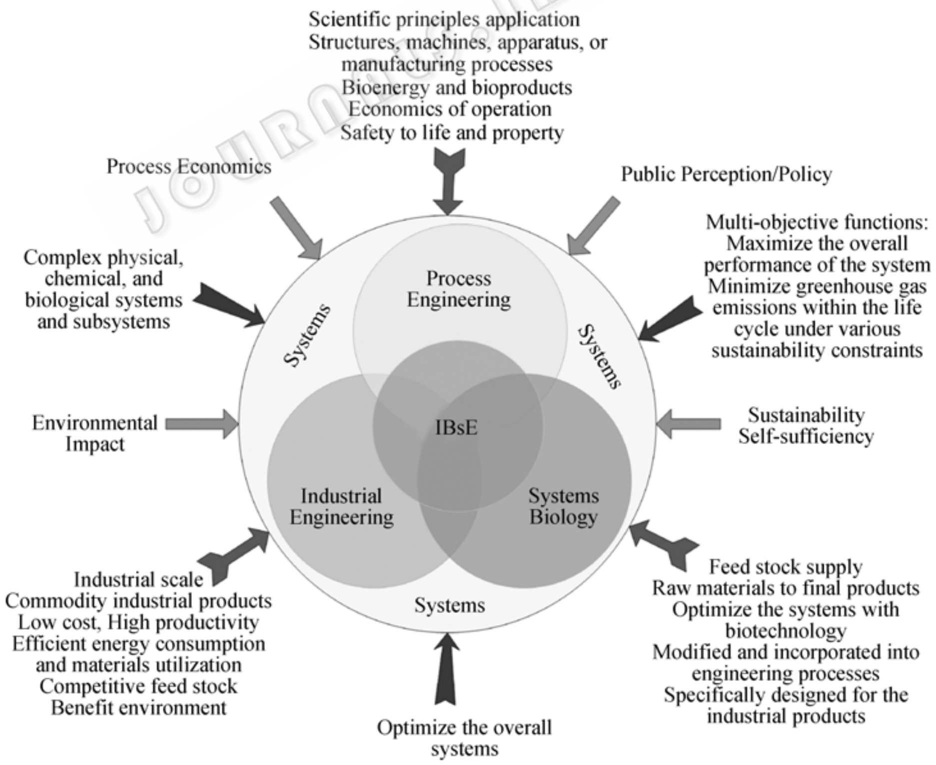

Fig. 1 Structure of Industrial Biosystems Engineering and associated factors of consideration

The theoretical framework of IBsE should cover the major processes occurred within these subsystems and the interaction of biorefinery system with other systems within the ecological system. In addition, as the major driver for the functionality of a biorefinery is the flow of carbon, the theoretical framework of IBsE should be built around the carbon cycle, considering also the energy that powers the carbon flow, and information (signals and data) that controls the carbon cycle. There are two types of energy that are involved in the various processes. The first type is the primary energy contained in the carbon molecule, and the second type is process or secondary energy from other sources used in the processes for maintaining the carbon flow. Therefore, the theoretical framework of IBsE will include carbon pathways that can be altered or impacted by human intervention within the biological, chemical, and physical processes of a biorefinery system. The overarching goal for IBsE study and implementation is the minimization of carbon accumulation in the atmosphere and the maximization of the capability of carbon as an energy carrier via biological processes with the least cost to society and with a minimum input of process or secondary energy. This goal will be accomplished via optimal design and operation, subject to the constraints of sustainability, of its subsystems, each of which consists of many subsystems of different levels. Therefore, mass flow of carbon and energy and information that are associated with carbon transformation across the boundaries of the systems are the major focus of the IBsE. Achieving this goal requires new ways of applying the existing knowledge to engineer and manage these subsystems, as well as development of new science and technologies for identifying and modifying the limiting pathways and rate control steps, or creating new ones. The main subjects include four topics: pathway analysis and design for highest efficiency of carbon utilization, regulation network analysis and design for effectiveness and robustness, system control for reliability, and system optimization for least cost and environmental impact. Embedded in each of the topics is energy consumption minimization.

As a new discipline, IBsE is not a completely new science, rather, it shares a set of basic scientific principles with the existing fields (or disciplines) of science, such as systems biology, bioprocess engineering, and systems engineering, and is supported by fundamental sciences such as chemistry, physics, and biology. Systems biology provides the principles and approaches for optimizing the biocatalysts, bioprocess engineering provides the principles and approaches for optimizing unit operations, and systems engineering provides the principles and approaches for systems integration, management, and environmental impact assessment. The difference between IBsE and these individual disciplines is that IBsE coherently integrates these disciplines as centered on carbon flow and applies these principles and approaches to the subsystems across different levels. In addition, the problem solving (or system design) within the IBsE context often involves more considerations than that of any of the individual disciplines, such as: (1) objective establishment and constraints identification, (2) pathway analysis and design, (3) limiting factor identification, (4) analysis of regulatory mechanisms, (5) pathway alternation, (6) limiting factor modification, and (7) optimization (by evaluating different alternatives for achieving the objective under given constraints). Consequently, the theoretical framework of IBsE includes three aspects: (1) principles and approaches of fundamental and applied sciences providing the theoretical base for all processes occurring in a biorefinery system; (2) methodology of quantification and design that provide the base for targeted analysis, modification/design, and predictions of these processes; and (3) approaches and tools for the evaluation and optimization of multi-level systems of different nature. Table 1 lists the major principles that constitute the core of IBsE theoretical framework and their applications.

The above discussions can be more specifically illustrated by tracking the carbon flow in the major steps of a biorefinery system. This would start with photosynthesis in the plants and the conversion of inorganic carbon to plant material, which is chiefly cellulose, hemicelluloses, lignin, etc. Then these biopolymers are broken down into fermentable sugar via pretreatment and hydrolysis. The sugar is directed into different pathways for conversion to targeted molecules of fuels and other chemicals as the products or by-products. These products are then purified and the by-products will be disposed of.

In each of these major steps of carbon flow, new scientific challenges exist, thus new research and approaches are required within the discipline of IBsE. During the conversion step of inorganic carbon into a biopolymer such as cellulose, the plant is treated as a “factory” (PF) for biological carbon production. The design objective of the PF is to harvest the maximum amount of carbon in the form of a biopolymer that later can be broken down into sugar. Therefore, the purpose of the plant is no longer only for the production of starch (sugar, or lipid), but rather to deliver the maximum amount of potential sugar. The PF will be treated as a subsystem in which the existing pathway will be altered and a new pathway will be created to facilitate organic carbon accumulation.

Table 1 Suggested theoretical framework for IBsE

Principles and methodology	Application	
	Level	Subsystems
Metabolism pathway analysis	Molecular	PF, CF
Regulatory network analysis	Molecular	PF, CF
Signal transduction nodeling	Molecular	PF, CF
Gene network and expression modeling	Molecular	PF, CF
Evolution modeling	Cell	PF, CF
Mass balance	Cell, UO, BrS	PF, CF, PH, CV, PS, BPD, BrS,
Energy balance	Cell, UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
Mass transfer	Cells, UO	PF, CF, PH, CV, PS, BPD
Heat transfer	UO	PH, CV, PS, BPD
Chemical equilibrium	Cell, UO	PF, CF, PH, CV, PS, BPD
Reactions	Cell, UO	PF, CF, PH, CV, PS, BPD
System design and analysis	Cell, UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
System dynamics control	Cell, UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
System optimization	Cell, UO, BrS	HT, PH, CV, PS, BPD, BrS
Multilevel integration/modeling	Cell, UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
Economic evaluation modeling	UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
Alternatives and decision modeling	UO, BrS	PF, CF, HT, PH, CV, PS, BPD, BrS
Systems engineering planning and management	BrS	PF, CF, HT, PH, CV, PS, BPD, BrS

A new regulatory network needs to be developed to control synthesis pathways and gene expressions so that the plant cell system will be so fundamentally different from the existing ones, that upon harvesting, the sugar unit locked within the biopolymers will be much easier to be liberated as sugar with minimum pretreatment and hydrolysis. Such science and technology will be considered as part of the IBsE discipline because they differ from traditional plant science in that they seek to optimize the PF design within the context of overall biorefinery system optimization subjected to the constraints of secondary energy input and land and water resources constraints.

In a biorefinery, the conversion of the carbon from the plant cell material to fuel and chemical molecules is accomplished via biocatalyst, mainly enzyme, either intra cellular or extra cellular. Either way, the enzyme is produced by a microbial cell "factory" (CF). Many new scientific challenges existing within the discipline of IBsE include design and optimization of the CFs so that the CF will produce the desirable molecules at high efficiency, high purity, and high rates. The objective is to create or modify existing pathways to direct the carbon and the energy associated with the carbon to the targeted molecules without severe product inhibition. Again, such science and technology will be considered as part of the IBsE discipline because they differ from traditional microbiology in that they seek to optimize the CF design to ensure stability of the CF under industrial scale applications.

Containing the CFs are reactors that provide the optimal environment for the maximum performance of these CFs, including providing the needed energy supplies (nutrients) to the CFs. Components of the biorefinery system within which a specific process is accomplished call unit operations (UO). In doing so, second energy is required for the reactors to perform their functions. Different from chemical reactors, optimization of these reactors should have full considerations of the physiology of the CF. The difference between IBsE and other engineering disciplines is that processes can only be designed with narrow parameters windows in order for the biocatalyst to function with a reasonable stability.

A unique feature of IBsE is its emphasis on information flow and control. Cells are often controlled by a combination of signaling molecules in addition to typical physical and chemical parameters. The control of UO that has biocatalyst involved can no longer be accomplished with simple chemical or physical parameters. Much more information (data) is needed because the performance of subsystems at different levels will have impacts upon the ultimate system performance. Factors affecting optimization results of the system are not limited to only physical, chemical, biological, and economical, since other elements such as social factors (e.g., policy) also play important roles.

IBsE employs core methodologies in BrS design and analysis. Examples of these methodologies are multiscale modeling and modeling of transport of mass, energy and information cross the boundaries of subsystems. Multiscale analysis was developed as an analytic approach to the study of complex systems that directly addresses the complexity of the system and its relationship to structure and function. This approach provides basic insight into design trade-offs[6]. In a recent review on application of systems biology, the authors[7] suggested that control of bioreaction engineering should be based on regulatory networks and metabolic flux analysis. By means of further experiments, optimization of fermentation processes on several scales was realized on the basis of data correlations and scale-up strategy with multi- variable modulation. By providing a framework describing different spatial and temporal scale of all components, this approach provides a potentially powerful tool for integrating strain improvement and process optimization for industrial biotechnology. Transport processes crossing boundaries of subsystems are critical in IBsE as such processes not only govern the performances of the system, but also affect the interactions among the subsystems, and the their regulation and control. Modeling transport processes associated with biological process possesses great challenges but also provides exciting opportunities. The author's research group has demonstrated some initial results in this area[8].

5 Future perspective

To be recognized as a new engineering discipline, IBsE must provide more added value than merely a collection of the three closely related disciplines (i.e., systems biology, bioprocess engineering, and systems engineering). The contribution of IBsE to the upcoming bioeconomy via BrS can be realized in three areas. First, as a concept, IBsE reminds people of the extent and complexity of a BrS. Second, upon further development, IBsE may provide unique principles and methodologies that are more applicable to BrS than the existing ones. Third, scientific exploration and technical research and development within the context of IBsE may produce more effective technical tools such as mathematical models that are applicable to BrS. There is no doubt that the re-arrangement of whole economies to biological raw materials as a source for increased value requires completely new approaches in research and development. New synergies between biological, physical, chemical and technical sciences have to be elaborated and established[9]. IBsE as discussed in this paper provides a new scientific discipline for the synergies of the related disciplines to occur and flourish in biorefinery process and system analysis and problem solving, with many dimensions including time, space, levels (sub-systems), and scales, both economical and social. Nonetheless, thoughtful considerations and additional discussions are needed in determining the merit to developing IBsE as a new engineering branch, its structure, and how it fits into current educational systems and existing disciplines.

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