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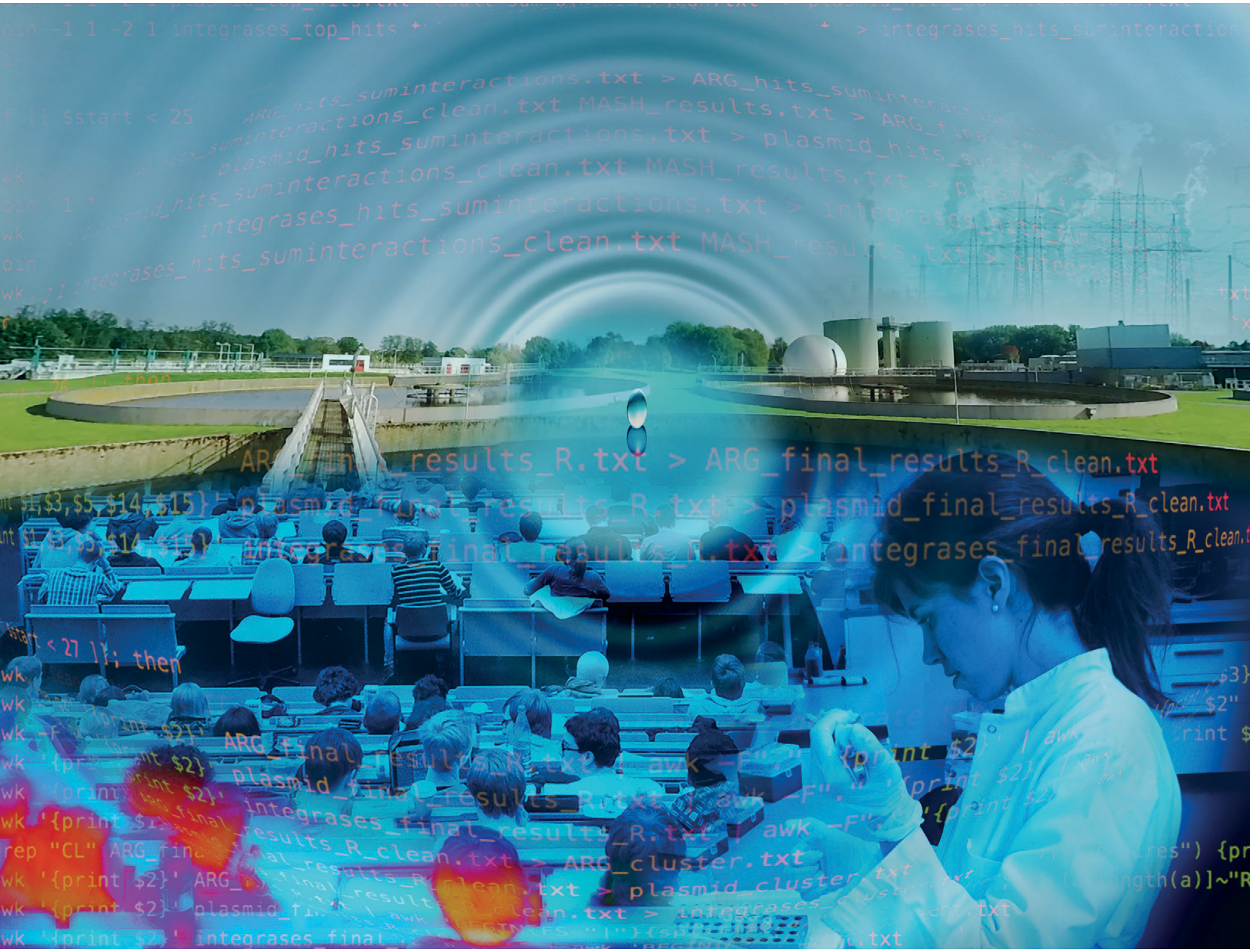

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Responsible science, engineering and education for water resource recovery and circularity†

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Water resource recovery is central to the circular economy framework. It underlies the transition of environmental engineering from pollution prevention to responsible innovation for sustainable systems engineering. In order to speed this transition, resource recovery and circularity need integration into new higher education curricula to train the next generation of young professionals. However, training of new concepts requires the development of new course materials and books, while integrating substantial illustrations and problems on circularity and resource recovery in new editions of existing textbooks in environmental science and engineering. Moreover, university–utility–industry partnerships are important mechanisms to bridge theoretical fundamentals to concepts for engineering practice, and to promote knowledge exchange and technology adoption between practitioners and academics. Interactive platforms should be designed to facilitate the integration and development of resource recovery and circularity concepts from science and practice into education. Consensus was built on this perspective article from interaction with the members of the Association of Environmental Engineering and Science Professors in a workshop that we organized at the AEESP Research and Education Conference 2017. Overall, this paper gives actionable roadmaps to (i) apprehend how new science and technological findings need to get integrated to sustain resource recovery and circularity in practice, along with the fact that (ii) skills sets can be engineered with relatively minor changes to existing lecture material that will have maximal impact on the scope of the thought material. It lays out (iii) how partnership with engineering practitioners can make a lecture more vivid by giving students reasoning for why the learned material is important, and (iv) how a platform for an integrated science, education, and practice can deliver them with concrete tools for practical implementation for benefits at community level.

Water impact

Water resource recovery is central to circular economy frameworks. Resource recovery and circularity concepts need inception into the engineer's daily vocabulary during university education. Novel higher education efforts require curriculum design in environmental engineering. University–utility–industry partnerships foster applied training and theory integration. Platforms need to be developed to bridge science, engineering, and education.

1 Introduction

The environmental engineering and science sector is in the midst of a revolutionary transition to sustain responsible innovation for the achievement of circular economies in ecologically-balanced and healthy communities.[1] The water sector occupies a central role, by managing flows of water, nutrients, and emerging contaminants to protect public health and the environment, and to valorize used resources within cities and watersheds.[2–8] Science and engineering practice are active in inventing and elucidating the design of new technological solutions that support the enhancement of water quality and environmental health. Concepts of resource recovery and circularity are rapidly becoming reputable and established paradigms,[9,10] while transition to practice will require more time and as a result the positive effects on communities will become apparent over the next decades.

Integration of these concepts into educational curricula is lagging behind, although it is paramount to fuel pioneering minds for future innovation in our field. Following the

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thorough science, technology, and sustainability developments that occurred over the last fifteen years,[11,12] new interdisciplinary programs should implement this vision into environmental engineering and science education with the goal to train the next generation of professional experts. Complemented or new higher educational models are needed to accelerate pedagogical innovation and disciplinary boundary crossing at the water–energy–food nexus.[13–15] A platform bridging scientists, lecturers, students, and practitioners is required to interactively handle needs and ways for shaping responsible research, education, innovation and practice to harness new concepts of water resource recovery and circularity, and to monitor benefits. This has been lately illustrated in the context of the global phosphorus challenge by the pressing need to develop a new generation of nutrient sustainability professionals able to work collectively and interactively at large scale across urban and rural planning to implement the UNESCO Global Action Programme on Education for Sustainable Development.[16] This links further to actions of "Environmental Engineering for the 21st Century: Addressing Grand Challenges" addressed by the US National Academies of Sciences, Engineering, and Medicine,[17] where one of the key challenges consists of "A world without waste or pollution", which is central to resource recovery and a circular water economy.

In this perspective article, we address needs and themes to re-thinking environmental engineering education in the context of water resource recovery and circularity. The latest scientific findings and engineering technologies require translation into new education challenges and perspectives. We cover the current integration of resource recovery concepts in learning processes in higher education and research, and compare it to education practices within our peers. We questioned (i) how and how fast new science and technological findings of water resource recovery and circularity are being integrated into education and knowledge utilization; (ii) how we can engineer skills sets to form the

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Mari Winkler

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new generation of professionals in sanitation, resource recovery, and community sustainability; (iii) what perspectives and challenges arise for establishing university–utility partnerships to propel education and community integration of water resource recovery; and (iv) how we can generate a platform for an integrated science, education, practice, and community development. We involved our core expertise in environmental biotechnology to translate concepts of engineered biological systems into educational processes for circularity. The foundations of this perspective stems from interaction and consensus building with members of the Association of Environmental Engineering and Science Professors (AEESP) in a workshop that we organized at the AEESP Research and Education Conference 2017 at the University of Michigan, USA. This critical and peer-thinking process led to the constitution of actionable roadmaps to promote the new-generation leaders of the profession, by educational design.

2 The need and a roadmap to integrate resource recovery and circularity concepts in educational curricula

A roadmap (Fig. 1) was developed to drive the inception, integration, and application of resource recovery and circularity concepts into environmental engineering programs. The roadmap was built from an on-line questionnaire and the workshop discussions with the AEESP delegates. This interaction helped to frame and build consensus on the arguments for a need for innovation in education to environmental science and engineering.

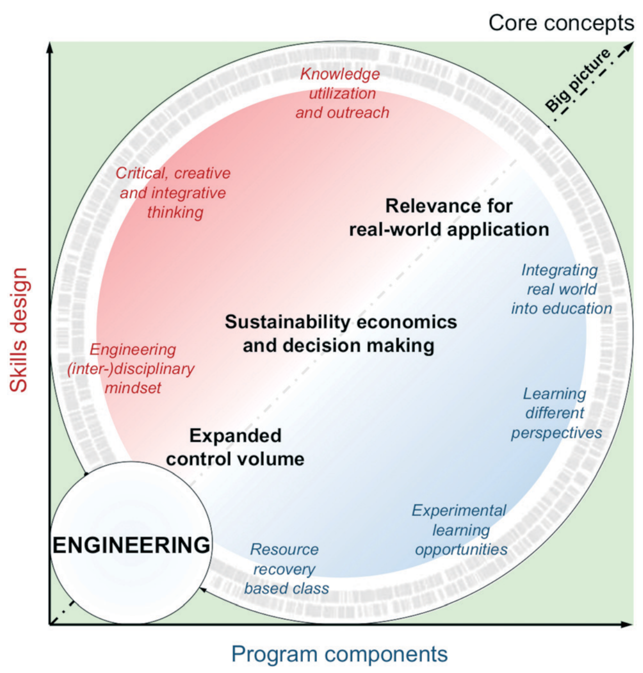

Fig. 1 Core concepts (black), program components (blue), and skills design (red) to shape the 'genome' of the next generation of sustainability engineering leaders *via* tailored educational curricula for resource recovery and circularity. The core concepts, program components, and skills design are further detailed in Table 1 hereafter.

The need to shape new educational targets for the integration of resource recovery and circularity concepts was identified from the on-line questionnaire addressed individually to the 43 workshop participants. The sample was composed of undergraduate (2%), master (9%) and doctoral (45%) students, postdocs (2%), utility research managers (5%), and faculty members (36%). They originated from R1 (80%, doctoral universities with highest research activity), R2 (9%, doctoral universities with higher research activity), M3 (2%, master's colleges and universities with smaller programs) and primarily undergraduate (4%) institutions of higher education, and public utilities (4%).

The questionnaire was based on the following 5 main questions. Readers can use the questions to delineate the current extent of and potential need for integration of educational lines in resource recovery and circularity in their home university program: (i) Does the lecturer currently integrate concepts of resource recovery or circular economy into course material in environmental engineering and science? (ii) Is resource recovery and circular economy a central theme in the environmental engineering and science degree(s) at the home institution? (iii) What needs for novel education lines on resource recovery and circularity can be identified from the home institution? (iv) How can water resource recovery and circularity be integrated from science and engineering practice to education and communities? (v) What skills should we develop in the next generation of professionals and scientists to implement water resource recovery and circularity to engineer benefits at the community level?

It was unanimously accepted that new skills should be developed to train the next generation of professionals and leaders to implement resource recovery and circularity, and to design benefits at community level. Less consensual agreement was obtained on whether these are core components of educational programs at their home institutions. Only 9% indicated a central theme (others: 9% not at all, 21% peripheral focus, 33% somewhat, 28% one of several important themes). Only 5% indicated that these concepts are central to the courses taught or taken (others: 21% not at all, 9% touch on in one lecture, 47% touch on in a few lectures, 19% play a relative important role throughout the course). These survey results, while informal, provide evidence of expectations to integrate concepts of circularity and resource recovery into environmental engineering curricula.

The roadmap was further designed by on-site interaction, peer learning, and consensus building with the AEESP workshop delegates dispatched in 6 groups. Three core questions were addressed in group chalkboard talks and mind maps: (i) What core concepts from resource recovery and circularity could serve as anchors of education? (ii) What specific program components should be targeted to bridge the

Table 1 Compilation of core concepts, program components, and skillsets to engineer in higher education for the inception of resource recovery and circularity concepts and methods into professional practice (detailed from Fig. 1). The recommendations arose from interaction and consensus building with the workshop delegates of the AEESP Research and Education Conference 2017 (University of Michigan, USA)

Roadmap targets	Recommendations from peers
Core concepts	**The big picture**
	Water–energy–food nexus, carbon neutralization, and ecosystem perspective
	Quantification of embedded value(s) in streams
	Engineering as a tool in larger context
	Scientific fundamental principles for resource valorization
	Problem identification *vs.* problem solving
	Expanded control volume
	Systems thinking and conceptualization for waste-to-value
	Environmental and macro economics
	Techno-economic analyses, life cycle assessment (LCA) and cost (LCC) analyses
	Stakeholders analyses, gaming and scenario workshops
	Benefits and impacts of resource recovery: conflict, balance, driver, ethics
	Liberal arts: broad spectrum of skills
	Sustainability economics and decision making
	Interdisciplinarity and sustainability integration
	Environmental impacts and societal benefits
	Hazard liability to opportunity as resource
	Innovative and siloed regulations
	Policy shaping and analysis, policy-making exercises, decision seminars
	Relevance for real-world application
	Connecting parts of treatment and recovery
	Resource limitations and energy conservation
	Applicability of the concept, market niche identification and tradeoff
	Collaboration with industries, utilities, governmental and non-governmental organizations (NGOs)
	Effective communication with stakeholders
Program components	**Resource recovery based class**
	Bringing new research/practice into program early on
	In-class and out-of-class exposure to real problems and solutions
	Present real world problems (students will solve)
	Field trips and tour to industries and utilities
	Experimental learning opportunities
	Extracurriculars (design competitions, solar decathlons, engineers w/o borders)
	Case studies on locally relevant topics
	Relevant workshops, conferences, public meetings
	Learning different perspectives
	Academic and practice, policy and regulation, business and entrepreneurship
	Certifying and monitoring recovered products
	Guest lectures by practitioners
	Undergraduate, graduate, exchange programs
	Integrating real world into education
	University–utility partnerships take time to build relationships
	Develop classes that work with utilities and companies
	Summer internships with hands on component
	Professional exams in leadership in energy and environmental design (LEED)
Skills design	**Science and engineering disciplinary and interdisciplinary mindset**
	Engineering *vs.* other disciplines (economics, social sciences)
	Engineering bases *vs.* design-based thinking
	Interdisciplinarity, collaboration, teamwork
	Practicality approach to solutions
	Social and community awareness
	Critical, creative and integrative thinking
	Looking at the state of the art with a critical eye
	System thinking, systems modelling
	Life cycle analysis, technoeconomics, environmental and health impacts
	Uncertainty modelling
	Knowledge utilization and outreach
	Communication, leadership, public engagement
	Communication with communities, middle/high schools
	Client based, marketing skills focus
	Jargon-free talks, layman's terms formulations

science, practice, and community assessment? (iii) Which skills should be designed by next-generation professionals to implement resource recovery and circularity, and engineer benefits at community level? The peer-recommendations were detailed in Table 1, resulting in the abstract sketch of Fig. 1. The roadmap was delineated along three main targets on core concepts, program components, and skills sets to be designed.

The core concepts address the big picture at the nexus of water, energy, resource valorization, and sanitation. Systems thinking in an expanded control volume along with sustainability economics, decision making, and relevance for real-word application should help to address the benefits and impacts of resource recovery in the ecological balance, societal setting, and circular economy. Techno-economic analyses, life cycle assessment and costs analyses[18,19] are dedicated methods to this end. They can be efficiently complemented by stakeholder analyses, game tools and scenario investigations as well as ethics, decision, and policy-making seminars.[20–22]

The program components integrate resource recovery-based classes, experimental learning opportunities from different perspective, and real-world outcomes into education. In-class and out-of-class exposure to real problems and solutions can directly immerse the students into the specific challenges in practice. Cases studies, extracurriculars like design competitions, and industry/public meetings help shape applied, creative, critical, and real-time active thinking. The integration of entrepreneurship and policy mindsets need to complement the traditional basic science and engineering skillset of environmental engineers. Students need to be exposed to entrepreneurs, industry, and (non-)governmental representatives to this end. This is a process that can be developed stepwise across the curriculum from foundation to undergraduate and graduate training, toward post-graduated professional certification to match the application outcome.

In terms of skills design, scientific and engineering disciplinary and interdisciplinary mindsets need to be crafted to master the fundamentals of resource recovery but also to develop, as teams, technologies and practical solutions that can solve the complex sanitation, environmental and resource recovery problems of communities. Communication, leadership and public engagement are important aspects that need to be considered in education to better translate in layman's terms the scientific and engineering outputs into knowledge utilization and beneficial outcomes for the society and the environment, and to address the impact pathway.[23] Crafting economical thinking skills to environmental scientists and engineers is important to think upfront on whether there is a market niche and opportunity for the recovered products. Uncertainty analysis and modelling is further essential to cope with the complexity of environmental, rural, and urban systems.

It can be further questioned why resource recovery and circularity needs to be considered as focus when several other areas need modernization in the environmental engineering curricula. The recreating and rebranding of programs need an integrated view of the multiple challenges and solutions for public health sanitation, such as formulated in the 17 sustainable development goals (SDGs) and cooperation framework of the United Nations,[24,25] and for which a new generation of trained professionals is required. Water resource recovery and circularity is one part of it with several links to, *e.g.*, clean water and sanitation (goal 6), affordable and clean energy (goal 7), industry, innovation and infrastructure (goal 9), sustainable cities and communities (goal 11), responsible consumption and production (goal 12), and partnerships (goal 17). These goals can be translated from the international scale to regional prerogatives, and for which new training is needed. In the context of the SDGs, water resource recovery becomes an important educational target, on top of bridging environmental engineering curricula across mathematical, physical, chemical, and life sciences and technologies.

3 New concepts of water resource recovery and circular economy: an analogy between societal and biological systems

New models for a circular economy contrast with the traditional activities of resource extraction, products manufacturing, consumption, and disposal.[26–28] These models drive resource efficiency by closing resource loops, re-defining waste as a value, thriving on pioneering concepts of sustainable development,[29] systems resiliency,[30] energy, exergy, material flow analysis,[31–33] life cycle assessment,[34] city metabolisms,[35] industrial symbiosis,[36] and by industrial and urban ecology.[37–39] The new terminology and concepts of a circular economy are transformative since at the same time embracing the broader vision of industrial ecology and placing it into the economical perspective to reach out interests across society, activity sectors, municipalities, communities, and citizens.

Circular economy is articulated along three core principles:[40] (i) the natural capital is preserved by controlling finite stocks and balancing renewable resource flows; (ii) resource yields are optimized by circulating products, components and materials at highest utility through technical and biological cycles; (iii) system effectiveness is fostered by revealing and designing out negative externalities. Circular economy aims for the design of complex, adaptive, feedback-rich and dynamic systems.

By analogy to biological and life-support systems,[41–43] societal metabolisms are driven by linkages of catabolisms for the generation of energy coupled to maintenance to keep societal systems functioning well and of anabolisms for the transformation of materials and resources into food, goods and services. Similar to biology and microbial communities experienced in the field of environmental biotechnology, society is composed of a diversity of units and functions that should interact to minimize entropic waste streams. Circular economy models therefore aim to design societal metabolic networks for the recovery and recirculation of resources from used streams, using feed-back controlled loops. More than feed-back control, we advocate that educating environmental engineers by design should sustain a feed-forward control of circularity implementation in the profession. Inception of circularity principles in environmental engineering and science education can drive the anticipation of societal needs and responses. Here, we are not just taking a retroactive approach (where resource recovery is changing practice, so we need to change education), but a proactive one: by changing education we can change how practice and society functions.

Together with municipal solid waste management facilities, wastewater treatment plants (WWTPs) are central units handling resource/waste streams. Recycling strategies are well established to recover energy, materials, and value from solid wastes. Technological methods to recover value from used aqueous streams have emerged, while valorization of gas emissions remains rather sporadically targeted. In this re-cycling context, WWTPs are re-conceptualized as water resource recovery facilities (WRRFs),[44–46] water resource factories (WRFs)[51] or installations for sewage treatment and resource recovery (STaRR[119] – initiated from French: stations de récupération des ressources de l'eau, StaRRE)[47,48] as central elements for a sustainable water engineering cycle. An analogous acronym is used in the waste management field for the design of a systems thinking approach to resource recovery (STARR).[49] Strategies and methodologies for planning and design to identify the most sustainable contextual solutions are lacking,[50] stressing the need to develop new skillsets in the field. Methodologies are under development to this end as well as to identify the bottlenecks and markets for the recovered products.[51,52]

Priority objectives of wastewater treatment imperatively remain public health sanitation, water recycling, and environmental protection. This involves physical–chemical and biological methods for the removal of (bio)solids, organics, and nutrients, supplemented by advanced processes for the elimination of xenobiotic and xenogenetic contaminants of emerging concern, such as micropollutants[53–57] and antibiotic resistance determinants.[58,59,120] Future abatement needs will be driven by clearly demonstrated environmental and public health concern.[60,61] Novel supplementary approaches integrate technologies to produce energy, recover nutrients, and capture and convert carbon into low-entropy and high-value biomaterials such as intracellular and extracellular biopolymers (*e.g.*, polyhydroxyalkanoates and bacterial alginates, respectively), from used water.[62] The implementation of water resource recovery targets on the site of (existing) sewage treatment installations requires strategies of process extension, intensification, and integration.

Biological methods most often provide technological opportunities that offer substantial savings in capital and operational expenditures. Environmental biotechnologies rely on the engineering of microbial communities (or microbiomes) as complex as activated sludge to remove contaminants and nutrients – or capture them – from the wastewater solution. Their performance therefore relies on the design of a robust and resilient ecosystem composed of specialized metabolizing guilds of microorganisms as well as populations that connect the microbiome network. The interaction of metabolic processes inside activated sludge or biofilm biocoenoses underlines the biological traits of a circular economy. Economic markets are defined by imports, exports, growth and trades between producers and consumers. Similarly, biological markets[63] are delineated between different populations of microorganisms that compete for, share, and recycle resources in natural and engineered ecosystems. This analogy between microbial and economic markets can pave the way for an efficient abstraction of resource recovery and circularity into useful concepts and models for design.

Bridging scientific inquiry and engineering design approaches of biotechnological to economical systems can compose one specific milestone to establish circular economy paradigms in environmental engineering education. This can be driven by the design of transdisciplinary partnerships between environmental, engineering, and economics programs.

4 Generating a platform for integration and development

The role of WWTPs has expanded dramatically since the introduction of activated sludge 100 years ago[64,65] to include an emphasis on sustainability in addition to its traditional role of complying with different regulations and directives[66,67] to protect water quality. Major developments of the 21st century include increasing needs for nutrient removal such as *via* biofilm and granular sludge reactor technologies.[62,68–73] It is expected that, besides effluent quality, secondary objectives dealing with the sustainability of wastewater treatment will gain importance in future, aiming for compact processes, reduced energy consumption, minimal addition of chemicals, and reduced emissions of greenhouse gases, among others. Acceleration of innovation in the water sector can help deliver maximum economic, environmental, and social benefits to communities, primarily through improved water resource management and protection, and enhanced resiliency.

It is therefore necessary to provide an opportunity for academics and water utilities to collaborate in the development, assessment, and implementation of these new technologies. Actionable roadmaps need to be established for the further development, demonstration, and implementation of new technologies in the field. New curricula and course material are required that will actively engage all students in the development and demonstration of new technologies in the classroom, allowing for a training of the next-generation environmental engineers that care about sustainable water reclamation. It is necessary to bring together universities, utilities, and industrial partners to develop defined initiatives and tasks to advance leading edge technologies, to train a new generation of resource recovery professionals, and to help launch them onto the market.

The possibility of providing an interactive platform for the integration and development of resource recovery and circularity concepts from science and practice into education fits current needs as well as scientific and engineering interests of the water profession. In order to bridge the knowledge gap between science and engineering practice, resource recovery must be integrated in current lecture material. The new students entering the workforce will be able to quickly lead development and implementation of novel technological concepts for resource recovery implementation.

The field of wastewater treatment has rapidly evolved over the last decade with inventive approaches and innovative technologies for water resource recovery, process intensification, and integration. New educational textbooks or chapters are required to cover the theoretical fundaments and engineering concepts of resource recovery. New chapters should notably incorporate the design principles of bioprocess intensification using examples of new technological concepts that lead to reduction in space, energy requirements, and infrastructure costs, beside others. The new paradigm in wastewater treatment is resource recovery and energy reduction especially for the treatment of nitrogen from wastewater, and a number of technologies exist that lower costs while producing a high quality effluent.[74,75] In addition, the deployment of water technologies for a rapidly growing world population requires solutions not only for energy efficiency and resource recovery but also for space reduction. Examples for bio-based intensification approaches are granular sludge and attached biofilms, *e.g.*, to fluidized carrier materials in moving-bed bioreactors or to immerged filtration modules in membrane bioreactors.[68,73,76–78] The integration of new biofilm technologies into existing chapters may not be too difficult as current textbooks already contain design principles that may be adapted to new concepts.

Besides breakthroughs in biofilm and granular sludge technologies, the science and engineering sectors have benefitted from various innovations for carbon, nitrogen, and phosphorus capture. Applications in decentralized sanitation target the separation of urine from feces for the production of struvite and other nutrient concentrates that can be valorised as fertilizers.[79,80] Nutrients can also be recovered from the wastewater solution using biological and physical–chemical methods, or a combination of both.[81,82] The enhanced biological removal of phosphorus is a well-known process where microorganisms accumulate orthophosphate as intracellular polyphosphate.[83] The phosphorus-rich waste sludge purged from the process can be disposed in an anaerobic holding tank to release the phosphorus in a concentrated stream and precipitate it as a usable product. The conversion of organic matter into higher value products and hi-tech biomaterials is an emerging field. Recovery options include (i) alginate-like exopolymers[84] for coatings of concrete surfaces to protect them from moisture loss and drying, (ii) intracellular biopolymers like poly-β-hydroxyalkanoates or polylactate that can be manufactured as bioplastics for various applications,[85] (iii) cellulose fibers out of the massive loads of toilet paper,[86] as well as (iv) the replacement of coal by sludge biodrying,[87] beside other technologies.

Such conceptualization work on design principles of new technologies and technology integrations should go hand in hand with research and utilities, and can form excellent case studies for student practice. New textbooks on resource recovery will provide state-of-the-art lecture material and will equip the new generation of engineers with knowledge that can be carried and implemented in companies. It is also important that the industrial sector appreciates the necessity of research in engineering practice and that funding agencies encourage universities to work with utilities and industrial partners to implement new findings on the engineering market such as it the case for, *e.g.*, the NSF funded Grant Opportunity for Academic Liaison with Industry (GOALI) program in the USA, for the Applied and Engineering Sciences division of the Dutch Research Council, or the Horizon Europe program of the European Union funding collaborations between academia and the industry.

5 Designing an education for the next generation of science and engineering leaders

The educational gap in water mining needs to be filled by the design of new modules, courses or interdisciplinary programs, by the involvement of university–utility partnerships, and the establishment of platforms for integration and development. Pioneering new curricula necessitates the transition from concepts to new skill sets, development, and careers.

Curriculum design should be adapted to the different higher educational levels (foundation, undergraduate, graduate, postgraduate). Undergraduate education is much more framed by, *e.g.*, constraints of the Accreditation Board for Engineering and Technology (ABET).[88,89] Because of the accreditation constraints, programs are often slow to implement novel components in their curriculum, like lately the UN SDGs and other topics of critical importance to society and the environment. More degrees of freedom are available to rebrand graduate programs with tailored courses on water resource circularity and innovative educational partnerships, where the students can implement the basic science and engineering knowledge processed at bachelor level into concepts at master and doctoral levels. Graduate students are also better equipped to manage such interdisciplinarity with, *e.g.*, industry collaboration, experiential learning, economics, and community focus, among others. Nonetheless, the inception of resource recovery and circularity concepts can already take place in the traditional introductory courses to environmental science and engineering. This can also be integrated in illustrations, exercises, and problems used to process and validate undergraduate learning processes, such as described further in this section.

As invoked by Morriss-Olson,[90] the development of new academic programs in resource-constrained institutions (which most higher-education bodies are) requires the adoption of an academic entrepreneurial mindset. It should target the five following criteria for (i) mission and opportunity, (ii) operational feasibility, (iii) market niche, (iv) internal support, and (v) opportunity assessment and failure potential, besides developing a financial strategy to support the program development.

Once an idea for a new academic program is generated, one should define ways to sustain and implement the idea.[91] This should go by defining how education can be leveraged in unique ways starting from what is currently outstandingly achieved in the existing program, and by targeting what market opportunities will meet with learning outcomes of the program. A rigorous, flexible and supported process will have to be designed to cultivate the new program ideas and to build a culture.

The development of new educational lines for a circular economy will have to meet with the factual criterion of revenue potential and projection. From the attractiveness of these new approaches and technologies, programs that will empower students from knowledge acquisition to knowledge utilization on these new pillars will make a difference.

The design of an educational curriculum starts from the postulate that students' attitudes about the field of engineering are strongly linked to their retention.[92–95] Authors have highlighted that the students' perception of an interesting activity evokes a positive emotional response, propelling them to persist. A negative experience hampers their learning process. Intrinsic satisfaction develops when mastering a subject along with rigorous study and success in the classroom. Definitely, educational topics relating to resource recovery and circularity will drive students' motivation from theoretical knowledge to the broader application context, meeting with concrete milestones for their profession.

Sustainability-related concepts contribute to the recruitment and retention of a more diverse student body.[96–98] The eight main factors impacting an individual's selection of a profession according to under-represented students in engineering relate by preponderance to economics (compensation, jobs, cost of education), the image of the profession, social relevance, career advancement opportunities, academic advising (high school, grade school), informal advising (by parents or teachers), the difficulty to transition from high school to college, and the knowledge about the profession.[99,100]

More broadly, emphasizing positive societal outcomes may increase intrinsic motivation among students. From a survey over more than 6000 students from 17 institutions in the USA, Besterfield-Sacre and colleagues[101] have identified a tendency that male students would more strongly agree than their female classmates that engineers contribute to improving the welfare of society.

The development of course materials that peak student interest is a low risk opportunity to increase retention. The classical hazard mitigation framework of the environmental engineer, characterized by reactive engineering, end-of-pipe strategies, and contaminant quantification and removal, needs re-thinking into a resource-oriented framework propelled by proactive engineering, industrial ecology, and resource quantification and recovery. This paradigm shift is exemplified in the context of nutrient removal from wastewater. Pollution mitigation strategies specifically aim for contaminant removal from wastewater, while novel resource-oriented strategy aim for instance for bioenergy production *via* the growth of algal biomass on these nutrients and its conversion into fuel.[102] In this context, the intended decrease of pollutant concentration over time is translated into an increase in the bioenergy feedstock concentration. This is transformative and didactically appealing in the sense that pollution becomes a resource. The combination of resource recovery on top of pollution mitigation is an added value, with definite benefits in both engineering practice and educational attractiveness.

Transitioning to an aspirational framework can thus be achieved through new and existing courses. This transition does not require a complete curriculum redesign, but instead can be initiated by relatively small changes in current courses. One place to start in a traditional Environmental Engineering syllabus can consist of keeping existing course objectives, but updating the context. Learning objectives and approaches matching program outcomes of ABET commonly focus on (i) the formulation and solving of mass and energy balances in engineered and natural systems, in addition to (ii) determination of contaminant concentrations in air, soil, and water, (iii) balancing of environmentally relevant chemical reactions and determination of their orders, (iv) design of ideal reactors to achieve a target effluent pollutant concentration, (v) identification of the fate and transport pathways for contaminants in air, soil, and water, and (iv) description of impacts of major sources of pollution on ecosystem, human health and socioeconomy *via* literature review and team work. In many cases these approaches can readily be adapted to incorporate elements of resource recovery and circularity. One illustration of the prevalence of the hazard mitigation framework in environmental engineering education was identified from four core textbooks traditionally used in the field of environmental engineering and science.[103–106] These primers harbor up to 43 mass balance problems (9 on innocuous compounds, 32 on contaminant removal, and 2 on contaminant production). A good illustration targets phosphorus removal and recovery, where mass balances are broadly useful, since enabling to easily design resource recovery problems (*via*, *e.g.*, phosphorus precipitation or biological phosphorus removal). Hence, it becomes essential to develop teaching approaches to foster students' ability to think critically and identify meaningful (in both attribute and magnitude) impacts on society by starting with existing course objectives on hazard mitigation, and to supplement and balance them with a clear aspirational context oriented on water resource recovery.

The implementation of new program components is attractive, while one should think about the practical implementation in study plans. The factual, challenging, follow-up question may arise on what will have to be omitted from current programs. Environmental science and engineering often belongs already to the most diverse programs in university education. Instead of a full reshaping of programs – and not to reinvent the wheel periodically – roundtables of faculty members should help identifying major topics (or concentrations) that programs should focus on. Concentrations can become a very efficient tool to rebrand programs on selected topics for the next 10 years, without a complete re-creation. A concentration in water resource recovery can bridge several existing standard courses in, *e.g.*, water resources, sanitary engineering, water and wastewater treatment (physical, chemical, biological processes), environmental biotechnology, pollution control, analytical chemistry and bioanalytics, ecological engineering and remediation, systems analysis and water technology, process engineering, design and modelling, with additional ones like material sciences, energy systems, environmental economics, management, policy, environmental communication, among others. Too often, the different courses of a program are taught as individual components without a clear view of the lecturer(s) of the position of the course in the program and its links with the other courses of colleagues. The use of key topics can better build the bridges between lecturers and courses, and drive students' interest and skillset into targeted overarching problematics. This can be a very good starting point to refresh programs. An additional way can consist in regularly rejuvenating the environmental engineering fundamentals as a function of the evolving needs and solutions for society and the environment.

6 The role of university–utility partnerships in propelling education and community integration of water resource recovery

Resource recovery from used water is by no means a concept that is limited to the ivory tower. Utilities are leading the way on circularization of flows of energy, water, nutrients, and materials in urban water systems, and are at the forefront of the transition to water resource recovery. This is evidenced by the position statement by the Water Environment Federation that "wastewater treatment plants are not waste disposal facilities, but rather water resource recovery facilities that produce clean water, recover nutrients (such as phosphorus and nitrogen), and have the potential to reduce the nation's dependence upon fossil fuel through the production and use of renewable energy".[107] To maximize impact, the integration of resource recovery into environmental engineering education should leverage and build on these new applications and modes of thinking in practice. An ideal way to do so is to integrate students' training with practice *via* university–utility partnerships.

More broadly, education and community integration of resource recovery would greatly benefit from thinking beyond the water sector alone to synergies between multiple low-value societal waste streams. This systems-level thinking has strong potential to lead to the design of integrated biorefineries at the urban mining and water–energy–food nexus.[108–111] Potential inputs to the urban biorefinery include not only "used" water but also a diverse array of additional streams, including municipal solid waste and lignocellulosic materials. The advantage of co-processing these "waste" streams is that synergies can be identified to valorize high-value products such as water, nutrients, biogas and heat, but also liquid biofuels and platform chemicals. The combination of water, nutrients and heat is then notably interesting to feed aquaponics, hydroponics, urban agriculture, wetlands, and biomass production systems, and for which utilities contribute by, *e.g.*, co-digestion of food waste.

University–utility partnerships can result in a win–win strategy for both universities and utilities.[112–114] This includes training and inspiration for university students, but also includes additional profound benefits and potential for long-term positive impact for both sectors. Academics benefit from improved understanding of key needs of technology adopters, thus increasing the chance that academic research is transformational to industry, while practitioners benefit from new fundamental insights from academia, and also have the opportunity to explore emerging technologies at minimal cost and risk.[115–118] From our experience, three main values can be highlighted from university–utility partnerships.

First, such partnerships enable collaborative and transformative applied research that would be difficult for either the utility or academic partner to tackle alone. This is fostered by progressive and forward-looking regional utilities committed to energy neutrality, resource recovery, and transforming water. Current research on the assessment of strategies to implement new suites of processes for, *e.g.*, energy-efficient nitrogen removal using anaerobic ammonium oxidation, process intensification for biological nutrient removal using granular sludge, carbon capture from wastewater into exopolymers, or sunlight-driven conversion of organic matter into biofuel using phototrophic systems can strongly benefit from applied investigation conducted onsite at WRRFs. This consists of high-risk/high-reward research that a utility would not undertake on its own. Partnering with the utility can allow academic research groups to build a suite of reactors onsite to investigate process stability and performance with real wastewater, as a prerequisite to demonstrate the applicability of new technologies. The utility in turn has the opportunity to gain experience with and knowledge about new technologies at the lab- or bench-scale, thereby increasing awareness of process options to promote resource recovery and enhancing the potential for technology transfer from the academic lab to practice.

The second crucial value that we see in utility–university partnerships is practical experience in the form of internships for students. On-the-ground training is critically important for the aspiring environmental bioprocess engineer and researcher, and also opens the door to enhanced communication between academia and practitioners. This paves the way for students to be immersed into the real engineering world, to interact with practitioners, but also to bring new ideas from academia to integration in practice. Efficient examples of student integration into the field of biological wastewater treatment can cover, among other activities, the development of molecular methods and early-warning biomarkers to anticipate process performance and upsets. Such opportunities provide students with excellent educational experience to demonstrate utilities' interests and needs related to water resource recovery, and demonstrates application of cutting-edge methods to actual practice.

The third value we see in university–utility partnerships is the opportunity for collaborative education not just in the field but also in the classroom. Collaborative education can be as simple as organizing field trips to WRRFs, inviting practitioners to give guest lectures in courses, or involving practitioners as mentors or judges in class projects. For instance, traditional courses in environmental biotechnology can be expanded with advanced modules on microbial ecology and community engineering for resource recovery, where students look at diversity, interactions, and emergent function of microbial communities through the lens of engineered systems designed for wastewater treatment and resource recovery. Such classes emphasize conceptual and process modeling, reading of primary literature, and peer-learning activities. Because of the strong connection of the microbial world to resource recovery, strong links can be built to practice and educational modules. Such relatively simple examples of collaborative classroom education is very well received by students because they aid in translation of concepts from lecture slides and textbooks into practice.

Overall, university–utility partnerships are crucial to driving collaborative research (*i.e.*, bringing researchers and practitioners to each other), practical experience (*i.e.*, bringing students to practitioners), and collaborative education (*i.e.*, bringing practitioners to students). University benefits arise from real-world training and experience for students *via* on the ground educational opportunities, and from transformational research toward better outcomes with higher likelihood of solutions being adopted by the industry. Utilities can benefit from proactive and progressive approaches to problem solving and testing of innovative high-risk/high-reward technologies, while identifying new talents, *i.e.*, their future workforce. University–utility partnerships translate into strong educational and personal development benefits for young professionals and environmental engineering students; indeed, integration with education should be a primary objective of such partnerships.

Selected student fellowship and research support programs do exist through industries, engineering firms, governmental agencies (*e.g.*, King County in the US), water authorities and foundations (*e.g.*, the Water Research Foundation, WRF, in the US and the Foundation for Applied Water Research, STOWA, in the Netherlands). Some programs are prone to fund students (and their tuition) with the idea that these promising young professionals might work in their offices or partner organisations after their graduation. Such strategies invest in education since they do not only see the benefit of the resulting research but also as an investment in next-generation engineers.

7 Conclusion

Circular economy is an innovation engine that fosters restorative and regenerative industrial systems that benefits all stakeholders and citizens. Resource recovery is central within circularity, and forms a central pillar of environmental engineering science. The field of environmental science and engineering requires new educational approaches and media to integrate resource recovery and circularity in the students' daily vocabulary and activities for the development of next-generation leaders of the profession. In this article we highlighted that:

1. New science and engineering concepts require translation into higher education concepts and theory. Technological innovations foster educational innovations, and *vice versa*. Empowerment generates higher skills sets and knowledge valorization.
2. Participants in an AEESP sponsored workshop acknowledged the need to better integrate concepts of resource recovery and circularity into curricula.
3. Integration can increase student motivation and retention by promoting value-added product generation rather than just hazard mitigation.
4. University–utility partnerships can play a critical role by promoting knowledge exchange between academics and practitioners, encouraging collaborative research projects and education, and promoting on-the-ground training for students.
5. Implementation can involve simple adaptation of existing curricula, but longer term will require next textbooks and courses to fully communicate new concepts in resource recovery. Currently, there is a gap in terms of textbooks on the field of resource recovery and circularity to sustain environmental engineering education.

Contributions

D. G. W. wrote the manuscript with direct inputs, edits, and critical feedback by all co-authors. All authors contributed to the development of the cornerstone concepts of this perspective article in the workshop on "Responsible science, engineering and education for water resource recovery and circularity" given during the AEESP Research and Education Conference 2017.

Conflicts of interest

The authors declare that no competing financial interests exist.

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References

1 C. Kristan, A Failure Reveals Success, *J. Ind. Ecol.*, 2013, **17**(5), 633–641.
2 G. T. Daigger, A vision for urban water and wastewater management in 2050, in *Toward a Sustainable Water Future: Visions for 2050*, ed. W. M. Grayman, D. P. Loucks and L. Saito, American Society of Civil Engineers, 2012, pp. 166–174.
3 S. J. Kenway, P. A. Lant, A. Priestley and P. Daniels, The connection between water and energy in cities: A review, *Water Sci. Technol.*, 2011, **63**(9), 1983–1990.
4 S. Lehmann, Resource recovery and materials flow in the city: Zero waste and sustainable consumption as paradigm in urban development, *J. Green Build.*, 2011, **6**(3), 88–105.
5 P. M. Sutton, B. E. Rittmann, O. J. Schraa, J. E. Banaszak and A. P. Togna, Wastewater as a resource: A unique approach to achieving energy sustainability, *Water Sci. Technol.*, 2011, **63**(9), 2004–2009.
6 J. T. Trimmer and J. S. Guest, Recirculation of human-derived nutrients from cities to agriculture across six continents, *Nat. Sustain.*, 2018, **1**(8), 427–435.
7 C. Vaneeckhaute, E. Remigi, F. M. G. Tack, E. Meers, E. Belia and P. A. Vanrolleghem, Optimizing the configuration of integrated nutrient and energy recovery treatment trains: A new application of global sensitivity analysis to the generic nutrient recovery model (NRM) library, *Bioresour. Technol.*, 2018, **269**, 375–383.
8 W. Verstraete and S. E. Vlaeminck, ZeroWasteWater: Short-cycling of wastewater resources for sustainable cities of the future, *Int. J. Sustainable Dev. World Ecol.*, 2011, **18**(3), 253–264.
9 G. T. Daigger, Changing Paradigms: From Wastewater Treatment to Resource Recovery, *Proceedings of the Water Environment Federation*, 2011, vol. 20116, pp. 942–957.
10 M. Ries, M. Trotz and K. Vairavamoorthy, Fit-for-purpose sustainability index: A simplified approach for U.S. water utility sustainability assessment, *Water Pract. Technol.*, 2016, **11**(1), 35–47.
11 E. Morgenroth, G. T. Daigger, A. Ledin and J. Keller, International evaluation of current and future requirements for environmental engineering education, *Water Sci. Technol.*, 2004, **49**(8), 11–18.
12 *An Education Program in Support of a Sustainable Future*, ed. J. W. Sutherland, V. Kumar, J. C. Crittenden, M. H. Durfee, J. K. Gershenson and H. Gorman, *et al.*, American Society of Mechanical Engineers, Manufacturing Engineering Division, MED, 2003.
13 Ş. Kılkış and B. Kılkış, Integrated circular economy and education model to address aspects of an energy-water-food nexus in a dairy facility and local contexts, *J. Cleaner Prod.*, 2017, **167**, 1084–1098.
14 H. Leck, D. Conway, M. Bradshaw and J. Rees, Tracing the Water-Energy-Food Nexus: Description, Theory and Practice, *Geogr. Compass.*, 2015, **9**(8), 445–460.
15 E. D. Schoolman, J. S. Guest, K. F. Bush and A. R. Bell, How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field, *Sustain. Sci.*, 2012, **7**(1), 67–80.
16 K. Reitzel, W. W. Bennett, N. Berger, W. J. Brownlie, S. Bruun and M. L. Christensen, *et al.* New Training to Meet the Global Phosphorus Challenge, *Environ. Sci. Technol.*, 2019, **53**(15), 8479–8481.
17 National Academies, *Environmental Engineering for the 21st Century: Addressing Grand Challenges*, The National Academies Press, Washington, DC, 2019, p. 124.
18 M. Spiller, M. Muys, G. Papini, M. Sakarika, M. Buyle and S. E. Vlaeminck, Environmental impact of microbial protein from potato wastewater as feed ingredient: Comparative consequential life cycle assessment of three production systems and soybean meal, *Water Res.*, 2020, **171**, 115406.
19 M. Spiller, J. H. G. Vreeburg, I. Leusbrock and G. Zeeman, Flexible design in water and wastewater engineering – Definitions, literature and decision guide, *J. Environ. Manage.*, 2015, **149**, 271–281.
20 I. Mayer, Y. Vries and J. Geurts, An Evaluation of the Effects of Participation in a Consensus Conference, in *Public Participation in Science: The Role of Consensus Conferences in Europe*, ed. S. Joss and J. Durant, NMSI Trading Ltd, London, UK, 1995.
21 B. Bouchaut and L. Asveld, Safe-by-Design: Stakeholders' Perceptions and Expectations of How to Deal with Uncertain Risks of Emerging Biotechnologies in the Netherlands, *Risk Anal.*, 2020, 13501.
22 I. Van de Poel, L. Asveld, S. Flipse, P. Klaassen, V. Scholten and E. Yaghmaei, Company Strategies for Responsible Research and Innovation (RRI): A Conceptual Model, *Sustainability*, 2017, **9**(11), 2045.
23 B. Douthwaite, T. Kuby, E. van de Fliert and S. Schulz, Impact pathway evaluation: An approach for achieving and attributing impact in complex systems, *Agric. Syst.*, 2003, **78**, 243–265.

24 SDG U, *United Nations Sustainable Development Cooperation Framework*, United Nations Sustainable Development Group, 2019.

25 SDG U, *Transforming our World: the 2030 Agenda for Sustainable Development*, United Nations Sustainable Development Group, 2019, Contract No.: A/RES/70/1.

26 M. Geissdoerfer, P. Savaget, N. M. P. Bocken and E. J. Hultink, The Circular Economy – A new sustainability paradigm?, *J. Cleaner Prod.*, 2017, **143**, 757–768.

27 J. Kirchherr, D. Reike and M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions, *Resour., Conserv. Recycl.*, 2017, **127**, 221–232.

28 P. Ghisellini, C. Cialani and S. Ulgiati, A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems, *J. Cleaner Prod.*, 2016, **114**, 11–32.

29 J. R. Mihelcic, J. C. Crittenden, M. J. Small, D. R. Shonnard, D. R. Hokanson and Q. Zhang, *et al.* Sustainability Science and Engineering: The Emergence of a New Metadiscipline, *Environ. Sci. Technol.*, 2003, **37**(23), 5314–5324.

30 J. Fiksel, Designing Resilient, Sustainable Systems, *Environ. Sci. Technol.*, 2003, **37**(23), 5330–5339.

31 C. Kennedy, J. Cuddihy and J. Engel-Yan, The changing metabolism of cities, *J. Ind. Ecol.*, 2007, **11**(2), 43–59.

32 E. H. Decker, S. Elliott, F. A. Smith, D. R. Blake and F. S. Rowland, Energy and material flow through the urban ecosystem, *Annu. Rev. Energ. Environ.*, 2000, **25**, 685–740.

33 M. Fischer-Kowalski, F. Krausmann, S. Giljum, S. Lutter, A. Mayer and S. Bringezu, *et al.* Methodology and indicators of economy-wide material flow accounting: State of the art and reliability across sources, *J. Ind. Ecol.*, 2011, **15**(6), 855–876.

34 P. T. Anastas and R. L. Lankey, Life cycle assessment and green chemistry: The yin and yang of industrial ecology, *Green Chem.*, 2000, **2**(6), 289–295.

35 P. W. G. Newman, Sustainability and cities: Extending the metabolism model, *Landsc. Urban. Plan.*, 1999, **44**(4), 219–226.

36 M. R. Chertow, "Uncovering" industrial symbiosis, *J. Ind. Ecol.*, 2007, **11**(1), 11–30.

37 J. Ehrenfeld and N. Gertler, Industrial ecology in practice: The evolution of interdependence at Kalundborg, *J. Ind. Ecol.*, 1997, **1**(1), 67–79.

38 S. Erkman, Industrial ecology: An historical view, *J. Cleaner Prod.*, 1997, **5**(1–2), 1–10.

39 J. Wu, Urban ecology and sustainability: The state-of-the-science and future directions, *Landsc. Urban. Plan.*, 2014, **125**, 209–221.

40 W. R. Stahel, The circular economy, *Nature*, 2016, **531**(7595), 435–438.

41 J. J. Heijnen, R. Kleerebezem and M. C. Flickinger, Bioenergetics of Microbial Growth, *Encyclopedia of Industrial Biotechnology*, John Wiley & Sons, Inc., 2009.

42 J. B. Gros, L. Poughon, C. Lasseur and A. A. Tikhomirov, Recycling efficiencies of C,H,O,N,S, and P elements in a biological life support system based on micro-organisms and higher plants, *Adv. Space Res.*, 2003, **31**(1), 195–199.

43 C. Lasseur, W. Verstraete, J. B. Gros, G. Dubertret and F. Rogalla, Melissa: A potential experiment for a precursor mission to the moon, *Adv. Space Res.*, 1996, **18**(11), 111–117.

44 J. S. Guest, S. J. Skerlos, J. L. Barnard, M. B. Beck, G. T. Daigger and H. Hilger, *et al.* A new planning and design paradigm to achieve sustainable resource recovery from wastewater, *Environ. Sci. Technol.*, 2009, **43**(16), 6126–6130.

45 G. T. Daigger, Flexibility and adaptability: Essential elements of the WRRF of the future, *Water Pract. Technol.*, 2017, **12**(1), 156–165.

46 T. Braun, J. Gillaspie, M. Kim, R. Larson, F. McCann and M. Moacyr, *et al.*, *Water Resources Utility of the Future: 2015 Annual Report*, USA: NACWA, WEF, WERF, WateReuse, 2015.

47 A. Lalumière, Le PEX StaRRE: Un nouveau programme destiné aux ouvrages d'assainissement des eaux usées, *Vecteur Environ.*, 2016, 58–59.

48 D. G. Weissbrodt, StaRRE – Stations de récupération des ressources de l'eau, *Aqua & Gas*, 2018, **1**, 20–24.

49 K. S. Ng, A. Yang and N. Yakoleva, Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK, *J. Cleaner Prod.*, 2019, **227**, 248–262.

50 J. P. van der Hoek, H. de Fooij and A. Struker, Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater, *Resour., Conserv. Recycl.*, 2016, **113**, 53–64.

51 P. Kehrein, M. van Loosdrecht, P. Osseweijer, J. Posada and J. Dewulf, The SPPD-WRF Framework: A Novel and Holistic Methodology for Strategical Planning and Process Design of Water Resource Factories, *Sustainability*, 2020, **12**(10), 4168.

52 P. Kehrein, M. van Loosdrecht, P. Osseweijer, M. Garfí, J. Dewulf and J. Posada, A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials, technologies and bottlenecks, *Environ. Sci.: Water Res. Technol.*, 2020, **6**(4), 877–910.

53 Y. Luo, W. Guo, H. H. Ngo, L. D. Nghiem, F. I. Hai and J. Zhang, *et al.* A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment, *Sci. Total Environ.*, 2014, **473–474**, 619–641.

54 T. Ternes, The occurrence of micopollutants in the aquatic environment: A new challenge for water management, *Water Sci. Technol.*, 2007, **55**(12), 327–332.

55 D. Weissbrodt, L. Kovalova, C. Ort, V. Pazhepurackel, R. Moser and J. Hollender, *et al.* Mass Flows of X-ray Contrast Media and Cytostatics in Hospital Wastewater, *Environ. Sci. Technol.*, 2009, **43**(13), 4810–4817.

56 J. Hollender, S. G. Zimmermann, S. Koepke, M. Krauss, C. S. McArdell and C. Ort, *et al.* Elimination of organic micropollutants in a municipal wastewater treatment plant upgraded with a full-scale post-ozonation followed by sand filtration, *Environ. Sci. Technol.*, 2009, **43**(20), 7862–7869.

57 J. Margot, C. Kienle, A. Magnet, M. Weil, L. Rossi and L. F. de Alencastro, *et al.* Treatment of micropollutants in municipal wastewater: ozone or powdered activated carbon?, *Sci. Total Environ.*, 2013, **461–462**, 480–498.
58 H. Bürgmann, D. Frigon, W. H. Gaze, C. M. Manaia, A. Pruden and A. C. Singer, *et al.* Water and sanitation: an essential battlefront in the war on antimicrobial resistance, *FEMS Microbiol. Ecol.*, 2018, **94**(9), fiy101.
59 M. Petrovich, B. Chu, D. Wright, J. Griffin, M. Elfeki and B. T. Murphy, *et al.* Antibiotic resistance genes show enhanced mobilization through suspended growth and biofilm-based wastewater treatment processes, *FEMS Microbiol. Ecol.*, 2018, **94**(11), fiy041.
60 R. P. Schwarzenbach, T. Egli, T. B. Hofstetter, U. Von Gunten and B. Wehrli, Global water pollution and human health, *Annu. Rev. Environ. Resour.*, 2010, 109–136.
61 B. Petrie, R. Barden and B. Kasprzyk-Hordern, A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring, *Water Res.*, 2014, **72**, 3–27.
62 M. C. M. van Loosdrecht and D. Brdjanovic, Anticipating the next century of wastewater treatment, *Science*, 2014, **344**(6191), 1452–1453.
63 J. Tasoff, M. T. Mee and H. H. Wang, An Economic Framework of Microbial Trade, *PLoS One*, 2015, **10**(7), e0132907.
64 *Activated Sludge – 100 Years and Counting*, ed. D. Jenkins and J. Wanner, 1st edn, IWA Publishing, London, UK, 2014.
65 A. R. Sheik, E. E. L. Muller and P. Wilmes, A hundred years of activated sludge: time for a rethink, *Front. Microbiol.*, 2014, **5**, 47.
66 EPA US, *Clean Watersheds Needs Survey 2004 – Report to Congress*, 2008.
67 EPA US, *Nutrient Control Design Manual*, 2009.
68 H. Odegaard, Innovations in wastewater treatment: The moving bed biofilm process, *Water Sci. Technol.*, 2006, **53**(9), 17–33.
69 P. Regmi, C. DeBarbadillo and D. G. Weissbrodt, Biofilm Reactor Technology and Design, in *Design of Water Resource Recovery Facilities – MOP 8. WEF Manual of Practice No. 8, ASCE Manuals and Reports on Engineering Practice No. 76*, ed. T. L. Krause, *et al.*, Water Environment Federation, American Society of Civil Engineers and Environmental and Water Resources Institute, McGraw-Hill Education, Alexandria VA, Reston VA, New York, USA, 6th edn, 2017.
70 B. E. Rittmann, Where are we with biofilms now? Where are we going?, *Water Sci. Technol.*, 2007, **55**(8–9), 1–7.
71 J. P. Boltz, B. F. Smets, B. E. Rittmann, M. C. M. Van Loosdrecht, E. Morgenroth and G. T. Daigger, From biofilm ecology to reactors: A focused review, *Water Sci. Technol.*, 2017, **75**(8), 1753–1760.
72 H. Aqeel, D. Weissbrodt, M. Cerruti, G. M. Wolfaardt, B.-M. Wilen and S. N. Liss, Drivers of bioaggregation from flocs to biofilms and granular sludge, *Environ. Sci.: Water Res. Technol.*, 2019, **5**, 2072–2089.
73 M. K. H. Winkler, C. Meunier, O. Henriet, J. Mahillon, M. E. Suarez-Ojeda and G. Del Moro, *et al.* An integrative review of granular sludge for the biological removal of nutrients and of recalcitrant organic matter from wastewater, *Chem. Eng. J.*, 2018, **336**, 489–502.
74 M. K. H. Winkler and L. Straka, New directions in biological nitrogen removal and recovery from wastewater, *Curr. Opin. Biotechnol.*, 2019, **57**, 50–55.
75 H. Gao, Y. D. Scherson and G. F. Wells, Towards energy neutral wastewater treatment: methodology and state of the art, *Environ. Sci.: Processes Impacts*, 2014, **16**(6), 1223–1246.
76 M.-K. H. Winkler, J. Yang, R. Kleerebezem, E. Plaza, J. Trela and B. Hultman, *et al.* Nitrate reduction by organotrophic Anammox bacteria in a nitritation/anammox granular sludge and a moving bed biofilm reactor, *Bioresour. Technol.*, 2012, **114**, 217–223.
77 R. Nerenberg, The membrane-biofilm reactor (MBfR) as a counter-diffusional biofilm process, *Curr. Opin. Biotechnol.*, 2016, **38**, 131–136.
78 H. F. van der Roest, L. M. M. de Bruin, G. Gademan and F. Coelho, Towards sustainable waste water treatment with Dutch Nereda® technology, *Water Pract. Technol.*, 2011, **6**(3), 59.
79 K. M. Udert, T. A. Larsen, M. Biebow and W. Gujer, Urea hydrolysis and precipitation dynamics in a urine-collecting system, *Water Res.*, 2003, **37**(11), 2571–2582.
80 S. P. Wei, F. van Rossum, G. J. van de Pol and M.-K. H. Winkler, Recovery of phosphorus and nitrogen from human urine by struvite precipitation, air stripping and acid scrubbing: A pilot study, *Chemosphere*, 2018, **212**, 1030–1037.
81 K. S. Le Corre, E. Valsami-Jones, P. Hobbs and S. A. Parsons, Phosphorus Recovery from Wastewater by Struvite Crystallization: A Review, *Crit. Rev. Environ. Sci. Technol.*, 2009, **39**(6), 433–477.
82 D. J. Batstone, T. Hülsen, C. M. Mehta and J. Keller, Platforms for energy and nutrient recovery from domestic wastewater: A review, *Chemosphere*, 2015, **140**, 2–11.
83 T. Mino, M. C. M. van Loosdrecht and J. J. Heijnen, Microbiology and biochemistry of the enhanced biological phosphate removal process, *Water Res.*, 1998, **32**(11), 3193–3207.
84 Y. Lin, M. de Kreuk, M. C. M. van Loosdrecht and A. Adin, Characterization of alginate-like exopolysaccharides isolated from aerobic granular sludge in pilot-plant, *Water Res.*, 2010, **44**(11), 3355–3364.
85 K. Johnson, R. Kleerebezem and M. C. M. van Loosdrecht, Influence of ammonium on the accumulation of polyhydroxybutyrate (PHB) in aerobic open mixed cultures, *J. Biotechnol.*, 2010, **147**(2), 73–79.
86 C. J. Ruiken, G. Breuer, E. Klaversma, T. Santiago and M. C. M. van Loosdrecht, Sieving wastewater – Cellulose recovery, economic and energy evaluation, *Water Res.*, 2013, **47**(1), 43–48.
87 M.-K. H. Winkler, M. H. Bennenbroek, F. H. Horstink, M. C. M. van Loosdrecht and G. J. van de Pol, The biodrying

concept: An innovative technology creating energy from sewage sludge, *Bioresour. Technol.*, 2013, **147**, 124–129.

88 J. McGourty, L. Shuman, M. Besterfield-Sacre, C. Atman, R. Miller and B. Olds, *et al.* Preparing for ABET EC 2000: Research-based assessment methods and processes, *Int. J. Eng. Educ.*, 2002, **18**(2 SPEC), 157–167.

89 L. J. Shuman, M. Besterfield-Sacre and J. McGourty, The ABET "professional skills" – Can they be taught? Can they be assessed?, *J. Eng. Educ.*, 2005, **94**(1), 41–55.

90 M. Morriss-Olson, *Is it Time to Launch that New Academic Program? The Art and Science of Answering that Question*, Academic Impressions, Denver, CO, USA, 2016.

91 M. Morriss-Olson, *Feasibility Checklist: The Science of Bringing New Academic Programs to Life*, Academic Impressions, Denver, CO, USA, 2016.

92 M. Besterfield-Sacre, C. J. Atman and L. J. Shuman, Characteristics of freshman engineering students: Models for determining student attrition in engineering, *J. Eng. Educ.*, 1997, **86**(2), 139–149.

93 M. L. Russell and M. M. Atwater, Traveling the road to success: A discourse on persistence throughout the science pipeline with African American students at a predominantly white institution, *J. Res. Sci. Teach.*, 2005, **42**(6), 691–715.

94 B. F. French, J. C. Immekus and W. C. Oakes, An Examination of Indicators of Engineering Students' Success and Persistence, *J. Eng. Educ.*, 2005, **94**(4), 419–425.

95 J. L. White, J. W. Altschuld and Y.-F. Lee, Persitence of Interest in Science, Technology, Engineering, and Mathematics: A Minority Retention Study, *J. Women Minor. Sci. Eng.*, 2006, **12**(1), 47–64.

96 D. R. Hokanson, L. D. Phillips and J. R. Mihelcic, Educating engineers in the sustainable futures model with a global perspective: Education, research and diversity initiatives, *Int. J. Eng. Educ.*, 2007, **23**(2), 254–265.

97 J. R. Mihelcic and D. R. Hokanson, Educational solutions, *Environmental Solutions*, 2005, pp. 35–58.

98 J. Zimmerman and J. Vanegas, Using Sustainability Education to Enable the Increase of Diversity in Science, Engineering and Technology-Related Disciplines, *Int. J. Eng. Educ.*, 2007, **23**, 242–253.

99 P. Akosah-Twumasi, T. I. Emeto, D. Lindsay, K. Tsey and B. S. Malau-Aduli, *A systematic review of factors that influence youths career choices – the role of culture*, Frontiers in Education, 2018, vol. 3, p. 58.

100 R. Jain, B. Shanahan and C. Roe, Broadening the Appeal of Engineering – Addressing Factors Contributing to Low Appeal and High Attrition, *Int. J. Eng. Educ.*, 2005, **25**(3), 405–418.

101 M. Besterfield-Sacre, M. Moreno, L. J. Shuman and C. J. Atman, Gender and ethnicity differences in freshmen engineering student attitudes: A cross-institutional study, *J. Eng. Educ.*, 2001, **90**(4), 477–489.

102 B. D. Shoener, I. M. Bradley, R. D. Cusick and J. S. Guest, Energy positive domestic wastewater treatment: The roles of anaerobic and phototrophic technologies, *Environ. Sci.: Processes Impacts*, 2014, **16**(6), 1204–1222.

103 M. L. Davis and S. J. Masten, *Principles of Environmental Engineering & Science*, McGraw-Hill Education, Columbus, OH, USA, 3rd edn, 2013, p. 864.

104 G. M. Masters and W. P. Ela, *Introduction to Environmental Engineering and Science*, Pearson Education Limited, London, UK, 3rd edn, 2013, p. 696.

105 J. R. Mihelcic and J. B. Zimmerman, *Environmental Engineering: Fundamentals, Sustainability, Design*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2nd edn, 2014, p. 704.

106 W. W. Nazaroff and L. Alvarez-Cohen, *Environmental Engineering Science*, John Wiley & Sons, Inc., New York, USA, 2000.

107 WEF, *Water Environment Federation Position Statement Renewable Energy Generation From Wastewater*, Water Environment Federation, Alexandria, USA, 2011.

108 A. C. Kokossis, Design of integrated biorefineries, *Comput.-Aided Chem. Eng.*, 2014, **34**, 173–185.

109 S. Satchatippavarn, E. Martinez-Hernandez, P. H. M. Y. Leung, M. Leach and A. Yang, Urban biorefinery for waste processing, *Chem. Eng. Res. Des.*, 2016, **107**, 81–90.

110 E. Montoneri, D. Mainero, V. Boffa, D. G. Perrone and C. Montoneri, Biochemenergy: A project to turn an urban wastes treatment plant into biorefinery for the production of energy, chemicals and consumer's products with friendly environmental impact, *Int. J. Global. Environ. Issues.*, 2011, **11**(2), 170–196.

111 C. Makropoulos, E. Rozos, I. Tsoukalas, A. Plevri, G. Karakatsanis and L. Karagiannidis, *et al.* Sewer-mining: A water reuse option supporting circular economy, public service provision and entrepreneurship, *J. Environ. Manage.*, 2018, **216**, 285–298.

112 WEF, *University-Utility Collaborative Partnerships*, Water Environment Federation, Alexandria, USA, 2017.

113 M. Pogatsnik, Dual Education: The Win-Win Model of Collaboration between Universities and Industry, *International Journal of Engineering Pedagogy*, 2018, **8**(3), 145–152.

114 K. Pagilla, University-utility collaborative applied research–a win–win combination, *Water Environ. Res.*, 2007, **79**(6), 579–580.

115 L. E. Brown, G. Mitchell, J. Holden, A. Folkard, N. Wright and N. Beharry-Borg, *et al.* Priority water research questions as determined by UK practitioners and policy makers, *Sci. Total Environ.*, 2010, **409**(2), 256–266.

116 Y. D. Scherson, A. Roa, G. Darling and C. S. Criddle, Sidestream Treatment with Energy Recovery from Nitrogen Waste: The Coupled Aerobic-anoxic Nitrous Decomposition Operation (CANDO), *Proceedings of the Water Environment Federation*, 2014, vol. 2014, issue 9, pp. 1114–1125.

117 WERF, *Better Link Utilities to Universities Alexandria*, Water Environment Research Foundation, Virginia, USA, 2018, Available from: http://www.werf.org/lift/lift/docs/LIFT_MA_Affiliate/Better_Link_Utilities_with_Universities.aspx.

118 Y. D. Scherson and C. S. Criddle, Recovery of freshwater from wastewater: upgrading process configurations to

maximize energy reovery and minimize residuals, *Environ. Sci. Technol.*, 2014, **48**(15), 8420–8432.

119 I. S. A. Abeysiriwardana-Arachchige, S. P. Munasinghe-Arachchige, H. M. K. Delanka-Pedige and N. Nirmalakhandan, Removal and recovery of nutrients from municipal sewage: Algal vs. conventional approaches, *Water Res.*, 2020, **175**, 115709.

120 M. R. Gillings, M. Westoby and T. M. Ghaly, Pollutants That Replicate: Xenogenetic DNAs, *Trends Microbiol.*, 2018, **26**(12), 975–977.