THE "THREADS" OF BIOSYSTEMS ENGINEERING

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ABSTRACT. *The core concepts, or threads, of biosystems engineering (BSEN) are variously understood by those within the discipline but have never been unequivocally defined due to BSEN's early stage of development. This makes communication and teaching difficult compared to other well-established engineering disciplines. Biosystems engineering is a field of engineering that integrates engineering science and design with applied biological, environmental, and agricultural sciences. It represents an evolution of the agricultural engineering discipline applied to all living organisms but generally does not include biomedical applications. The key element for the emerging EU biosystems engineering program of studies is to ensure that it offers essential minimum fundamental engineering knowledge and competences. A core curriculum developed by successive Erasmus thematic networks has benchmarked agricultural and biosystems engineering studies in Europe. The common basis of a core curriculum for the discipline across European countries and the U.S. has been defined by an EU-US Atlantis project, but this needs to be taken further by defining the threads that link courses together. This article presents a structured approach to define the threads of BSEN. Definition of the mid-level competences and the associated learning outcomes has been one of the objectives of the EU-US Atlantis project TABE.NET. The mid-level competences and learning outcomes for each of six specializations within BSEN are defined, while the domain-specific knowledge to be acquired for each outcome is proposed. Once the proposed definitions are discussed, modified, and ultimately adopted, these threads will be available for the global development of BSEN.*

Keywords. *Agricultural sciences, Applied biological sciences, Biosystems engineering, Competences, Core curriculum, Engineering science, Environmental sciences, Knowledge, Learning outcomes.*

The core concepts, or threads, of biosystems engineering (BSEN) are variously understood by those within the discipline but have never been unequivocally defined due to the early stage of development of the discipline (Kaleita and Raman, 2012; Fox et al., 2011; He et al., 2007; Tao et al., 2006; Cuello, 2006; Young, 2006; Riley, 2007; Scott, 2006). This complicates communication and consistency in the use and interpretation of terminology and in compatibility of the programs of study compared to other well-established engineering disciplines. A clear definition and recognition of the emerging discipline of biosystems engineering is needed at the European and the international level.

Traditional agricultural engineering is the engineering discipline that applies engineering science and technology to agricultural production and processing. Agricultural engineering combines the disciplines of animal biology, plant biology, and mechanical, civil, electrical, and chemical engineering principles with knowledge of agricultural principles (Hills, 2004; Field and Solie, 2008). Accordingly, the emerging biosystems engineering discipline is a field of engineering that integrates engineering science and design with applied biological, environmental, and agricultural sciences. The field has been described in various ways. In Europe, there is a consensus about the use of BSEN, but variable terms are used across the U.S. (e.g., biological engineering, biological systems engineering, biosystems engineering, and food engineering). Biosystems engineering is synonymous with biological engineering in some institutions in the U.S. In other U.S. institutions, biosystems engineering is considered a broader term that includes biological engineering and agricultural engineering (Johnson, 2012). According to ABET, the program criteria for biological and similarly named engineering programs apply to engineering programs including "biological," "biological systems," "food," and similar modifiers in their titles with the exception of bioengineering and biomedical engineering programs, while the program criteria for agricultural and similarly named engineering programs apply to engineering programs including "agricultural," "forest," and similar modifiers in their titles (ABET, 2011).

In the framework of recent European and international projects (ERABEE, 2010; POMSEBES, 2008) and in the context of the present work, biosystems engineering is con-

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sidered a common descriptor of the relevant programs of study in Europe, the U.S., and internationally. The overarching mission of biosystems engineering (encompassing agricultural, food, and biological engineering) is to "integrate life and engineering for enhancement of complex living systems" (Ting, 2009). It represents an evolution of the agricultural engineering discipline applied to all living organisms but generally not including biomedical applications (Aguado et al., 2011; Ayuga et al., 2010; Briassoulis et al., 2010). BSEN is "the branch of engineering that applies engineering sciences to solve problems involving biological systems" (ERABEE, 2010). The proposed definition of biosystems engineering (ERABEE, 2010) excludes two already established relevant disciplines: biomedical engineering and biotechnology. In particular:

Biomedical engineering is the application of engineering principles and techniques to the medical field. It combines the design and problem-solving skills of engineering with the medical and biological sciences to help improve patient health care and the quality of life of healthy individuals (http://en.wikiversity.org/wiki/Topic:Biomedical_engineering). Biomedical engineering includes a biology background prerequisite and is also referred to as bioengineering (ABET, 2011). Bioengineering, which also encompasses biomedical engineering and medical engineering, is an application of engineering principles and design to challenges in human health and medicine (http://en.wikipedia.org/wiki/Bioengineering).

Biotechnology is not an engineering discipline. Rather, it encompasses techniques that use living organisms or parts of organisms to produce a variety of products (from medicines to industrial enzymes) to improve plants or animals or to develop microorganisms to remove toxics from bodies of water or act as pesticides. It is a multidisciplinary field in which biological systems are developed and/or used for the provision of commercial goods or services (www.ecologydictionary.org/EPA-Terms-of-Environment-Dictionary).

The key objective of the emerging EU BSEN program of studies is to ensure that it offers essential minimum fundamental engineering knowledge and competences (POMSEBES, 2008), along with a minimum fundamental knowledge in biological and agricultural sciences. On this basis, the USAEE (2006) core curriculum, approved by the Fédération Européenne d'Associations Nationales d'Ingénieurs (European Federation of National Engineering Associations; FEANI, 2007) has been used as a benchmark for both agricultural and biosystems engineering studies in Europe and has been adopted by ERABEE. The core curriculum is available at the USAEE website (USAEE, 2007). The EU-US Atlantis project (POMSEBES, 2008) and the Erasmus Network (ERABEE, 2010) have worked toward defining the common basis of the core curriculum for the discipline across the EU and U.S., but this needs to be taken further by defining the threads that link courses together. This would especially help in the U.S. to clearly differentiate biosystems engineering programs of study (as defined above) from programs that focus on traditional agricultural engineering (limited to agricultural applications), from biomedical engineering, and from biotechnology, which is not an engineering discipline.

The first structural step in developing compatible BSEN programs in Europe is definition of the minimum desired core competences. Core competences include: (1) general competences (mostly related to basic sciences like math, physics, chemistry, and informatics); (2) generic competencies of the graduate (related to communication, cooperation, design ability, etc.); and (3) competences related to the engineering and agricultural, food, environmental, and biological sciences part of the BSEN program of studies.

The agricultural sciences part of the core curriculum concerns a corresponding non-engineering component of the traditional programs of study in agricultural engineering. However, agricultural engineering is considered a subset of the emerging BSEN discipline. Similarly, BSEN elements are found in environmental science/engineering and food science/engineering. Thus, the term "biological sciences" as part of a modern BSEN curriculum may be more appropriate. To avoid confusion during the current transition period from the traditional agricultural engineering to the emerging BSEN discipline, and in accordance with the corresponding terminology of the core curriculum of ERABEE, the dual term "agricultural/biological sciences" is used in this article.

The core BSEN curriculum of studies in Europe (ERABEE, 2010) includes core competences but does not include mid-level competences (specialization-dependent competences) related to applied BSEN topics, which are defined by the individual programs of study.

This article presents a structured approach to define the threads of biosystems engineering. Definition of the mid-level learning outcomes and the associated competences has been one of the objectives of the EU-US Atlantis project (TABE.NET, 2012; Wolfe et al., 2011). The mid-level competences and learning outcomes for each of six specializations within BSEN, selected for illustrative purposes, are defined, while the domain-specific knowledge to be acquired for each outcome is also proposed. Once the proposed definitions are adopted, these threads will be available for the global development of BSEN.

METHODOLOGY

This article is not a research paper in terms of scientific research (i.e., hypothesis, experimental design, methods, results, discussion, conclusions), but it is the outcome of a long, systematic, sometimes difficult, yet productive interaction of international academic stakeholders (i.e., faculty and academic staff from Europe and U.S. universities, students, administrators, professional associations, accreditation bodies, the European Commission, and industry) with a wide range of social histories, conditions, practices, and policies. All stakeholders have influenced the development of the emerging discipline of BSEN in Europe and the U.S. This coordinated and systematic interaction over the last ten years is considered to be the research methodology, and the participants, systems, policies, practices, and reported outputs are the materials.

The research tools used during the long development period of the two EU thematic networks and the two EU-US projects include many workshops and surveys resulting in analysis and synthesis documents on various thematic topics relating to BE programs of study. The organization of the outcomes of the previous projects and the updating of the relevant developments presented in this article were undertaken in the framework of the TABE.NET EU-US Atlantis project by a working group devoted to the definition of the threads of biosystems engineering. The work was accomplished through a strong collaboration of members of the academic staff from all of the universities included in the project. In addition, the opinions and comments of students, administrators, professional associations, accreditation bodies, the European Commission, and industry were taken into account, supported by relevant documents of other European projects. The work followed the spiral curriculum concept, which assumes that the development of new competences depends on those previously acquired. This means that mid-level competences are derived by taking into account the core competences for each specialization, and the learning outcomes must be in agreement with the competences. This methodology is based on Bruner's learning theory (Bruner, 1957) for the development of programs of study. The basic elements of the spiral curriculum concept include: authentic engagement from the beginning, thematic curricular organization, periodic revisiting of key topics and themes, increasing complexity with support, and student mastery of learning process.

Terminology

The terminology used in this work follows the corresponding Bologna Process terminology (Adelman, 2009). The two main terms used in this work, "competences" and "learning outcomes," are defined as follows:

"Competences represent a dynamic combination of cognitive and metacognitive skills, knowledge, and understanding; interpersonal, intellectual, and practical skills; and ethical values. Fostering these competences is the object of all educational programs. Competences are developed in all course units and assessed at different stages of a program. Some competences are subject-area related (specific to a field of study), others are generic (common to any degree course). It is normally the case that competence development proceeds in an integrated and cyclical manner throughout a program" (Pagani, 2003).

"Learning outcomes are statements of what a learner is expected to know, understand, and/or be able to demonstrate at the end of a period of learning. They are explicit statements about the outcomes of learning, the results of learning. They are usually defined in terms of a mixture of knowledge, skills, abilities, attitudes, and understanding that an individual will attain as a result of his or her successful engagement in a particular set of higher education experiences. In reality, they represent much more than this. They exemplify a particular methodological approach for the expression and description of the curriculum (modules, units, and qualifications) and levels, cycles, subject benchmark statements, and the 'new style' Bologna qualifications frameworks" (Adam, 2009). The proposed second-generation national qualifications framework in Europe defines learning outcomes by the knowledge acquired, the skills gained, and the competences the students are expected to have upon graduating (Gallavara et al., 2008).

The relationship between learning outcomes and competences is a complex area, and the subject of some debate and considerable confusion: "Competence and competences are used in association with learning outcomes in different countries in a number of ways, hence the problem. Competence can broadly refer to aptitude, proficiency, capability, skills, understanding, etc. A competent person is someone with sufficient skills, knowledge, and capabilities. Some take a narrow view and equate competence just with skills acquired by training. It should be recognized that there is no precise common understanding or use of the term" (Adam, 2009).

According to Adelman (2009), the Bologna Process has been very clear about the conceptual elements with which degrees should be described: learning outcomes, level of challenge, competences, and student workload. A first guidance for answering these questions can best be found in qualification frameworks. "A second key characteristic of a qualification framework is that the description of learning outcomes for a degree clearly indicates how that degree differs from the degree level below it and the degree level above it. The language of the framework accomplishes this end by a ratcheting up of benchmarks. This ratchet principle pervades all of the content challenge and performance statements of [the Bologna Process], and penetrates the credit system as well. This principle is an engine of accountability worth our serious consideration" (Adelman, 2009).

Core Curricula of Biosystems Engineering in Europe

The European perspective of BSEN is very much evolving through the ongoing transition from agricultural engineering programs to more general biologically based BSEN programs (that retain agricultural engineering in their core and also extend to a broader range of bio-based economy-related engineering applications, e.g., bio-based materials, bio-energy, etc.). The learning outcomes in terms of the competences that students should have following the initial stage of their BSEN studies were adopted from the corresponding thematic network (E4-TN, 2003) and incorporated into the core curricula approved by FEANI-EMC (USAEE, 2007). In addition to the general competences, the learning outcomes that compose the fundamental basis of the core curricula during transition from agricultural to biosystems engineering in Europe include fundamental competences and knowledge associated with the engineering part and the biological/agricultural sciences part of the core curricula, respectively. The description of the learning outcomes in this work follows the EUR-ACE framework standards (ENAEE, 2008).

FUNDAMENTAL BASIS OF THE EUROPEAN CORE CURRICULA OF BIOSYSTEMS ENGINEERING

The minimum set of the fundamental competences and knowledge associated with the learning outcomes of the engineering part of the core curricula includes the contents of fundamental engineering subjects that are mandatory for all specializations of agricultural/biosystems engineering. These contents are expressed in terms of the following well-defined and internationally recognized basic engineering courses: (1) engineering graphics and design (CAD), (2) mechanics (statics), (3) strength of materials, (4) mechanics (dynamics), (5) fluid mechanics, (6) applied thermodynamics, (7) heat and mass transfer, (8) electricity and electronics, and (9) system dynamics.

The minimum set of the fundamental competences and knowledge associated with the learning outcomes of the agricultural/biological sciences part of the core curricula is designed to include the required fundamental knowledge of agricultural/biological sciences subjects that are mandatory for all specializations within BSEN. These subjects represent the fundamental knowledge related to agricultural/biological sciences with a broader biological background for the BSEN discipline as compared to the traditional agricultural engineering discipline (this applies to the discipline level and not to the level of individual programs of study that may focus on specific subjects within BSEN). Based on the core curricula of USAEE (2007), the following courses may be considered the basic agricultural/biological courses (five courses may be selected out of six depending on the specializations offered): (1) plant biology, (2) animal biology, (3) introduction to soil science, (4) introduction to agricultural meteorology and micro-meteorology, (5) understanding the environment and its interaction with living organisms, and (6) microbiology.

SPECIALIZATION-SPECIFIC MID-LEVEL LEARNING OUTCOMES OF THE EUROPEAN CORE CURRICULA OF BIOSYSTEMS ENGINEERING

According to the design of the core curriculum in the framework of the USAEE (2007) and ERABEE (2010) thematic networks and the analysis of POMSEBES (2008), apart from the fundamental core learning outcomes and the associated core competencies and basic knowledge, a study program with a uniform structure leading to compatible learning outcomes has to incorporate mid-level competences that refer to the optional specializations part of the core curriculum. The mid-level learning outcomes and the associated mid-level competences and knowledge defined in the core curricula of USAEE (2007) abide to the following typical specializations (or equivalent or combinations of specializations): water resources engineering, mechanical systems and mechanisms, structural systems and materials, information technology and automation, bioprocessing, waste management, and energy supply and management. Following the corresponding scheme of the fundamental basis of the core curricula of agricultural and biosystems engineering in Europe, the mid-level learning outcomes of the core curricula of USAEE (2007) were also defined for the two main constituents of the curricula: the engineering and the biosystems (agricultural/biological sciences) parts of the core curricula.

The mid-level learning outcomes concern the foundation for the development of advanced-level learning outcomes related to various specializations. The associated mid-level competences, knowledge, and skills have to be enriched and strengthened through more specialized or advanced-level competences and knowledge so as to lead to the specific expertise to be acquired. Thus, the complete program of study requires that mid-level competences and knowledge are extended and completed with advanced-level courses in specialized areas of expertise over the second-cycle program of study (according to the European educational system, the second-cycle program of study refers to a two-year MS program, following the first cycle of a three-year BS program) or during the last two years of the integrated two-cycle program of study.

THE "THREADS" OF BIOSYSTEMS ENGINEERING

The mid-level learning outcomes and the associated competences and knowledge, as well as the advanced-level knowledge and skills that define the threads of BSEN, were defined in a structured way in the framework of the EU-US Atlantis project (TABE.NET, 2012). The mid-level competences and the learning outcomes for each of six specializations within BSEN, selected for illustrative purposes, are defined in the following sections, while the domain-specific knowledge to be acquired for each outcome is also proposed. The six selected specializations of BSEN of interest to EU and U.S. programs of study are: bioprocess engineering; bioenergy systems; bio-based materials; biosystems informatics and analysis; structural systems, materials, and environment for biological systems; and water resources engineering.

It should be emphasized that these six specializations were selected under the constraint of space limitations. The objective is to illustrate the way in which a biosystems engineering specialization is developed in terms of learning outcomes and competences as a result of the synthesis of engineering and biosystems components. The six specializations do not represent an exclusive list because traditional specializations, such as mechanical systems and mechanisms, waste management, and others (e.g., food engineering), are not included in the illustrative examples. This work is to be extended to include the learning outcomes of the remaining BSEN specializations in a follow-up publication.

MID-LEVEL COMPETENCES FOR EACH SPECIALIZATION

Bioprocess Engineering

Biosystems mid-level competences for this specialization:

- Acquire in-depth knowledge and understanding of the biological reactions that govern living organisms and their biological, mechanical, and physicochemical characteristics as related to production of value-added bio-based products.
- Acquire comprehensive understanding of the biological mechanisms that govern enzymatic reactions.
- Use acquired knowledge to conceptualize the biochemical

processes that occur in biomass conversion (aerobic digestion, anaerobic digestion, and enzymatic hydrolysis).
- Integrate knowledge from different branches of engineering (e.g., civil, mechanical, electrical, chemical, environmental, etc.) and possibly other domains (e.g., social, economic, political sciences, etc.), as applicable, to understand the complexity related to living organisms' interaction with bioprocess systems and the effects of the related physical, chemical, and biological factors.
- Acquire comprehensive understanding of matters related to the environmental impacts and sustainable production of various bio-based products and their supply chains.

Engineering mid-level competences for this specialization:
- Use the mass and energy balance in each step (unit operation) of a process to design and produce value-added bio-based products and develop new products.
- Evaluate the effect of process parameters in designing an enzyme reactor for the production of various bio-based products.
- Use the knowledge of material flow for a processing plant that produces valued-added bio-based products.
- Apply the processes of isolating enzymes from specific microorganisms for the purpose of producing value-added bio-based products.
- Acquire in-depth knowledge and understanding of application of process kinetics principles to design fermenters and bioreactors.
- Evaluate the different required technologies to separate products from fermentation broths and select the most adequate technology.
- Evaluate the required technologies to effectively utilize genetically engineered microorganisms for bioprocessing.
- Acquire in-depth knowledge and understanding of the techniques, principles, and computational methods used to model and simulate bioprocess operations as related to value-added bio-based product supply chains.

Bioenergy Systems

Biosystems mid-level competences for this specialization:
- Acquire in-depth knowledge and understanding of the biological mechanisms that govern living organisms and their biological, mechanical, and physicochemical characteristics as related to various aspects of energy conversion processes of organic-based materials.
- Use the biochemical energy conversion processes applied to biomass (anaerobic digestion, hydrolysis, esterification and etherification processes, and second-generation biological conversion processes).
- Evaluate matters related to living organisms and apply them in the interaction of organisms with energy systems and the effects of the related physical, chemical, and biological factors.
- Acquire comprehensive understanding of matters related to environmental protection and sustainability as related to various aspects of energy systems and biomass-to-energy supply chains.

Engineering mid-level competences for this specialization:
- Evaluate the typologies and apply criteria for assessment of the organic by-products available in the agricultural, forestry, zootechnical, and agro-industrial sectors that are suitable for energy conversion.
- Acquire in-depth knowledge and understanding of the main physical and chemical characteristics of solid, liquid, and gaseous biofuels that influence their energy conversion and existing standards (pellets, wood chips, bio-oils, biogas and syngas, biodiesel, bioethanol).
- Acquire comprehensive understanding of the lignocellulosic biomass harvesting, loading, transport, storage, drying, chipping, densification, and pretreatment techniques for biomass conversion to energy, including in particular agricultural and forestry mechanization processes, pelletization, torrefaction, hydrotreatments, and agro-industrial by-products pretreatment and handling.
- Evaluate the storage, chemical and mechanical pretreatment, logistic issues, and techniques for energy conversion of fermentable biomass by biochemical processes; acquire comprehensive understanding of biogas upgrading processes to biomethane; acquire comprehensive understanding of digestate and anaerobic digestion wastewater processing techniques.
- Evaluate bio-oil extraction and bio-oil upgrading techniques in order to select and use them for fat-based biomass.
- Acquire in-depth knowledge and understanding of the pretreatment techniques and whole-energy balances for first-generation and second-generation bio-ethanol production processes.
- Acquire comprehensive understanding of the principles of analysis and design of thermochemical biomass-to-energy conversion processes, including combustion, gasification, pyrolysis, FT processes, air emission abatement systems, and related emission level standards.
- Use the principles of thermodynamic cycles for biomass to heat and power conversion, in particular the Otto, Diesel, Bryton, Stirling, and Rankine cycles.
- Apply the basic principles of heat exchange and sizing criteria of biomass boilers.
- Integrate knowledge from optimization techniques for modeling and planning of biomass supply chains and biomass-based energy generation, transmission, and distribution systems.
- Develop in-depth knowledge and understanding of mass-energy balances and GHG balances of biomass-to-energy chains during the life cycle to properly address the sustainability issues of bioenergy.
- Employ acquired knowledge of the energy demands of agricultural, forestry, zootechnical, and agro-industrial processes for heating, cooling, and power generation.
- Evaluate the main energy efficiency and energy-saving measures for their application to the agro-industrial sector.
- Acquire in-depth knowledge and understanding of on-site heating, cooling, and power generation systems specifically suitable for agro-industrial applications.

Bio-based Materials

Biosystems mid-level competences for this specialization:

- Acquire in-depth knowledge and understanding of the science and technology underpinning biomass feedstock production and conversion to bio-based materials.
- Use engineering judgment to select and apply the criteria for identification, classification, and description of bio-based material characteristics and structure-property performance relationships.
- Evaluate and select appropriate fundamentals of the biorefinery concept, as applicable to optimal biomass value recovery toward bio-based material production.
- Acquire comprehensive understanding of quality assessment attributes and benchmarks for bio-based materials and how to achieve them in feedstock-to-product chains.
- Evaluate the life cycle assessment (LCA) protocol in relation to the optimal coupling of biomass feedstock production and recovery, conversion technology and processes, and environmental impact mitigation.

Engineering mid-level competences for this specialization:

- Acquire in-depth understanding of the methods for identification, formulation, analysis, and resolution of engineering technology problems relevant to bio-based material deployment.
- Design and conduct experiments and apply a range of standard and specialized research tools and techniques relevant to bio-based material deployment.
- Select and apply the processing principles of biomass feedstock (including natural fibers) to bio-polymers or fiber-reinforced polymers.
- Critically evaluate the influence of raw material and/or fiber properties on bio-based material characteristics.
- Develop a comprehensive understanding of sensors and rapid assessment techniques for *in situ* and in-process characterization of biomass and biomass fractions toward targeted yield optimization.

Biosystems Informatics and Analysis

Biosystems mid-level competences for this specialization:

- Acquire in-depth understanding of biosystems at the system level.
- Integrate knowledge from different branches of engineering and other domains to select critical information needed for biosystems analysis and integration.
- Acquire a comprehensive understanding of methods for deriving quantitative and qualitative conclusions for questions related to biosystems in agriculture, food, energy, and the environment.
- Critically evaluate data and use engineering judgment to solve biosystems problems at the system level.
- Investigate the application of developments in heuristic and uncertainty analyses.
- Use acquired knowledge and understanding to provide support for decision making.

Engineering mid-level competences for this specialization:

- Apply knowledge and understanding from different branches of engineering and other domains on how to carry out the following eleven tasks of biosystems informatics and analysis:

1. Define the system scope and objectives.
2. Identify the system constraints.
3. Establish the system performance indicators.
4. Conduct system abstraction (transforming from physical space to information space to facilitate analysis).
5. Obtain and organize data and information.
6. Handle uncertain and incomplete information.
7. Develop a system model to represent the system and its operations.
8. Verify and validate the model.
9. Perform modeling studies including scenario simulation and optimization.
10. Draw conclusions about the system.
11. Communicate outcomes (transforming from information space to physical space to support actions).

Structural Systems, Materials, and Environment for Biological Systems

Biosystems mid-level competences for this specialization:

- Acquire in-depth knowledge and understanding of the biological mechanisms that govern living organisms and their biological, mechanical, and physicochemical characteristics as related to various aspects of structural systems and materials (design and analysis of structural systems in support of living organisms, related production, etc.).
- Integrate knowledge from different branches of engineering and other domains to understand the complexity related to living organisms' interaction with controlled or natural micro-environments and the effects of the related physical, chemical, and biological factors.
- Acquire comprehensive understanding of matters related to environmental protection and sustainability as related to various aspects of structural systems and materials.

Engineering mid-level competences for this specialization:

- Acquire in-depth knowledge and understanding of the principles of analysis and design and the behavior of structural systems and components for various conventional and innovative alternative materials designed in support of biosystems-related applications and functions.
- Integrate knowledge from different branches of engineering and other domains on the mechanical and physicochemical characteristics and behavior of conventional and innovative materials required for the design of structural systems.
- Acquire comprehensive understanding of the fundamental mechanical behavior of soils and their mechanical, hydraulic, and physical characteristic with regard to applications in biosystems engineering and as related to the design and analysis of structural systems for biosystems-related applications.
- Apply knowledge and understanding to conceptualize engineering models, systems, and processes through techniques, principles, and computational methods used to model and solve structural systems as related to biological systems.

Water Resources Engineering

Biosystems mid-level competences for this specialization:

- Acquire in-depth knowledge and understanding of the biological mechanisms that govern living organisms and their biological and physicochemical characteristics as related to various aspects of water resources engineering (design and analysis of hydraulic systems in support of living organisms, related production, etc.).
- Acquire comprehensive understanding of the interactions between water and soils and their effect on living organisms.
- Acquire comprehensive understanding of matters related to environmental protection and sustainability as related to various aspects of water resources engineering.
- Integrate knowledge from different branches of engineering and other domains to understand the complexity related to the interactions between water, soils, and contaminants or pollutants as applied to soil erosion or nonpoint-source pollution.

Engineering mid-level competences for this specialization:

- Apply knowledge of analysis and design of water flow in conveyed elements for the design and evaluation of irrigation and drainage systems in support of biological systems.
- Integrate knowledge from different branches of engineering and other domains on the flow of surface water and groundwater, the hydraulic and physical characteristics of soils required for the design of groundwater systems and hydraulic structures, and the development of nonpoint-source pollution models for biosystems-related applications.
- Integrate knowledge from different branches of engineering and other domains on the fundamental mechanical behavior of soils and their mechanical and physical characteristics as related to the design of surface water and groundwater systems and geotechnical structures for biosystems and environment-related applications.
- Apply knowledge and understanding to conceptualize engineering models, systems, and processes through techniques, principles, and computational methods used to model and solve hydrologic and hydraulic systems as related to biological systems and production and environmental protection systems.
- Evaluate and apply the principles of instrumentation and equipment design for the development of water resources engineering systems as related to biological, production, and environmental protection systems.

BASIC-LEVEL LEARNING OUTCOMES FOR ALL SPECIALIZATIONS

The biosystems engineering basic-level learning outcomes are to be achieved as a prerequisite for the mid-level learning outcomes of all specializations.

Acquire basic-level knowledge and understanding of fundamental principles of basic sciences, engineering sciences, biological/agricultural sciences, and humanities and economics:

- LOBS (learning outcome: basic sciences): Biosystems engineering is an engineering program of studies. Accordingly, a major prerequisite is that the students at mid-level must have already acquired a good knowledge in basic sciences and the ability to apply this knowledge to various biosystems engineering specializations, i.e., mathematics, informatics, physics, and chemistry in compliance with the basic sciences learning outcomes related to the general competences adopted from the corresponding E4-TN (E4-TN, 2003) and incorporated in the USAEE and ERABEE core curricula approved by FEANI-EMC.
- LOFES (learning outcome: fundamental engineering sciences): As biosystems engineering is based on several classical engineering disciplines, students must have acquired at the basic level a good knowledge and understanding of the fundamental principles of engineering sciences and the ability to apply this knowledge to biosystems engineering related problems in compliance with the core competences and learning outcomes referring to the fundamental engineering part of a biosystems engineering program of study (refer to the learning outcomes of fundamental engineering part of the USAEE and ERABEE core curricula).
- LOFBS (learning outcome: fundamental biological/agricultural sciences): The key characteristic of biosystems engineering programs of study that distinguishes them from the classical engineering disciplines is that they are built upon the interaction and integration of knowledge and understanding of basic principles of engineering sciences and technology with fundamental knowledge about living organisms, systems, and the environment. As a result, students must have acquired at the basic level a good knowledge and understanding of the fundamental principles of biological/agricultural sciences and the ability to apply this knowledge to biosystems engineering related problems in compliance with the core competences and learning outcomes referring to the fundamental biological/agricultural part of a biosystems engineering program of study (refer to the learning outcomes of fundamental biological/agricultural part of the USAEE and ERABEE core curricula).
- LOHE (learning outcome: humanities and economics): As technological advances, biological production, and the environment are issues of major concern to society with respect to social, economic, environmental, and quality of life aspects, students must have acquired at the basic level a knowledge and understanding of the basic principles of economics and some elements of the humanities as they apply to biosystems engineering related problems, in compliance with the electives-humanities learning outcomes related to the general competences adopted from the corresponding E4-TN (2003) and incorporated in the USAEE and ERABEE core curricula approved by FEANI-EMC.

Acquire basic skills in applying fundamental principles of basic sciences, engineering sciences, biological/agricultural sciences, and humanities and economics:

Using the knowledge and understanding acquired at this basic level, the students learn to apply fundamental principles of basic sciences, engineering sciences, biological/agricultural sciences, and humanities and economics in various biosystems engineering design and analysis problems. This includes learning the basic steps in engineering design following a methodical approach, programming techniques, mathematical and statistical analyses, and measurements using sensors and other devices and equipment.

Learning Outcomes to be Achieved in Each Specialization

Bioprocess Engineering

Mid-level learning outcomes for the specialization "bioprocess systems" in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary for the fields of biomass production, treatment, and conversion for production of value-added bio-based products.

Biosystems mid-level learning outcomes and knowledge to be achieved for this specialization:

- LOB1: Use in-depth knowledge of the physicochemical, mechanical, and biological characteristics of living organisms to critically evaluate the design parameters and process conditions of bioprocessing operations.
- LOB2: Use knowledge and understanding of the types of biochemical reactions (exothermic and endothermic) and reaction kinetics of enzyme-mediated reactions in production of value-added bio-based products and acquire comprehensive understanding of the relationships between microorganisms and their products.
- LOB3: Acquire comprehensive understanding of the process of isolation of enzymes from specific microorganisms in relation to production of value-added bio-based products.
- LOB4: Investigate the basics of bio-waste characteristics, including thermochemical and biological treatment alternatives.
- LOB5: Acquire in-depth knowledge and understanding of the principles of the unit operations and mechanical systems required for conversion of biomaterials to value-added products.
- LOB6: Integrate in-depth knowledge of the factors related to environmental impact and sustainability from production of various bio-based products and their supply chains.

Engineering mid-level learning outcomes and knowledge to be achieved for this specialization:

- LOE1: Design and critically analyze process flow diagrams, using knowledge and understanding to design a system and draw conclusions about the system boundaries for mass and energy balance.
- LOE2: Apply the knowledge gained from thermodynamics and transport phenomena to design various unit operations technologies in processing biological materials.
- LOE3: Use knowledge of the principles of operation and efficiencies of pumps, heat exchangers, conveyors, and size reduction apparatus for bioprocess design applications.
- LOE4: Use knowledge to conceptualize systems and processes in relation to unit operations to achieve a given task in the process of producing value-added bio-based materials.
- LOE5: Integrate the effect of process parameters in designing an enzyme reactor for the production of various bio-based products.
- LOE6: Apply process kinetics principles to design fermenters and bioreactors.
- LOE7: Use creativity to develop computational models to simulate bioprocess operations as related to value-added bio-based product supply chains.

Mid-level skills for specialization "bioprocess engineering" in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying principles of biosystems sciences and engineering sciences for this specialization:

- LOBE1: Integrate knowledge, including biosystems interaction, with technologies associated with other disciplines, based on the principles of sustainability and ecological impacts, toward developing a biorefinery.
- LOBE2: Show in-depth knowledge and understanding of the economic, financial, and commercial considerations related to innovation and marketing of bio-based value-added products.

Bioenergy Systems

Mid-level learning outcomes for the specialization "bioenergy systems" in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary in the fields of (1) biomass production, treatment, conversion for energy production; (2) energy efficiency and rationale use of energy in the agricultural, forestry, and agro-industrial sectors; and (3) use of renewable energy sources in agricultural, agro-industrial, and various biosystems engineering applications.

Biosystems mid-level learning outcomes to be achieved for this specialization:

- LOB1: Critically evaluate the physicochemical, mechanical, and biological characteristics of living organisms to that affect the design parameters, microenvironment, and operation of energy systems.
- LOB2: Integrate in-depth knowledge of the main environmental issues for selecting and using biomass sources for energy production and the main environmental impact of biomass-based energy generation plants.
- LOB3: Investigate the basics of bio-waste characteristics, including biological treatment alternatives for biomass-to-energy generation processes.

Engineering mid-level learning outcomes to be achieved for this specialization:

- LOE1: Integrate in-depth knowledge and understanding of the composition, physical characteristics, and chemical characteristics of organic-based materials suitable for energy production, especially wood, agricultural and forestry residues, agro-industrial by-products, and energy crops.
- LOE2: Use knowledge of thermochemical energy conversion processes and the main thermodynamic energy

cycles for energy conversion of biomasses into heat, cooling, power, and fuels for transport.

- LOE3: Use in-depth knowledge and understanding of the principles of operation and efficiencies of boilers, heat exchangers, engines, turbines, compressors, electrical machines, and adsorption chillers for system design.
- LOE4: Obtain a comprehensive understanding of the applicable techniques and methods in biomass harvesting, loading, transport, drying, storage, densification, and upgrading required in bioenergy chains.
- LOE5: Critically evaluate the techniques used to estimate the biomass energy potentials of a given territory, considering both dedicated energy crops and residual biomass.
- LOE6: Use engineering judgment to work with biomass standards, specifications and classifications, power plant emission standards and regulations, and codes and specifications of energy conversion devices (e.g., boilers, turbines, engines, and fuel cells).

Mid-level skills for the specialization “bioenergy systems” in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying the principles of biosystems sciences and engineering sciences in various biomass-to-energy conversion routes, including biomass production, treatment, transportation, and energy conversion.

- LOBE1: Design and use creativity to optimize the main elements of energy conversion systems fired by biomass fuels for heat, power, and transport fuels.
- LOBE2: Design and optimize the biomass production, harvesting, transport, handling, treatment, and storage steps in order to fulfill the technological, environmental, and economic requirements of bioenergy chains.
- LOBE3: Apply in-depth knowledge of the components of energy conversion systems to conceptualize processes related to air emissions abatement and waste management.
- LOBE4: Integrate in-depth knowledge and understanding of renewable energy sources to design solutions in agricultural and agro-industrial sectors (e.g., wind power, solar thermal, photovoltaic, small hydro, greenhouses integrated and rural buildings integrated renewable energy plants, and heat pumps).

Bio-based Materials

Mid-level learning outcomes for the specialization “bio-based materials” in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary for the field of (1) biomass resource production (including extraction from biological waste streams), (2) the associated conversion and refining processes and technologies, (3) the life cycle environmental impacts of bio-based materials and composites, and (4) the synergistically coupled by-products and co-products, geared to enhancement of entire value chains, in a biorefinery concept.

Bio-based material refers to organic material in which carbon is derived from contemporary biological sources (plant, animal, and aquatic matter). Bio-based products in this context are commercial or industrial products (other than food or feed) that are composed of bio-based material, in whole or significant part.

Biosystems mid-level learning outcomes and knowledge to be achieved for this specialization:

- LOB1: Critically evaluate the concepts of bio-based products and insights at the forefront of bio-based materials production and use, including end-of-life disposal or recycling.
- LOB2: Employ engineering judgment to work with the biorefinery concepts and pertinent extractive steps to design solutions involving the processing of various biomass classes into a spectrum of marketable bioproducts and biofuels.
- LOB3: Integrate in-depth knowledge of the main factors related to environmental impact and sustainability from production of various bio-based products and their supply chains.

Engineering mid-level learning outcomes and knowledge to be achieved for this specialization:

- LOE1: Use in-depth knowledge and understanding of materials science and engineering properties of biological materials to apply them to various design and analysis engineering applications.
- LOE2: Develop a comprehensive understanding of applicable techniques and methods for the measurement of mechanical, physical, chemical, thermal, and electromagnetic properties of biomaterials to critically evaluate, select, and use these properties in pertinent engineering applications.
- LOE3: Integrate knowledge from different branches of engineering and other domains to set resource constraints, health and safety issues, and risk assessment issues associated with feedstock production and processing, conversion, and refining of bio-based materials.
- LOE4: Design and conduct experiments pertaining to identification, classification, characterization, and correlation of structure-property performance through the use of analytical methods, tools, and modeling techniques.
- LOE5: Design and optimize biomaterial recovery process yield and enhance product quality and performance in use.

Mid-level skills for the specialization “bio-based materials” in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying principles of biosystems sciences and engineering sciences for this specialization:

- LOBE1: Integrate knowledge, including biosystems interaction with technologies associated with other disciplines and professions, based on the principles of sustainability, eco-efficiency, industrial ecology, and green chemistry for various design and analysis biosystems engineering applications.
- LOBE2: Use in-depth knowledge and understanding of the economic, financial, institutional, and commercial considerations for innovation and marketing of bio-based materials and products.

Biosystems Informatics and Analysis

Mid-level learning outcomes for the specialization "biosystems informatics and analysis" in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary for the topics of (1) systems-level thinking and understanding; (2) procedural methods for deriving solutions for problems in systems of agriculture, food, energy, and the environment; (3) concepts and numerical techniques of engineering economics and systems modeling, simulation, and optimization; (4) recent developments in heuristic and uncertainty analyses; and (5) formulation and provision of decision support.

Biosystems mid-level learning outcomes to be achieved for this specialization:

- LOB1: Use knowledge and understanding to conceptualize systems, subsystems, and components of bio-based production and processing systems.
- LOB2: Integrate knowledge from different branches of engineering and other domains to identify systems-level issues and problems to be addressed and solved, including: managing and utilizing resources to produce food, feed, fiber, and fuel while ensuring a sustainable natural environment and competitiveness; laborious operations under conditions not conducive to human productivity; advancement of technologies in other industries; increased market demand for product quality; and increased use of information and technologies.
- LOB3: Use creativity to develop new original ideas and methods by integrating systems informatics, modeling, analysis, decision support, design and specification, logistics, model-based control, and concurrent science, engineering, and technology.

Engineering mid-level learning outcomes to be achieved for this specialization:

- LOE1: Critically evaluate and use a systems approach for conducting quantitative analysis and providing engineering solutions for problems in agriculture, food, energy, and the environment.
- LOE2: Integrate knowledge from different branches of engineering and other domains to conceptualize, organize, and execute systems analyses that require engineering and computational methods, including informatics, modeling and analysis, and decision support system.
- LOE3: Employ mathematical, logical, and heuristic reasoning algorithms to derive computational solutions for complex systems level problems.

Mid-level skills for the specialization "biosystems informatics and analysis" in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying principles of biosystems sciences and engineering sciences in analyzing, optimizing, planning, design, management, and operating various biosystems:

- LOBE1: Apply engineering economics principles to evaluate economic viability of the biosystems under consideration, and conduct "what if" studies for various design scenarios.
- LOBE2: Identify key parameters and variables and evaluate the extent of their influence on the overall performance of the biosystem under consideration.
- LOBE3: Use engineering judgment to define the utility and effectiveness of systems informatics and analysis methodology through case studies on contemporary biosystems.
- LOBE4: Formulate and communicate effectively in national and international contexts outcomes and conclusions of systems analysis, as well as feasible engineering solutions, in appropriate forms for targeted audiences.

Structural Systems, Materials, and Environment for Biological Systems

Mid-level learning outcomes for the specialization "structural systems, materials, and environment for biological systems" in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary for the fields of structural systems, materials, and environment in various biosystems engineering applications.

Biosystems mid-level learning outcomes to be achieved for this specialization:

- LOB1: Critically evaluate the physicochemical, mechanical, and biological characteristics of living organisms that affect design parameters and the microenvironment and operation of structural systems.
- LOB2: Integrate in-depth knowledge of the main environmental issues for selecting and using materials and creating sustainable structural systems.
- LOB3: Investigate waste characteristics, biological reactions, and biological treatment alternatives.

Engineering mid-level learning outcomes to be achieved for this specialization:

- LOE1: Integrate in-depth knowledge and understanding of the composition, atomic and crystal structure, and chemical bond types of structural materials, especially concrete, wood, ceramics, polymers, and metallic materials, for various design and analysis applications in biosystems engineering.
- LOE2: Critically evaluate the mechanical and physicochemical characteristics of conventional and innovative alternative materials for use in structural systems.
- LOE3: Use knowledge and understanding to design solutions to soil mechanics related aspects of structural systems.
- LOE4: Apply knowledge and understanding to formulate and solve problems on the actions in structures and the associated loads.
- LOE5: Apply knowledge and understanding to conceptualize engineering models, systems, and processes on the behavior of various structural components and systems by identifying their main elements and developing numerical models to simulate structural systems.
- LOE6: Use engineering judgment to work with structural and materials related codes and specifications.

Mid-level skills for the specialization "structural systems, materials, and environment for biological systems" in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying principles of biosystems sciences and engineering sciences in various biosystems engineering analysis and design applications and projects related to the specialization of structural systems, materials, and environment.

- LOBE1: Use knowledge and understanding to design and optimize the main elements of structural systems by applying the specifications contained in standards.
- LOBE2: Design and conduct analytic, modeling, and experimental investigations to optimize the micro-environment of structural systems.
- LOBE3: Investigate the application of new and emerging technologies and integrate acquired knowledge to design the basic components of structural systems related to waste management systems.

Water Resources Engineering

Mid-level learning outcomes for the specialization "water resources engineering" in biosystems engineering: Acquire domain-specific mid-level knowledge and understanding of biosystems sciences and engineering sciences necessary for the field of water resources engineering in various biosystems engineering applications.

Biosystems mid-level learning outcomes to be achieved for this specialization:

- LOB1: Critically evaluate the physicochemical and biological characteristics of living organisms and the micro-meteorological and micro-environmental parameters for the design parameters, simulation, and operation of hydraulic systems such as irrigation and drainage systems.
- LOB2: Use knowledge an understanding of the relations between soil, water, contaminants or pollutants, and living organisms for the design of hydraulic and hydrological systems.
- LOB3: Integrate in-depth knowledge of the main environmental issues for selecting and using materials and creating sustainable hydraulic systems.
- LOB4: Apply the fundamentals of nonpoint-source pollution to investigate waste characteristics, biological reactions, and biological treatment alternatives.

Engineering mid-level learning outcomes to be achieved for this specialization:

- LOE1: Integrate knowledge of soil physics and soil mechanics to identify physical and hydraulic characteristics for the design of hydraulic and hydrological systems.
- LOE2: Use a comprehensive knowledge and understanding of the principles of water movement in porous media and conveyed elements to design irrigation systems and water facilities.
- LOE3: Critically evaluate the mechanical and physicochemical characteristics of conventional materials used in hydraulic systems to design and construct various elements of the systems.
- LOE4: Use engineering judgment to work with the design and technical characteristics of different irrigation systems and related equipment, such as pumps, valves, and flow-measuring devices.
- LOE5: Evaluate and use the characteristics and principles for the design of water facilities.
- LOE6: Apply knowledge and understanding to conceptualize engineering models, systems, and processes to develop numerical models to simulate hydraulic processes and hydrological systems.
- LOE7: Use knowledge and understanding of the main elements of structural and geotechnical systems to design water facilities and deal with structural and materials related codes and specifications.

Mid-level learning outcomes for the specialization "water resources engineering" in biosystems engineering: Acquire domain-specific mid-level skills in integrating and applying principles of biosystems sciences and engineering sciences in various biosystems engineering analysis and design applications and projects related to the field of water resources engineering:

- LOBE1: Apply geographical information system techniques and numerical modeling to assess environmental risks associated with hydraulic works and diffusion of contaminants and pollution.
- LOBE2: Integrate in-depth knowledge of the principles of water and environmental laws to apply them in the planning, design, and management of water resources.
- LOBE3: Design elements and systems to prevent soil erosion and to restore stream and riparian areas.
- LOBE4: Design the basic components of hydraulic systems as related to waste management systems.

Knowledge Associated with the Learning Outcomes for Each Specialization

The tables in the Appendix contain the knowledge associated with the mid-level learning outcomes defined in the preceding section. Three different levels have been identified for each specialization: basic, intermediate, and advanced. The knowledge associated with level 1 (basic) is assumed to have been achieved through the core curriculum requirements (refer to the core curriculum of USAEE, 2007).

Conclusion

The core concepts, or threads, of biosystems engineering (BSEN) have never been unequivocally defined due to the early stage of development of the discipline. This makes communication and teaching difficult compared to other well-established engineering disciplines.

Biosystems engineering is a field of engineering that integrates engineering science and design with applied biological, environmental, and agricultural sciences. It represents an evolution of the agricultural engineering discipline applied to all living organisms, excluding biomedical applications. Therefore, biosystems engineering is "the branch of engineering that applies engineering sciences to solve problems involving biological systems" (ERABEE, 2010). Biosystems engineering excludes two well-established disciplines: biomedical engineering (with its human biology background prerequisite, also referred to as bioengineering) and biotechnology.

The key objective of the emerging EU biosystems engineering program of study is to ensure that it offers essential minimum fundamental engineering knowledge and competences (POMSEBES, 2008). On this basis, the USAEE (2007) core curriculum, approved by FEANI (2007), has been used as a benchmark for both agricultural and biosystems engineering programs in Europe and has been adopted by ERABEE. The core curriculum is available at the USAEE website (USAEE, 2007). The Atlantis POMSEBES project and Erasmus Network (ERABEE) have worked toward defining the common basis of the core curriculum for the discipline across the Atlantic, but this needs to be taken further by defining the threads that link courses together. This would be especially helpful in the U.S. to clearly differentiate biosystems engineering programs of study from other programs that are actually focused on agricultural engineering or biomedical engineering.

The first structural step in developing compatible programs for the biosystems engineering discipline in Europe is definition of the minimum desired competences comprising the biosystems engineering core competences. Core competences concern both general competences (i.e., mostly related to basic sciences and to generic competencies related to communication, cooperation, design ability, etc.) and the competences related to the engineering and agricultural/biological sciences part of the biosystems engineering program of studies.

The core curriculum of biosystems engineering studies in Europe (ERABEE) includes core competences but does not include mid-level, specialization-dependent competences related to applied biosystems engineering topics, which are defined by the individual programs of study.

This article presents a structured approach to define the threads of biosystems engineering. The definition of the mid-level competences and the associated learning outcomes has been one of the objectives of the Atlantis program TABE.NET. The mid-level competences and the learning outcomes for each of six selected specializations within biosystems engineering are defined, while the domain-specific knowledge to be acquired for each outcome is also proposed. Once the proposed definitions are adopted, these threads will be available for the global development of biosystems engineering.

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Appendix

Knowledge Associated with the Learning Outcomes Defined for Each Specialization

The following tables specify the knowledge associated with the learning outcomes defined in this article. Three different levels are identified for each specialization: basic, intermediate and advanced. The knowledge associated with level 1 (basic) is assumed to have been achieved through the core curriculum requirements.

Table 1. Specialization: Bioprocess engineering.

Learning Outcome[a]	Knowledge for Each Learning Outcome: Level 2 (Intermediate)	Knowledge for Each Learning Outcome: Level 3 (Advanced)
LOB1: Use in-depth knowledge of the physico-chemical, mechanical, and biological characteristics of living organisms to critically evaluate the design parameters and process conditions of bioprocessing operations.	1. Biological growth characteristics, specifically for microorganisms. 2. Role of enzymes in a reaction. 3. Ways to inhibit or control enzymes in a reaction.	1. Metabolic pathways in living organisms, specifically for microorganisms. 2. Characteristics of enzymes and microorganisms. 3. Process of isolation of enzymes from specific microorganisms.
LOB2: Use knowledge and understanding of types of biochemical reactions (exothermic and endothermic) and reaction kinetics of enzyme-mediated reactions in production of value-added bio-based products and acquire comprehensive understanding of relationships between micro-organisms and their products.	1. Chemical reactions and reaction rate theory. 2. Enzyme catalysis reactions. 3. The role of enzymes in biochemical reactions.	1. Relationships between microorganisms and their products. 2. Biochemical reactions in living systems. 3. Products from biochemical reactions in living systems.
LOB3: Acquire comprehensive understanding of the process of isolation of enzymes from specific microorganisms in relation to production of value-added bio-based products.	1. Relationships between enzymes and their products. 2. Biochemical processes involving enzymes in living systems.	1. Relationships between microorganisms and their products. 2. Processes of extraction and isolation of enzymes from living systems (microorganisms, fungi, and plant and animal tissues.
LOB4: Investigate the basics of bio-waste characteristics, including thermochemical and biological treatment alternatives.	1. By-products from biochemical reactions. 2. Biological methods to treat wastes from bio-process operations.	1. Biochemical reactions in biological systems used to treat biowaste. 2. Biological treatment systems to convert biowaste into alternate value products.
LOB5: Acquire in-depth knowledge and understanding of the principles of unit operations and mechanical systems required for conversion of biomaterials to value-added products.	1. Energy and mass balance. 2. Transfer processes of energy, mass, and momentum. 3. Fluid dynamics.	1. Design requirements for handling biomass. 2. Design requirements for heat exchangers for biological materials. 3. Basic principles of unit operations for processing biomaterials.
LOB6: Integrate in-depth knowledge of factors related to environmental impact and sustainability from production of various bio-based products and their supply chains.	1. Environmental implications from bio-based industries. 2. Economic issues related to environmental impact from bio-waste management.	1. Regulatory (e.g., OSHA, GMP, HACCP), environmental, and ethical issues and considerations. 2. Life cycle assessment of bio-based products. 3. Sustainable solutions for value-added bioproducts and their supply chains.

Table 1. Specialization: Bioprocess engineering.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOE1: Design and critically analyze process flow diagrams, using knowledge and understanding to design a system and draw conclusions about the system boundaries for mass and energy balance.	1. Define what a process is. 2. Draw simple process flowcharts. 3. Differentiate between a unit operation and a process. 4. Identify the building blocks (unit operations) of a process.	1. Draw block diagrams for a processing plant. 2. Design a plant layout for processing. 3. Identify major process units in a processing plant. 4. Describe material flow through a processing plant. 5. Perform advanced mass balance for unit operations. 6. Optimize the flow of the material through the plant.
LOE2: Apply the knowledge gained from thermodynamics and transport phenomena to design various unit operations technologies in processing biological materials.	1. Components and modes of operation of a bioreactor. 2. Functions of a bioreactor. 3. Mass and energy balance for unit operations.	1. Advanced mass balance for unit operations. 2. Energy balance for unit operations.
LOE3: Use knowledge of the principles of operation and efficiencies of pumps, heat exchangers, conveyors, and size-reduction apparatus for bioprocess design applications.	1. Components and operation of mechanical systems. 2. Components of heat exchangers and various unit operations.	1. Design mechanical systems for handling biomass. 2. Design heat exchangers for biological materials. 3. Design unit operations for processing biomaterials.
LOE4: Use knowledge to conceptualize systems and processes in relation to unit operation steps to achieve a given task in the process of producing value-added bio-based materials.	1. Principles and applications of various unit operations. 2. Mass and energy balance for unit operations. 3. The economics of unit operations.	1. Design a complete process. 2. Identify appropriate unit operations for a task. 3. Design a unit operation step to achieve a task. 4. Perform economic analysis for processes.
LOE5: Integrate the effect of process parameters in designing an enzyme reactor for the production of various bio-based products.	1. Process parameters in bioreactors. 2. The effect of process parameters on bioreactor output. 3. The role of process parameters on production of selected bioproducts.	1. Optimize the bioreactor for maximum performance. 2. Optimize the bioreactor for maximum production of bio-based products. 3. Select the process parameters for process optimization. 4. Analyze the effect of process parameters on bioreactor performance.
LOE6: Apply process kinetics principles to design fermenters and bioreactors.	1. Types of reactions and reaction rate. 2. Role of enzymes in a reaction.	1. Modes of bioreactor operation. 2. Impact of reaction parameters on microbial systems. 3. Monitor reaction parameters effectively.
LOE7: Use creativity to develop computational models to simulate bioprocess operations as related to value-added bio-based product supply chains.	1. Simulation tools to simulate simple bioprocess operations. 2. Conduct "what if" scenarios using simulation models.	1. Processes and process control using software such as SuperPro.
LOBE1. Integrate knowledge, including biosystems interaction with technologies associated with other disciplines, based on the principles of sustainability and ecological impact toward developing a biorefinery.	1. Sustainability fundamentals. 2. Bioremediation, biodegradation, and biological waste management fundamentals. 3. Roles of microorganisms and plants in bioprocessing. 4. Strategies and technologies for waste minimization.	1. Bioprocessing case studies, e.g., biopolymers, biochemicals, biofuel, pharmaceuticals, food and feed supplements, etc. 2. Metabolic engineering applications for improved bioprocessing operations.
LOBE2: Show in-depth knowledge and understanding of the economic, financial, and commercial considerations related to innovation and marketing of bio-based value-added products.	1. Marketing functions related to innovative and emerging bioprocessing industries. 2. Lead market initiatives in sustainable production of bioproducts. 3. Product validation, quality management, and regulatory issues. 4. Fundamentals of cross-functional team-based approach to problem solving.	1. Strategic process planning, and environmental and marketing management. 2. Design of planning tools for bioproduct supply chain management, optimization of manufacturing processes, and general process modeling for continuous improvement. 3. Quantitative methods for decision making based on current market situation and future demand forecasts.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.

Table 2. Specialization: Bioenergy systems.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOB1: Critically evaluate the physicochemical, mechanical, and biological characteristics of living organisms that affect the design parameters, microenvironment, and operation of energy systems.	1. Principles of animal physiology and nutrition. 2. Systems of animal husbandry and fish farming, including their main constraints and requirements. 3. Micro-environmental parameters to be met by various animal and fish production and housing systems. 4. Physiological functions of different crops and other plants and biological systems (e.g., mushrooms, algae, and other micro-organisms) in protected production systems. 5. Management principles and micro-environmental requirements in relation to protected crop and other biosystems production. 6. Principles for biosystems nutrition.	1. Types of animal production, components, inputs, and organization of enterprises for cattle, sheep, pigs, poultry, rabbits, etc. 2. Sources of losses and quality and productivity problems arising with the management of animals and measures to overcome them. 3. Components, inputs, and organization of protected crop production systems. 4. Biosystems production systems for algae and other microorganisms. 5. Sources of damages, quality, and productivity losses and problems arising with the management of crops, fruits, horticultural products, and other biosystems and measures to overcome them.
LOB2: Integrate in-depth knowledge of the main environmental issues for selecting and using biomass sources for energy production and the main environmental impact of biomass-based energy generation plants.	1. Characteristics of environmental components (air, soil, water, cultural, or socioeconomic) in relation to the impacts derived from activities related to energy conversion of biomass. 2. Environmental impact assessment process and the main evaluation methods. 3. Life cycle assessment of bioenergy supply chains and energy conversion systems. 4. Fundamentals of the main impacts: noise, water, air pollution, biological, cultural, land use, and landscape.	1. Design an impact assessment technique. 2. Calculate and assess pollutant loading on the environment. 3. Evaluate the socioeconomic impact on the environment of energy generation systems and energy demand in agro-industrial and agricultural sectors. 4. Design bioenergy pretreatment, processing, and conversion plans to minimize the environmental impacts and propose measures to correct the impacts generated.
LOB3: Investigate the basics of bio-waste characteristics, including biological treatment alternatives for biomass-to-energy conversion processes.	1. Characteristics associated with waste materials derived from animal and plant management and from the agro-industrial sector. 2. Sources and categories of waste materials. 3. Legal framework of environmental issues, including general laws and major legislation related to waste management. 4. Characteristics of waste management technology options, e.g., biological treatment, composting, recycling, and energy recovery. 5. Physicochemical processes associated with the management of waste materials and the associated biological reactions.	1. Microbiology and biochemistry of liquid wastes. 2. Contamination of soil and water due to residues: processes, consequences, and strategies to be adopted. 3. Design a waste management plan in the framework of a project or activity. 4. Analysis of energy conversion options of biodegradable wastes from the agricultural, agro-industrial, and zootechnical sectors.
LOE1: Integrate in-depth knowledge and understanding of the composition, physical characteristics, and chemical characteristics of organic-based materials suitable for energy production, especially wood, agricultural and forestry residues, agro-industrial by-products, and energy crops.	1. Low heating values of various typologies of biomasses. 2. Bulk density and energy density. 3. Ash contents. 4. Influence of biomass physical and chemical parameters in storage. 5. Metals in biomass: typologies and influence in energy conversion processes. 6. BOD and COD of fermentable biomasses. 7. Chemical and physical parameters of biofuels from biomass processing. 8. Bioliquids: viscosity, oleic acid contents, chemical and physical parameters.	1. Techniques to measure ash melting point. 2. Fouling and slugging problems in boilers due to low melting point of biomass ash. 3. Bonding processes in pelletization, effect of natural binders, lignin behavior at various temperatures, and moisture contents in pelletization. 4. Techniques to measure biogas yield in anaerobic digestion processes: batch tests. 5. Acidity of bio-oils and effects of storage on bio-oil quality.
LOE2: Use knowledge of thermochemical energy conversion processes and the main thermodynamic energy cycles for energy conversion of biomasses into heat, cool, power, and fuels for transport.	1. Principles of thermodynamics. 2. Thermal cycles. 3. Principles of combustion, gasification, and pyrolysis processes. 4. Principles of anaerobic digestion. 5. Principles of hydrolysis, esterification, and distillation.	1. Use of biofuels in transport: technologies and biofuel upgrading processes. 2. Use of biogas in transport: upgrading technologies and environmental balances. 3. Enzymatic hydrolysis of lignocellulosic biomass. 4. Second-generation processes for lignocellulosic biomass: FT processes. 5. Second-generation processes for bioliquids: hydrogenation of bio-oils. 6. Dark fermentation and anaerobic fuel cells. 7. Biorefinery concept and: biochemical and thermochemical bioenergy pathways.
LOE3: Use in-depth knowledge and understanding of the principles of operation and efficiencies of boilers, heat exchangers, engines, turbines, compressors, electrical machines, and adsorption chillers for system design.	1. Principles of boilers, heat exchangers, heat distribution systems, and district heating. 2. Adsorption chillers technologies. 3. Principles of thermal machines, internal combustion engines, and gas turbines. 4. Principles of electrical machines.	1. Joule cycles: small and large scale turbines, typology of suitable biofuels, dual-fueling and cofiring options, cogeneration options, externally fired gas turbines, and environmental impacts. 2. Rankine cycles: efficiencies and technologies with steam and organic fluids, environmental impacts.

Table 2. Specialization: Bioenergy systems.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
		3. Internal combustion engines: spark ignition and diesel cycles, dual-fueling options, air emission levels, noise and other environmental impacts, efficiencies vs. size vs. fuel options, cogeneration configurations. 4. Fuel cells for biofuels and biological fuel cells.
LOE4: Obtain a comprehensive understanding of applicable techniques and methods in biomass harvesting, loading, transport, drying, storage, densification, and upgrading techniques required in bioenergy chains.	1. Principles of biomass drying processes. 2. Harvesting, loading, and transport techniques. 3. Storage techniques as a function of biomass typology. 4. Chipping and grinding modes. 5. Densification techniques	1. Costs assessment and environmental assessment of biomass logistics: transport and storage. 2. Costs and environmental impact of biomass chipping and drying: on site vs. centralized options. 3. Biomass torrefaction. 4. Hydrotreatment processes. 5. Biomass mechanical and chemical pretreatments for anaerobic digestion processes.
LOE5: Critically evaluate the techniques used to estimate the biomass energy potentials of a given territory, considering both dedicated energy crops and residual biomass.	1. Energy crop yield and influencing factors. 2. Biomass energy potentials estimates: techniques and classifications. 3. Seasonality of biomass availability and influence on bioenergy routes. 4. GIS-aided tools for potential estimates. 5. Alternative uses of biomass and cost-supply curves.	1. Energy crops potential estimates: short-rotation forestry. 2. Energy crops potential estimates: annual herbaceous crops. 3. Energy crops potential estimates: silage crops. 4. Energy crops potential estimates: oleagineous crops. 5. Case studies of agricultural residues estimates. 6. Case studies of forestry residues estimates. 7. Case studies of agro-industrial residues estimates.
LOE6: Use engineering judgment to work with biomass standards, specifications and classifications, power plant emission standards and regulations, codes, and specifications of energy conversion devices (boilers, turbines, engines, and fuel cells).	1. Introduction to technical standards for biomass classification. 2. Introduction to standards for biomass physical and chemical measurements. 3. Standards for energy conversion processes.	1. Specific standards for biogas: threads and trends. 2. Specific standards for bio-liquids: sustainability issues and LCA implications at a global level. 3. Specific standards for solid biomass: standardization of pellets, torrefied pellets, and wood chips.
LOBE1: Design and use creativity to optimize the main elements of energy conversion systems fired by biomass fuels for heat, power, and transport fuels.	1. Design thermal biomass plants components according to the corresponding design codes. 2. Design digester and biogas treatment and upgrading according to the corresponding design codes. 3. Design electrical machines for biomass power plants and basic elements of grid connection rules.	1. Optimize the design of storage, boiler, and heat exchanger size on the basis of energy demand. 2. Optimize diameters, insulation level, temperature, and pressure of district heating networks on the basis of length, energy demand, and techno-economic parameters. 3. Optimize the moisture content of biomass for energy conversion under various constraints and techno-economic parameters. 4. Optimize the size of biomass CHP plants and boilers on the basis of techno-economic parameters and energy demand. 5. Operational issues of CHP plants: baseload vs. peak vs. on-off operations.
LOBE2: Design and optimize the biomass production, harvesting, transport, handling, treatment, and storage steps to fulfill the technological, environmental, and economic requirements of bioenergy chains.	1. Optimal sizing of biomass conversion plants on the basis of supply chain transport costs, economies of scale, efficiency dynamics, and end uses. 2. Decoupling of biomass processing and biofuel energy conversion: opportunities and case studies.	1. MILP tools for optimal location and sizing of bioenergy conversion plants. 2. Optimal selection of biomass transport and storage modes by MILP tools.
LOBE3: Apply in-depth knowledge of the components of energy conversion systems to conceptualize processes related to air emissions abatement and waste management.	1. Air emissions abatement systems for biomass boilers. 2. Air emissions abatement systems for engines and turbines.	1. Air emissions regulations and costs assessment of optimal air emission abatement levels.
LOBE4: Integrate in-depth knowledge and understanding of renewable energy sources to design solutions in the agricultural and agro-industrial sectors (wind power, solar thermal, photovoltaic, small hydro, greenhouses integrated and rural buildings integrated renewable energy plants, and heat pumps).	1. Wind energy. 2. Solar thermal. 3. Photovoltaics. 4. Small hydro plants. 5. Energy efficiency in rural buildings. 6. Energy efficiency in agro-industrial sector.	1. Integration of solar thermal and biomass boilers. 2. Integration of bioenergy systems and heat pumps. 3. Energy efficiency and bioenergy routes.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.

Table 3. Specialization: Bio-based materials.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOB1: Critically evaluate the concepts of bio-based products and insights at the forefront of bio-based materials production and use, including end-of-life disposal or recycling.	1. Definition and classifications of bio-based materials. 2. Technologies for primary feedstock processing and feedstock physical properties influencing biomaterial production processes. 3. Process monitoring, control, and biomaterial yield optimization. 4. Biomaterial co-products and byproducts of primary biomass processing to biofuel and biochemicals. 5. Commercial bio-based and partly bio-based material formulations.	1. Biomaterial physiochemical processes and interaction with living organisms. 2. Enzyme-catalyzed oxidation reactions and biodegradation rates. 3. Understanding biodegradability characteristic of materials, including conditions for biodegradation. 4. Standardized tests for biodegradability: readily biodegradable, inherently biodegradable, and non-biodegradable. 5. Standards for sustainable bio-based materials and products.
LOB2: Employ engineering judgment to work with biorefinery concepts and pertinent extractive steps to design solutions involving the processing of various biomass classes into a spectrum of marketable bioproducts and biofuels.	1. Selective separation processes for the isolation of useful fractions from primary feedstock. 2. Processing water footprint, energy efficiency, environmental impacts (health, toxicity, safety, and risk issues). 3. Energy recovery from unit processes and material process waste stream, hence minimization of the consumption of non-renewable energy resources.	1. Process optimization for multiple product recovery from biomass at reduced environmental burden, hence achieving sustainability of the bio-based economy (e.g., biopolymer, biopolymer fractions, lipids, phytochemical extraction, etc.). 2. Process chain integration to include carbon capture and storage, and phycoremediation of process wastewaters.
LOB3: Integrate in-depth knowledge of the main factors related to environmental impact and sustainability from production of various bio-based products and their supply chains.	1. Life cycle assessment fundamentals. 2. Environmental regulations and guidelines governing life cycle process emissions. 3. Green chemistry concept for environmentally friendly design of chemical processes and products.	1. Life cycle assessment of bio-based material production process pathways: bioresource, material production, manufacturing, and use to end-of-life treatment. 2. Identification and evaluation of latent environmental impact factors, e.g., global warming, ozone depletion, acidification, eutrophication, resource depletion, toxicity, smog formation, etc. 3. Benchmarking of product or process performance to limit shift of environmental burdens between unit operations in the processing steps.
LOE1: Use in-depth knowledge and understanding of materials science and engineering properties of biological materials to apply them to various design and analysis engineering applications.	1. Relationships between composition, structure, and properties of biomaterials, including food plant and animal tissues. 2. *In situ* and non-destructive material characterization techniques. 3. Properties of biomaterials, smart materials, and eco-materials, including unique attributes and performance characteristics.	1. Modeling of properties and applications of biomaterials and composites. 2. Design, development, and maintenance of knowledge base pertaining to new and improved biomaterials.
LOE2: Develop a comprehensive understanding of applicable techniques and methods for the measurement of mechanical, physical, chemical, thermal, and electromagnetic properties of biomaterials to critically evaluate, select, and use these properties in pertinent engineering applications.	1. Composition, structure, and properties of industrial, biological, and environmental materials and processes. 2. Range, significance, and limitations of material variability. 3. Use of sensors and rapid assessment techniques for resource characterization and yield optimization.	1. Develop tools and reference measurement procedures, reference materials, critically evaluated data, and best practice guides for measurement quality assurance. 2. Design and develop sensors and rapid assessment techniques for *in situ* characterization of biomass resources and useful byproducts for optimization of desirable characteristics. 3. Biomaterial composites property optimization.
LOE3: Integrate knowledge from different engineering branches of engineering and other domains to set resource constraints, health and safety issues, and risk assessment issues associated with feedstock production and processing, conversion, and refining of bio-based materials.	1. Environmental and sustainability limitations. 2. Chemical reactions and exposure limits of humans and other organisms to toxicity process materials and emissions. 3. Active codes of practice and industry standards, and the need for their application to bio-based materials.	1. Bioresource mapping for quantity and utilization options. 2. Industrial chemical reactions in biomaterials processing and by-products extraction. 3. Design of material resource conversion process monitoring and control.
LOE4: Design and conduct experiments pertaining to identification, classification, characterization, and correlation of structure-property performance through the use of analytical methods, tools, and modeling techniques.	1. Bio-based content verification. 2. Biodegradability. 3. Environmental performance criteria. 4. Identification and evaluation of ethical issues and concerns.	1. Unit operations of biomaterial and bioproduct engineering and manufacture. 2. Heat and mass transfer as applied to biomaterial processing. 3. Industrial research with biomaterials and composites.
LOE5: Design and optimize biomaterial recovery process yield, and enhance product quality and performance in use.	1. Needs and range of applications of biomaterials in packaging, structural material, energy, etc. 2. Evaluation of quality and performance of biomaterial-based products. 3. Nanotechnology and nanomanufacture as applied to biomaterials.	1. Purification, modification, and performance enhancement of biomaterials. 2. Development of technologies for enhancing biodegradability and for eco-efficient recycling or disposal. 3. Design of molecular and nano-scale manipulation technologies of biopolymer structures. 4. Nanotechnology standards for biomaterial characterization for health (occupational exposure),

Table 3. Specialization: Bio-based materials.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
		safety (toxicity or hazard potential), and environmental performance (toxicological screening).
LOBE1: Integrate knowledge, including biosystems interaction with technologies associated with other disciplines and professions, based on the principles of sustainability, eco-efficiency, industrial ecology, and green chemistry for various design and analysis biosystems engineering applications.	1. Sustainability fundamentals. 2. Bioremediation, biodegradation, biotransformation, and biological waste treatment. 3. Roles of tissue culture and genetic engineering in biomaterial synthesis. 4. Strategies and technologies for waste prevention and minimization of process energy requirement.	1. Environmental biotechnology research. 2. Biomaterial production case studies, e.g., biodegradable polymer, biopesticide, biofuel generation, and biosyntheses of enzymatic detergents, surfactants, biological dyes, food and feed supplements, etc. 3. Synthesis methods and applications for designer biomaterials with unique physical properties.
LOBE2: Use in-depth knowledge and understanding of the economic, financial, institutional, and commercial considerations for innovation and marketing of bio-based materials and products.	1. Marketing functions related to innovative and emerging biomaterials and bio-based products industries. 2. Lead market initiatives in sustainable construction, protective textiles, mulch for agriculture, recycling (waste bags + shopping bags), renewable energy, etc. 3. Product validation, quality management, and regulatory issues. 4. Fundamentals of cross-functional team-based approach to problem solving.	1. Strategic product planning and environmental marketing management. 2. Design of planning tools for biomaterial supply chain management, optimization of manufacturing processes, and general process modeling for continuous improvement. 3. Quantitative methods for decision making based on current market situation and future demand forecasts.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.

Table 4. Specialization: Biosystems informatics and analysis.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOB1: Use knowledge and understanding to conceptualize systems, subsystems, and components of bio-based production and processing systems.	1. Boundaries and components of a system. 2. Underlying concept of system abstraction. 3. Tasks, processes, and operations within bio-based production systems. 4. External factors influencing bio-based systems.	1. Graphical representations of systems. 2. Object-oriented approach to system abstraction. 3. Quantitative and qualitative descriptions of tasks, processes, and operations. 4. Interfaces of the system with its external environment.
LOB2: Integrate knowledge from branches of engineering and other domains to identify systems-level issues and problems to be addressed and solved, including managing and utilizing resources to produce food, feed, fiber, and fuel while ensuring a sustainable natural environment and competitiveness; laborious operations under conditions not conducive to human productivity; advancement of technologies in other industries; increased market demand for product quality; and increased use of information and technologies.	1. The concept of local versus global system issues. 2. Objectives of the bio-based system under study. 3. Measurement of system performance toward achieving its goals. 4. Data and information required for system analysis. 5. Methods for data and information processing.	1. Criticality of each system objective. 2. System constraints. 3. Reliability of data and information. 4. Limitation of data and information processing algorithms and methods. 5. Unique characteristics and practical expectations of bio-based systems.
LOB3: Use creativity to develop new original ideas and methods by integrating systems informatics, modeling, analysis, decision support, design and specification, logistics, model-based control, and concurrent science, engineering, and technology.	1. System descriptors in a form useful for analysis, design, integration, and operation. 2. Interrelationships of tasks, processes, and operations. 3. Analysis in physical space versus informational space. 4. Models that represent the real bio-based systems. 5. Mathematical models versus physical models.	1. Concept of sufficient and complete set of system descriptors. 2. Correlation of component interactions using mathematical, logical, relational, and heuristic methods. 3. Parameters and variables, as well as their relationships (e.g., equations and formulas). 4. Concurrency of bio-based systems in their analyses and operations. 5. Information environment for decision support.
LOE1: Critically evaluate and use systems approach for conducting quantitative analysis and providing engineering solutions for problems in agriculture, food, energy, and the environment.	1. Critical problems in the systems of agriculture, food, energy, and the environment. 2. Steps involved in systems analysis. 3. Concepts and principles of problem solving.	1. Typical cases that are representatives of current systems of agriculture, food, energy, and the environment. 2. Apply computational methods to carry out systems analysis steps. 3. Apply engineering analysis and design methods to solving system-level problems.
LOE2: Integrate knowledge from different branches of engineering and other domains to conceptualize, organize, and execute systems analyses that require strong engineering and computational methods, including informatics, modeling and analysis, and decision support systems.	1. Mathematical models that contains descriptors and their relationships of systems. 2. Digital computing techniques for solving equations. 3. Concept of decision support and its theoretical foundations.	1. Develop computerized mathematical models. 2. Apply computer models to simulate system performance and possibly carry out optimization algorithms. 3. Develop decision support tools and contents for use by decision makers.
LOE3: Employ mathematical, logical, and heuristic reasoning algorithms to derive computational solutions for complex systems-level problems.	1. Numerical methods for solving equations. 2. Methods for handling incomplete and uncertain data and information. 3. The concept of conducting "experiments" using computer models.	1. Conduct stochastic simulation. 2. Develop artificial neural networks. 3. Perform fuzzy reasoning. 4. Perform optimization using genetic algorithms.
LOBE1: Apply engineering economics principles to evaluate economic viability of the biosystems under consideration and conduct "what if" studies for various design scenarios.	1. Critical problems in the systems of agriculture, food, energy, and the environment. 2. Steps involved in systems analysis. 3. Concepts and principles of problem solving.	1. Typical cases that are representatives of current systems of agriculture, food, energy, and the environment. 2. Apply computational methods to carry out systems analysis steps. 3. Apply engineering analysis and design methods to solving system-level problems.
LOBE2: Identify key parameters and variables and evaluate the extent of their influence on the overall performance of the biosystems under consideration.	1. Mathematical models that contains descriptors and their relationships of systems. 2. Digital computing techniques for solving equations. 3. Decision support and its theoretical foundations.	1. Develop computerized mathematical models. 2. Apply computer models to simulate system performance and possibly carry out optimization algorithms. 3. Develop decision support tools and contents for use by decision makers.
LOBE3: Use engineering judgment to define the utility and effectiveness of systems informatics and analysis methodology through case studies of contemporary biosystems.	1. Numerical methods for solving equations. 2. Methods for handling incomplete and uncertain data and information. 3. The concept of conducting "experiments" using computer models.	1. Conduct stochastic simulation. 2. Develop artificial neural networks. 3. Perform fuzzy reasoning. 4. Perform optimization using genetic algorithms.
LOBE4: Formulate and communicate effectively in national and international contexts the outcomes and conclusions of systems analysis, as well as feasible engineering solutions, in appropriate forms for targeted audiences.	1. Principles for communicating outcomes of systems analysis.	1. Prepare technical reports that clearly state the scope and objectives of the system analyzed, the critical problems addressed, the methods used in the analysis, and the results of the analysis.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.

Table 5. Specialization: Structural systems, materials, and environment for biological systems.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOB1: Critically evaluate the physicochemical, mechanical, and biological characteristics of living organisms that affect the design parameters, microenvironment, and operation of structural systems.	1. Principles of animal physiology and nutrition. 2. Systems for animal husbandry and fish farming, identifying their main constraints and requirements. 3. Identify and quantify micro-environmental parameters to be met by various animal and fish production and housing systems. 4. Main physiological functions of the different crops and other plants and biological systems (e.g., mushrooms, algae, and other microorganisms) in protected production systems. 5. Management principles and micro-environmental requirements in relation to protected crop and other biosystems production. 6. Principles for biosystems nutrition.	1. Types of animal production, components, inputs, and organization of enterprises for cattle, sheep, pigs, poultry, rabbits, etc. 2. Analyze and quantify the sources of losses, quality and productivity problems arising with management of animals, and measures to overcome them. 3. Main components, inputs, and organization of protected crop production systems. 4. Main biosystems production systems for algae and other microorganisms. 5. Analyze and quantify the sources of damages, quality, and productivity losses; problems arising with the management of crops, fruits, horticultural products, and other biosystems; and measures to overcome them.
LOB2: Integrate in-depth knowledge of the main environmental issues for selecting and using materials and creating sustainable structural systems.	1. Main characteristics of environmental components (air, soil, water, cultural, or socioeconomic) in relation to the impacts derived from activities related to materials selection and use and structural design. 2. Environmental impact assessment process and the main evaluation methods. 3. Life cycle assessment of materials. 4. Fundamentals of the main impacts: noise, water, air pollution, biological, cultural, land use, and landscape.	1. Design an impact assessment technique. 2. Calculate and assess pollutant loading on the environment. 3. Evaluate the socioeconomic impact on the environment of structural systems and materials. 4. Design plans to minimize the impacts derived from structural systems and materials, and propose measures to correct the impacts generated.
LOB3: Investigate waste characteristics, biological reactions, and biological treatment alternatives.	1. Main characteristics associated with waste materials derived from animal and plant management and that of other biosystems. 2. Sources and categories of waste materials. 3. Legal framework of environmental issues, including general laws and major legislation related to waste management. 4. Characteristics of waste management technology options, e.g., biological treatment, composting, recycling, or energy recovery. 5. Physicochemical processes associated with the management of waste materials and the associated biological reactions.	1. Microbiology and biochemistry of liquid wastes. 2. Contamination of soil and water due to residues: processes, consequences, and mitigation strategies. 3. Design a waste management plan in the framework of a project or activity.
LOE1: Integrate in-depth knowledge and understanding of the composition, atomic and crystal structure, and chemical bond types of structural materials, especially concrete, wood, ceramics, polymers, and metallic materials for various design and analysis biosystems engineering applications.	1. Atomic structure and bonding in solids. 2. Crystal structures. 3. Ceramics: structure, properties, and processing. 4. Polymers: structure, characteristics, and processing. 5. Metals: phase diagrams, phase transformations, and thermal processing. 6. Imperfections in solids.	1. Composite materials: composition, molding methods, mechanical properties, applications. 2. Corrosion and degradation of materials. 3. Fatigue of materials, especially in concrete and metallic materials. 4. Thermal, magnetic, electric, and optical properties of materials. 5. Material selection and design considerations.
LOE2: Critically evaluate the mechanical and physicochemical characteristics of conventional and innovative alternative materials used in structural systems.	1. Principles of constitutive equations for solids: classical elasticity, plasticity. 2. Fluids: idealized fluids, Newtonian fluids, laminar and turbulent fluids. 3. Stress-strain diagrams of wood, steel, concrete, polymers, and other structural materials. 4. Basic mechanical properties and behavior of wood, steel, concrete, and polymers.	1. Mechanics of solids: viscoelasticity, hypoelasticity, and advanced concepts of plastiticity (hypoplasticity, hardening and softening, deformation theory). 2. Properties and behavior of innovative or alternative materials: composite materials, bio-based materials, glass, and aluminum.
LOE3: Use knowledge and understanding to design solutions to soil mechanics related design aspects of structural systems.	1. Characteristics of granular materials behavior: softening and hardening, permanent deformations, influence of path loads or load rates. 2. Determine properties of soils through specific laboratory tests and site examinations. 3. Practical significance of different soil behavior for the problems of design foundation and construction. 4. Calculate basic shallow foundations and earth-retaining walls.	1. Soil mechanics theories and the basic mechanic parameters applied to soils. 2. Calculate slab-on-grade and deep foundations. 3. Pathologies associated with foundations due to construction. 4. Slope stability and its applicability for calculating dams and embankments.
LOE4: Apply knowledge and understanding to formulate and solve problems on the actions in structures and the associated loads.	1. Design philosophies: load and resistance factor design (LRFD) and allowable strength design (ASD). 2. Safety factors for materials and loads.	1. Calculate and apply dynamic loads (earthquake, cyclic loads). 2. Second-order analysis due to applied loads. 3. Calculation and effects of thermal loads in struc-

Table 5. Specialization: Structural systems, materials, and environment for biological systems.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
	3. Concepts of stability and deformation. 4. Static and pseudostatic loads (live loads, use, snow, and wind) and apply them in structures.	tures, particularly for fire in steel, concrete, and wood materials (influence on loads and material properties).
LOE5: Apply knowledge and understanding to conceptualize engineering models, systems, and processes for the behavior of various structural components and systems by identifying their main elements and developing numerical models to simulate structural systems.	1. Numerical solution techniques. 2. Analysis techniques used to discretize continuous systems. 3. Common methods for solving equations, both linear and non-linear. 4. Fundamentals of computer-based analysis: matrix equation solution techniques, least-square, numerical integration, finite difference, and time integration. 5. Computational mechanics: static and dynamic finite element analysis, control volume in fluid flow. 6. Types and behavior of main structural elements: beams, shells, and solids. Principles for finite element formulation.	1. Discrete element method. 2. Develop a complete finite element model for a complex system with dynamic analysis. 3. Develop a complete CFD model for a complex system. 4. Parametric analyses of mechanical or geometric parameters of the model.
LOE6: Use engineering judgment to work with structural and materials related codes and specifications.	1. Structural Eurocodes system. 2. EN standards for materials. 3. Specify the constraints and limitations imposed by the standard applied to the problem in question.	1. Propose design changes to optimize the structural design in agreement with the requirements of the structural Eurocodes. 2. Alternative and simplified methods for designing structural components meeting the standard requirements.
LOBE1: Use knowledge and understanding to design and optimize the main elements of structural systems by applying the specifications contained in standards.	1. Design structural components according to the corresponding design codes. 2. Apply design procedure for a specific design project. 3. Identify and apply landscape impact criteria in the design using GIS-based modeling.	1. Optimize the design of structural components according to the corresponding design codes. 2. Apply the design optimization procedure for a specific design project.
LOBE2: Design and conduct analytic, modeling, and experimental investigations to optimize the micro-environment of the structural system.	1. Micro-environment requirements of various biosystems (as defined in LOB1) by proper design of the structural system and materials selection. 2. Design structural systems and materials adapted to biological micro-environment requirements.	1. Analyze the influence of biological and environmental factors in the development of structural systems to improve the designs. 2. Optimize the design of structural systems and materials selection to best meet the biological micro-environment requirements.
LOBE3: Investigate the application of new and emerging technologies and integrate knowledge to design the basic components of the structural system related to the waste management system.	1. Requirements of designed structural systems according to the type of the biosystems waste managed. 2. Design the structural system elements related to alternative waste disposal management systems for various biosystems. 3. Estimate waste disposal costs as affected by the structural design and materials.	1. Plan site investigations. 2. Plan research to analyze the effect of new uses or treatments of residues on the structural design and selection of materials.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.

Table 6. Specialization: Water resources engineering.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOB1: Critically evaluate the physicochemical and biological characteristics of living organisms and the micro-meteorological and micro-environmental parameters for the design parameters, simulation, and operation of hydraulic systems such as irrigation and drainage systems.	1. Biosystems physiology and nutrition. 2. Physiological functions of the different crops and other plants and biological systems (e.g., mushrooms, algae, and other micro-organisms) in relation to micro-meteorological and micro-environmental parameters. 3. Management principles and micro-environmental requirements in relation to protected crop and other biosystems production. 4. Animal physiology and nutrition. 5. Systems for animal husbandry and fish farming, identifying their main constraints and requirements, especially with respect to waste management issues. 6. Quantify the micro-environmental parameters to be met by various animal and fish production and housing systems.	1. Analyze and quantify the water needs of plants (crops, tress, vegetables, and vines) and other biosystems under various micro-meteorological and micro-environmental conditions. 2. Analyze and quantify the sources of damages, quality, and productivity losses, and problems arising with the management of crops, trees, or vegetables and other biosystems and measures to overcome them. 3. Components, inputs, and organization of protected crop production systems. 4. Biosystems production systems for algae and other microorganisms. 5. Types of animal production; components, inputs, and organization of enterprises for cattle, sheep, pigs, poultry, rabbits, etc.; and waste management solutions.
LOB2: Use knowledge and understanding of the relations between soil, water, contaminants or pollutants, and living organisms for the design of hydraulic and hydrological systems.	1. Plant nutrients contained in soils. 2. Groups of microorganisms in soil and water, their interrelationships and responses to environmental changes, and their interaction with plants and livestock. 3. Effects of fertilizers, cover crops, compost, and other soil improvement supplements on plant productivity and soil quality. 4. Plant interactions with soil and water environments (nutrient and water uptake, transport or transpiration) and applications in crop and environmental management. 5. Sources and types of soil and water contaminants and pollutants. 6. Chemical and physical mechanisms for the diffusion of contaminants in soils and water.	1. Soil fertility assays and procedures to prevent soil from erosion and loss of fertility. 2. Requirements of water quality for plant and animal consumption. 3. Techniques to protect plants from water stress. 4. Interactions of contaminants and pollutants with biosystems. 5. Consequences of contaminants and pollutants in biosystems.
LOB3: Integrate in-depth knowledge of the main environmental issues for selecting and using materials and creating sustainable hydraulic systems.	1. Characteristics of environmental components (air, soil, water, cultural, or socioeconomic) in relation to the impacts derived from activities related to materials selection and use in hydraulic systems. 2. Environmental impact assessment and the main evaluation methods. 3. Life cycle assessment of materials. 4. Fundamentals of the main impacts: noise, water, air pollution, biological, cultural, land use, and landscape.	1. Design an impact assessment technique. 2. Calculate and assess pollutant loading on the environment. 3. Evaluate the socioeconomic impact on the environment of hydraulic systems and the construction materials used in them. 4. Design plans to minimize the impacts derived from hydraulic systems and construction materials, and propose measures to correct the impacts.
LOB4: Apply the fundamentals of nonpoint-source pollution to investigate waste characteristics, biological reactions, and biological treatment alternatives.	1. Sources and categories of waste materials. 2. Nonpoint-source pollution and transport mechanisms. 3. Characteristics associated with waste materials and pollutants derived from agricultural activities and those of other biosystems. 4. Legal framework of environmental issues, including general laws and major legislation related to waste management. 5. Characteristics of the main waste management technology options: biological treatment, composting, recycling, and energy recovery. 6. Physicochemical processes associated with the management of waste materials and the associated biological reactions.	1. Introduction to microbiology and biochemistry of liquid wastes. 2. Contamination of soil and water due to residues: processes, consequences, and mitigation strategies. 3. Design a waste management plan in the framework of a project or activity. 4. Evaluate and quantify the existence of nonpoint-source pollution in the framework of an agricultural activity. 5. Describe the main practices and techniques used to minimize nonpoint-source pollution in plant and animal management.
LOE1: Integrate knowledge of soil physics and soil mechanics to identify physical and hydraulic characteristics for the design of hydraulic and hydrological systems.	1. Distinguish the characteristics of granular materials behavior: softening and hardening, permanent deformations, and influence of path loads or load rates. 2. Hydraulic properties of soil: permeability, electrical conductivity, diffusivity, velocity gradient, and dispersion. 3. Theory of soil mechanics. 4. Slope stability and its applicability for calculating dams and embankments.	1. Determine properties of soils through specific laboratory tests and site examination. 2. Soil mechanics theories and the main parameters involved in each theory. 3. Significance of different soil behaviors for the design and construction of water facilities. 4. Calculate basic shallow foundations and retaining walls.
LOE2: Use a comprehensive knowledge and understanding of the principles of water move-	1. Water flow and chemical transport in the vadose zone, including hydraulic properties,	1. Calculate drainage of saturated soils. 2. Apply standard energy approaches and formulas,

Table 6. Specialization: Water resources engineering.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
ment in porous media and conveyed elements to design irrigation systems and water facilities.	diffusive transport, and convective transport. 2. Principles used for the design of pipe systems and open channels. 3. Apply energy and momentum principles to fluid flow situations and be able to solve problems for forces in static and moving fluids, including different flow regimes (laminar and turbulent) and the concepts of energy loss in pipe systems and open channels. 4. Principles that govern the geomorphology of estuaries and deltas, with special attention to sediment deposition and erosion phenomena.	solve for and design pressure pipe systems. 3. Apply standard approaches and formulas, solve for and design open-channel flow systems.
LOE3: Critically evaluate the mechanical and physicochemical characteristics of conventional materials used in hydraulic systems to design and construct various elements.	1. Constitutive equations for solids: classical elasticity and plasticity. 2. Fluids: idealized fluids, Newtonian fluids, laminar and turbulent fluids. 3. Stress-strain diagrams of wood, steel, concrete, polymers, and other structural materials. 4. Mechanical properties and behavior of wood, steel, and concrete.	1. Mechanics of solids: Viscoelasticity, hypoelasticity, and advanced concepts of plasticity (hypoplasticity, hardening and softening, deformation theory).
LOE4: Use engineering judgment to work with the design and technical characteristics of different irrigation systems and related equipment such as pumps, valves, and flow-measuring devices.	1. Characteristics and components of irrigation system designs: surface, sprinkler, or drip. 2. Apply the principles of irrigation systems in the design of networks. 3. Elements of pump and turbine flow, and analysis and selection of the pumps needed for pressurizing situations. 4. Flow measurement in conveyed pipes and open channels. 5. Collect and interpret information about the earth's surface through non-contact methods.	1. Interactions existing between irrigation and drainage. 2. Apply mathematical models for the management of vast irrigation areas. 3. Measurement systems, including signal conditioning, systems response, and data acquisition or interfacing microcomputers. 4. Electrotechnics principles used in pumps, valves, and electrical equipment in hydraulic systems.
LOE5: Evaluate and use the appropriate characteristics and principles for the design of water facilities.	1. Constraints and studies required to design water facilities, including climatologic data, hydrological data, soil properties, land uses and morphology, and water requirements. 2. Design requirements of water facilities such as dams, spillways, pipe networks, sewer systems, groundwater dams, and canals. 3. Apply analytical and hydraulic design approaches to common water facilities such as culverts, spillways, pipe networks, sewer systems, canals, and scour and sediment transport.	1. Statistical treatment of spatial data applied to hydrologic problems. 2. Analysis of spatial processes. 3. Groundwater exploration techniques and their applicability to assess water quality.
LOE6: Apply knowledge and understanding to conceptualize engineering models, systems, and processes to develop numerical models to simulate hydraulic processes and hydrological systems.	1. Surface hydrology: hydrographs, precipitation, and runoff. 2. Development and calibration of models to simulate groundwater flow and transport. 3. Modeling watersheds related to the design of water facilities: dams, spillways, culverts, and ditches. 4. Empirical streamflow models for simulating processes in surface hydrology.	1. Model water flow in the vadose zone by applying numerical methods, such as finite element or finite differences, in unsaturated soils. 2. Apply the principles of surface hydrology for calculation of peak flows in storms or calculation of reservoir storage. 3. Apply watershed models to analyze the influence of irrigation in aquifers, draw wells, and groundwater transport of contaminants and pollutants.
LOE7: Use knowledge and understanding of the main elements of structural and geotechnical systems to design water facilities including structural and materials related codes and specifications.	1. Numerical solution techniques. 2. Structural Eurocode system. 3. Constraints and limitations imposed by the standard applied to the problem in question. 4. Computer-based analysis: matrix equation solution, least-square, numerical integration, finite difference, time integration, finite element analysis, control volume in fluid flow. 5. Types and behavior of main structural elements: beams, shells, and solids. Principles for finite element formulation. 6. Analysis techniques used to discretize continuous systems.	1. Discrete element method. 2. Development of a complete finite element model for a complex system with dynamic analysis. 3. Development of a complete CFD model for a complex system. 4. Propose design changes to optimize the structural design in agreement with the requirements of the structural Eurocodes.
LOBE1: Apply geographical information system techniques and numerical modeling to assess environmental risks associated with hydraulic works and diffusion of contaminants and pollution.	1. GIS, including spatial database structures, scripting, data models, and errors. 2. Conduct in-depth investigation of advanced topics in remote sensing applications, measurements, and theory. 3. Develop basic GIS models to study runoff, erosion, and contaminant transport.	1. Apply GIS and numerical models to assess risks associated with failures in water facilities, e.g., dams, main pipes, and groundwater damns. 2. Apply GIS and numerical models to study groundwater flow and contaminant transport.

Table 6. Specialization: Water resources engineering.

Learning Outcome[a]	Knowledge for Each Learning Outcome	
	Level 2 (Intermediate)	Level 3 (Advanced)
LOBE2: Integrate in-depth knowledge of the principles of water and environmental laws and apply them for the planning, design, and management of water resources.	1. Principles and issues contained in water laws. 2. Types of water rights, groundwater rights, and management and protection of in-stream uses. 3. Limits for pollutants and contaminants in water. 4. Principles used for planning irrigation and controlling irrigation operation in vast areas.	1. Apply GIS models for planning water resources in a vast area. 2. Apply mathematical programming techniques to solve specific items of water resources planning, such as water allocation, capacity expansion, or reservoir operation. 3. Develop plans to guarantee water quality.
LOBE3: Design elements and systems to prevent soil erosion and to restore stream and riparian areas.	1. Theoretical and empirical foundations of sediment production on hillslopes using computer models and field experiments. 2. Techniques used to prevent erosion caused by precipitation runoff. 3. Crop and irrigation management practices in soil erosion.	1. Develop restoration strategies for eroded riparian areas. 2. Develop hillslope and riparian restoration concepts. 3. Apply geomorphic principles to coastal management.
LOBE4: Design the basic components of hydraulic systems related to the waste management systems.	1. Specify the requirements of designed hydraulic systems according to the type of the biosystems waste managed. 2. Design the elements related to alternative waste disposal management systems for various biosystems. 3. Determine waste disposal costs as affected by the hydraulic design and materials used.	1. Plan site investigations. 2. Plan research to analyze the effect of new uses or treatments of residues on the structural components of hydraulic systems.

[a] LOB = biosystems learning outcome, LOE = engineering learning outcome, and LOBE = integrated biosystems and engineering learning outcome.