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Resource Recovery and Reuse for Sustainable Future Introduction and Overview

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1.1 Introduction

In recent years, resource (i.e. water, raw materials, and nutrients) and energy have been subject to high pressure caused by climate change, demographic and land use changes, increase in world population, and high standards of living together with urbanization [1]. Moreover, traditional water management (i.e. take–make–waste approach) and waste management (i.e. waste dumping in landfill sites) techniques have aggravated resource scarcity and environmental, social, and economic problems [2]. Additionally, rare and precious resources (i.e. indium, silver) will be used up by traditional supplies of these elements [3]. It is predicted that the annual energy demand will reach around 23 TW worldwide by 2050 [4]. Therefore, resource and energy recovery and reuse should be realized to alleviate resource scarcity and environmental degradation, and enable economic benefits.

Resource recovery can be achieved from two sources: water and waste. Current studies have focused on the recovery of heat, organic carbon, and nutrients from various types of wastewaters. The heat is recovered from household water (i.e. shower water), sewer, or wastewater treatment plants by a heat recovery system, which mainly contains a heat exchanger and a heat pump [5]. Nutrient recovery from wastewater, especially phosphorus recovery, is commonly achieved by struvite formation. Moreover, energy, nutrients, and materials can also be recovered from different kinds of wastes; one such example is the recovery of renewable energy from waste in the form of value-added products (e.g. methane containing biogas and ethanol), phosphorus from animal manures, food waste and sewage sludge, and materials in terms of heavy metals and scarce and valuable metals from mining waste, municipal and industrial waste, and e-waste [3, 6, 7].

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This chapter gives a brief introduction, key drivers, current status, and future perspectives of resource and energy recovery and reuse. The chapter is divided into four sections: background, the current status for waste generation and recovery, the research needs of resource and energy recovery and reuse, and a brief review on the core ideas and key researches for each book chapter.

1.2 Background

1.2.1 Hierarchy of Resource Use

For effective resource management, an alternative "hierarchy of resource use" (HRU) has been proposed by Gharfalkar et al. [8] to clarify "prevention, preparing for re-use, re-cycling, other recovery and disposal" in the latest version of European Commission's Waste Framework Directive 2008/98/EC and consider the "waste" as "resource." Figure 1.1 displays the proposed alternative HRU. HRU consists of five sections as follows:

(i) Replacement: rethinking, reinventing, or redesigning to remove or replace existing demand with demand for environmentally benign materials or objects and/or replace nonrenewable resources with renewable resources.
(ii) Reduction: reinventing or redesigning to "reduce" use of resources, including reduction in consumption of resources, waste generation and resultant environmental degradation.
(iii) Recovery involves preparing materials for reuse (a reusable material or an object can be reused by the preparing operation); reuse (reuse without any further operation, repair and reuse, refurbish and reuse, recondition on and reuse, remanufacture and reuse, any other operation and reuse); reprocessing (recycle, downcycle, and upcycle ["waste" is reprocessed into materials with the same, lower, and higher purpose/value than the original, respectively)]), and other recovery (energy recovery and/or recovery of materials to be used as fuels or for backfilling operations).
(iv) Rectification (a waste treatment operation before disposal).
(v) Return (disposal).

1.2.2 Analyzing the Needs for Resource and Energy Recovery and Reuse

The key drivers for resource and energy recovery and reuse mainly comprise population growth, environmental impacts, resource scarcity, and economic aspects. Figure 1.2 shows the interaction among the four key drivers for resource and energy recovery and reuse.

1.2.2.1 Population Growth

In 2019, the global world population reached 7.7 billion and it has been predicted that the global population will increase dramatically up to 9.7 billion in 2050 and 10.9 billion in 2100 [9]. Less developed countries play a key role in urban growth,

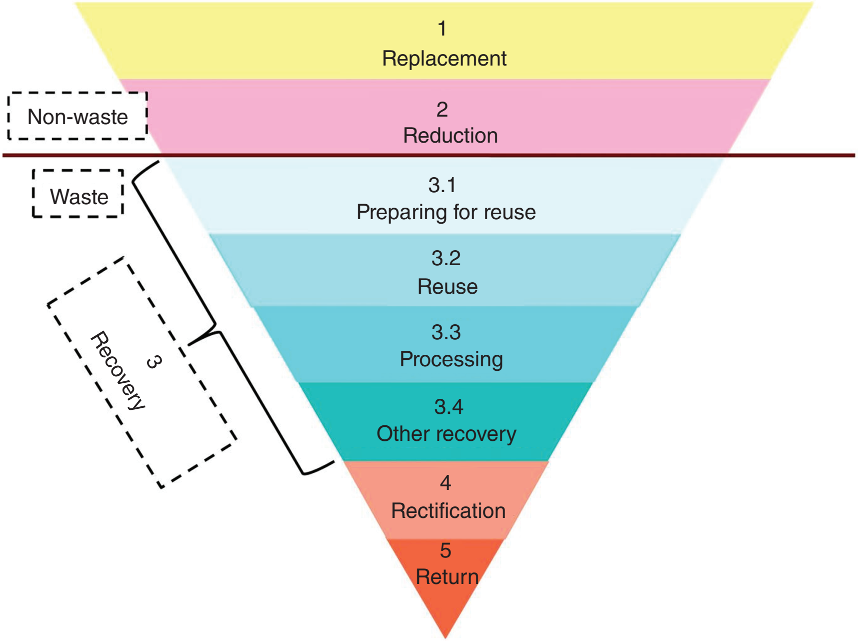

Figure 1.1 Proposed alternative “hierarchy of resource use” (reverse triangle) (Source: Modified from Gharfalkar et al. [8]).

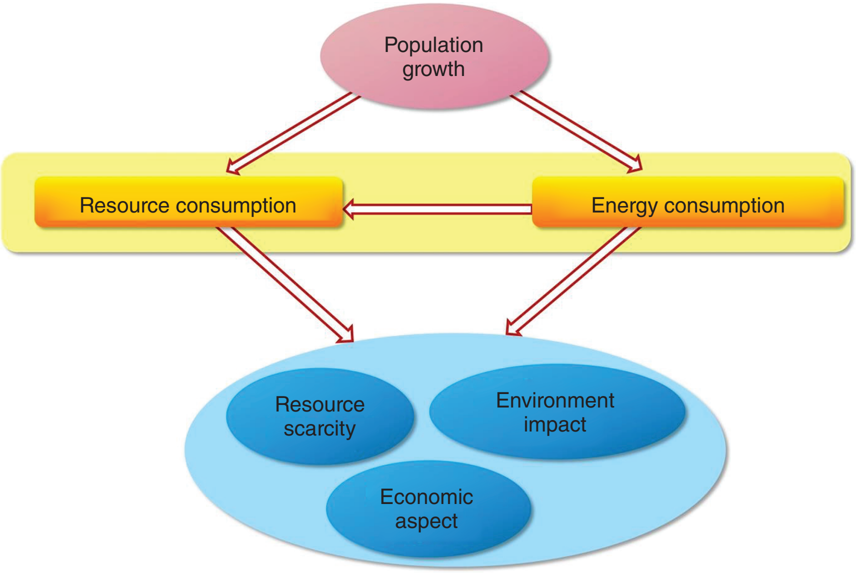

Figure 1.2 Interaction among the four key drivers for resource and energy recovery and reuse.

which contributes greatly to population growth. The world energy demand mainly comes from urban demands, with more than 2/3 of the world's energy expected to be consumed by cities from 2006 to 2030 [10]. World energy consumption is estimated to increase by approximately 23% from 2020 to 2040, reaching 820 quadrillion Btu [11]. Rapid urbanization also induces other striking problems, including land degradation, desertification, deforestation, resource (e.g. water, materials) depletion and pollution, and loss of biodiversity [12].

1.2.2.2 Resource Scarcity

Natural resources are commonly classified into two types, namely renewable (water, land, forest, fish, etc.) and depletable (minerals, metals, oil, etc.) resources [13]. Resource scarcity is caused by the increase in population growth, economic level, standard of living, and the limited supply of resources. Although it is possible to obtain more and more energy from renewable and nuclear energy sources, the amount of generated energy is still lower than the increasing energy demands. It has been pointed out that the higher energy demand in Asia significantly induces CO_2 emissions by combusting carbon-based energy sources (gas, oil, and coal), which annually increase by 2.3, 2.1, and 1.9% in India, China, and rest of Asia, respectively. It is also estimated that a large fraction of energy (> 76%) will originate from carbon-based source in 2040, which increases the diminishing rate of primary energy resources [14–16].

1.2.2.3 Environmental Impacts

The excessive discharge of nutrients into water bodies causes algal bloom and overgrowth of plants and "dead zones" in coastal marine ecosystems [17]. Nutrients exported from urbanized river basin in 2050 are projected to be around five times the level in 2000; these mainly come from sewage, industries, and urban agriculture [18]. Drinking water, soil, fodder and food are contaminated by heavy metals from industrial waste. Furthermore, contaminated sites being important sources of pollution can lead to ecotoxicological effects on terrestrial and aquatic ecosystems (e.g. increased cell size, shortened life span, and decreased body weight) [19, 20]. Resource consumption (e.g. fossil fuel for energy) together with increased life quality and world population, as well as industrialization of developing nations, exerts adverse impacts on the environment.

1.2.2.4 Economical Aspect

Zaman [21] pointed out that per capita gross domestic product (GDP/capita/year) is positively correlated with per capita waste generation (Table 1.1). It was reported that average waste generation rates in high-income (HIC, GDP = more than $12275/cap), upper middle-income (UMIC, GDP = $3976–$12275/cap), lower middle-income (LMIC, GDP = $1006–$3975/cap), and low-income (LIC, GDP = less than $1005) countries were 2.1, 1.2, 0.79, and 0.6 kg/cap/day, respectively [23]. Although 84% of waste generated is collected in the world, only 15% is recycled. In the future, waste generation would increase because of constant economic growth,

Table 1.1 Total nitrogen (TN) and total phosphorus (TP) content of different waste streams.

Wastewater	Description	TN (mg/L)	TP (mg/L)
Municipal wastewater	Sewage	15–90	5–20
Animal wastewater	Dairy	185–2636	30–727
	Poultry	802–1825	50–446
	Swine	1110[a)]–3213	310–987
	Beef feedlot	63–4165	14–1195
Industrial wastewater	Textile	21–57[a)]	1.0–9.7[b)]
	Winery	110[a)]	52
	Tannery	273[a)]	21[b)]
	Paper mill	1.1–10.9	0.6–5.8
	Olive mill	532	182
Anaerobic digestion effluent	Dairy manure	125–3456	18–250
	Poultry manure	1380–1580	370–382
	Sewage sludge	427–467	134–321
	Food waste and dairy manure	1640–1885[a)]	296–302

a) Total Kjeldahl nitrogen (TKN).
b) Total orthophosphates (PO_4^{3}–P).
Source: Cai et al. (2013) [22].

especially in the developing countries. Moreover, HIC could gain remarkable economic benefits from resource recovery and energy savings compared to other income groups. In the United States, Japan, and the European Union, the supply of raw materials influences the economy (e.g. jobs) [1].

1.3 Current Status of Resource Recovery and Reuse

1.3.1 Wastewater

Water contamination is now a serious issue due to surface water and ground water being heavily polluted by industrial and municipal wastewater, agricultural activities, and household wastes, especially in developing countries. For example, the amount of wastewater discharged in China was 68.5 billion tons in 2012 and this contained 24.2 million tons (Mt) of chemical oxygen demand (COD) and 2.5 Mt of ammonia nitrogen emission [24]. However, wastewater can be considered as a collection of resources that can be recovered, including energy, organic carbon, nutrients, and clean water. Thus, many efforts have been made to recover available resources from wastewater, mainly focusing on the recovery of nutrients, organic carbon, and heat.

1.3.1.1 Nutrient Recovery

The composition of wastewater is heavily dependent on its sources. Table 1.1 shows the total nitrogen (TN) and total phosphorus (TP) content in different wastewaters.

The key challenge for domestic wastewater treatment is the recovery of energy and nutrients (e.g. phosphorus, nitrogen, and potassium). There are two alternative wastewater treatment platforms to overcome these difficulties [25, 26]:

1. Low energy mainline (LEM), which enables net energy recovery through anaerobic processes (e.g. upflow anaerobic sludge blanket reactor and anaerobic membrane bioreactor) and phosphorus recovery through advanced ion adsorption techniques. However, although LEM removes nitrogen by main line anaerobic deammonification (Anammox) at low energy unit (20% of power consumption of conventional process), it cannot recover nitrogen and other elements (i.e. potassium).
2. Partition–release–recover (PRR), in which nutrients and organics are concentrated through assimilation into solids using heterotrophic or phototrophic microbes. Afterward, nutrients (nitrogen and potassium) can be recovered from the digestate subsequent anaerobic digestion by electrochemical techniques, struvite precipitation, etc.

Mainline anaerobic processes are favorable to be utilized in the shorter term for phosphorus and energy recovery due to its lower energy costs and it being closer to market status. Recovery of nitrogen and potassium can be accomplished by PRR for higher strength wastewaters, or higher COD:N ratio of wastewaters [26]. In general, phosphorus can also be recovered as calcium phosphate or struvite by feeding the phosphorus-rich wastewater into a precipitation/crystallization tank with addition of calcium or magnesium salts in a mixed or fluidized state. Municipal wastewater, which is dilute in nature, contains large amounts of greywater, flush water, and even storm water. Hence, the recovery of nitrogen and phosphorus from municipal wastewater is more expensive in view of economic and energy aspects. As wastewaters from agricultural diary, brewery, and starch-manufacturing industries contain lower phosphorus levels, the recovery of phosphorus as struvite is expensive from these industrial wastewaters [27].

1.3.1.2 Organic Carbon Recovery

COD concentration of the influent significantly affects organic energy in the form of methane. Hao et al. [28] pointed out that 53% of total energy consumption could be offset by organic energy when influent COD was 400 mg/L in a case study of a typical municipal wastewater treatment plant (WWTP) in China . Another case study was conducted by Khiewwijit et al. [29], and the proposed treatment contains bioflocculation, partial nitritation/Anammox, P recovery process, anaerobic sludge digestion, and combined heat and power. Compared to conventional activated sludge systems (no net energy yield, −0.08 kWh/m^3), the results revealed the possibility of improving the net energy yield up to 0.24 kWh/m^3 and reducing carbon emissions by 35%. Moreover, when COD increased by 20%, 26% increase in energy yield could be achieved.

As a renewable carbon resource, the recovery of volatile fatty acid (VFA) from different waste streams is attracting more and more attention for producing various valuable products, such as biogas, biodiesel, bioplastics (thermoplastic biodegradable polyesters), and biohydrogen. The amount of VFA generated from a given waste stream is determined by the acidification degree, which is related to the fraction of readily fermentable organics. Higher degree of acidification results in higher VFA generation. The composition of VFA (e.g. acetic acid, butyric acid, propionic acid, and others) is related to the characteristics of the organic matter contents in wastewater. The key VFA recovery methods include gas stripping with absorption, adsorption, electrodialysis, solvent extraction, nanofiltration, reverse osmosis, and membrane contractors [30].

1.3.1.3 Heat Recovery

Thermal energy, being another large reserve of energy, can be recovered from different types of wastewaters by heat exchangers or heat pumps.

It has been indicated that 1.16 kWh of thermal energy could be released by cooling one cubic meter of wastewater by 1 °C for specific heat of water. A water source heat pump (WSHP) can be used to capture the heat to effectively offset the difference between the total energy consumed and energy produced by anaerobic digestion. The amount of energy obtained from wastewater is affected by pump efficiency (i.e. coefficient of performance), the flow through the pump, the change of temperature in wastewater when passing through the pump, the distance between the location to be heated and the pump, and the total area available to be heated [31, 32]. Hao et al. [28] evaluated the energy recovered from a typical municipal WWTP in China and the results suggested that considering all relevant factors (i.e. boiler heating efficiency, average power generation efficiency, heat supply grid efficiency, and power grid loss), a net energy equivalent to 0.26 kWh/m^3 could be supplied by WSHP through decreasing the temperature of 1 m^3 of wastewater effluent by 1 °C.

1.3.2 Waste

The world generates 2.01 billion tonnes of municipal solid waste annually, with at least 33% of waste not managed in an environmentally safe manner. Worldwide, the average amount of waste generated per person per day ranges from 0.11 to 4.54 kg with an average of 0.74 kg. High-income countries generate about 34% (683 million tonnes) of the world's waste, but they only account for 16% of the world's population. The global waste generated is expected to grow to 3.40 billion tonnes by 2050 [33]. Depending on the economic situation of different countries, waste can be classified into different categories, including municipal solid waste (e.g. food waste, and sewage sludge), industrial waste (e.g. mining waste and construction and demolition waste), electronic waste, and hazardous waste. The disposal of waste into the environment not only leads to contamination of waterways and soil due to non-point source pollution, but also causes air pollution.

The total amount of global food waste is about 1.3 billion tonnes every year, with no remarkable difference between the developed and developing countries (670 and

630 million tonnes, respectively). China and India are the major contributors for FW generation from developing countries, with values of 195 and 72 million tons, respectively. In developing countries, food waste accounts for 50–55% of municipal solid waste (MSW). The worldwide urban food waste will increase by 44% between 2005 and 2025 [34].

The variable chemical composition in food waste is due to different origin of production, which contains carbohydrates, lipids, and proteins or high concentration of these constituents [35]. Current studies have explored the recovery of value-added products (i.e. proteins, polysaccharides, flavor compounds, fibers, and phytochemicals that can be used as nutritionally and pharmacologically functional ingredients) from food waste. The recovered biomolecules and by-products can be employed for food and food processing uses (e.g. as gelling agents in sweets, food additives), as well as medicinal and pharmaceutical uses (e.g. as appetite modulators). The extraction techniques include solid–liquid extraction, soxhlet extraction, ultrasound-assisted extraction, microwave-assisted extraction, pressurized fluid extraction, and supercritical fluid extraction, pulsed electric field extraction, and enzyme-assisted extraction [36].

Biosolids generated by removing the part of chemical oxygen demand during biological wastewater treatment process are often referred to as sewage sludge. It was reported that half of wastewater phosphorus (2–8 mg/L) is integrated into biosolids. The enhanced biological phosphorus removal process prompts the accumulation of phosphorus in sludge from 0.02 to 0.06–0.15 mg/g VSS (volatile suspended solids). A small proportion of the activated sludge dry mass contains 24–67 g N/kg dry mass of nitrogen and the remaining N in the form of N_2 gas. Potassium accounted for 0.5–0.7% K_2O weight of dry solids of sewage sludge. The complete recovery and reuse of nutrients from 30 million tons of sludge generated annually in the world could meet the demands of 5% of phosphorus, 1.7% of nitrogen, and 0.64% of potassium [37, 38].

Mining involves various activities such as mine development, mineral beneficiation, metal extraction, smelting, refining, reclamation, and remediation. In the mining and metal extraction industry, different types of wastes are produced (e.g. waste rock, mineral beneficial tailings, metallurgical slags, wastewater, and water treatment sludge). In fact, these waste streams can be considered as secondary sources of valuable minerals and metals. The recovery of value metals from ferrous metallurgical dusts that are generated in the iron and steel manufacturing processes can be realized through pyrometallurgical and hydrometallurgical processes. Compared to the pyrometallurgical processes, the hydrometallurgical processes have more advantages of higher flexibility of operation, the required economies of scale, lower capital costs, and the minimum environmental challenges related to flue gases, dusts, and noise. Nevertheless, careful management of water, wastewater, and process solutions is required for its technical and economic feasibility. Moreover, the complex characteristics of the dust materials also restrict the wide application of the hydrometallurgical processes [39].

The high consumption of electronic equipment and their short lifespan prompt an increase in manufacture of electronic and electrical equipment and the production of electronic waste (e-waste) [40]. E-waste generally comes from individual households, small business sections, original manufacturing sectors, large corporations, and institutions and governmental sectors. In recent years, approximately 20–50 million tons of e-waste are generated per year in the world with an annual growth rate of up to 5%, while around 12 million tons of them are disposed [41]. Currently, valuable metals production system is subjected to some challenges owing to the scarcity of primary resources and earth's intrinsic limitations [42]. Therefore, as the key component of electronic devices, the waste printed circuit boards (WPCB) contain higher concentration of several precious metals than their corresponding ores. For example, concentrations of silver, gold, and palladium in minerals ($< 10\,\text{g/tonne}$) are lower than those found in computer printed circuit boards (typically average of 1000, 250, and 110 g/tonne PCB, respectively). Besides, it is estimated that the value of copper and precious metals in waste mobile phones and WPCB accounted for up to 80% of the total value [43]. Some metals (e.g. Cu, Pb, Fe, Au, and Hg) have been successfully recovered from PCB. Spent batteries and used machines and instruments are also used for recovery of metals (e.g. Co, Li, Zn, Mn, Pb, Ni, Au, Pd, and Pt) and rare earths [41].

1.4 Research Needs

1.4.1 Development of Novel Technologies

New processes and improvements in the existing technologies for resource recovery should be carried out due to the complex characteristics of resources. Moreover, hybrid systems incorporating different kinds of technologies are suggested to be developed to enhance resource recovery and reuse from wastewater and waste, such as bioelectrochemical systems combined with current wastewater treatment plant, specific bacteria (e.g. hydrogen-oxidizing bacteria) coupled with other systems (e.g. electrochemical or bioelectrochemical system) [4], and integration of membrane-based process with anaerobic treatment. Some aspects that should be considered when developing novel technologies include:

- Less complicated operation.
- High efficiency of resource recovery.
- Efficient and economic production of value-added products.
- Generation of few or several high-volume liquid transportation fuel to fulfill some national requirements of energy [44].
- Production of electricity and process heat available for its own use [44].
- Reduction of sludge production during wastewater treatment process.
- Less greenhouse gas emissions.

1.4.2 Social and Economic Feasibility of Resource Recovery and Reuse

Economic sustainability should be considered when implementing large-scale operations. Based on the principles of efficient resource recovery and economic operation, substantial research should be performed to scale up current and emerging techniques for resource recovery from waste and wastewater. Detailed techno-economic analysis of the novel technologies should be conducted, such as energy demand, operating and maintenance costs, reproducibility of lab-scale results in large scale, and market demands. Social feasibility is a key point as high acceptance of the technology could ensure its market place and wide application.

1.4.3 Development of Internationally Coordinated Framework and Strategy

The cooperation among governments, researchers , and companies in developing and developed countries with regard to coordinated framework and strategy is required to ensure a global sustainable market for the application of resource recovery technologies. Rigorous legislative frameworks should also be given for wastewater and waste discharges and resource recovery to reduce environmental contamination and maximize the recovery and reuse of resource.

1.5 Book Overview

The primary objective of this 25-chapter book is to elucidate basic scientific principles and technological advances of current technologies for resource and energy recovery and reuse.

Food waste, an abundant bioresource, can be a potential feed to establish a sustainable supply chain of high-energy density biofuels with low carbon footprint. The urgent need for clean fuels to curb the alarming greenhouse gas emissions and the prerequisite to meet the growing energy demand have propelled the development of the hydrothermal liquefaction (HTL) technology. HTL-driven wet food waste valorization has garnered global attention for resource recovery in the form of bio-oil/bio-crude, bio-char, and other gaseous products that can be upgraded to useful platform chemicals and biofuels. Chapter 2 showcases HTL of food waste as a commercially feasible energy recovery alternative that can be highly beneficial to conventional fossil-driven sectors.

In the context of ambitions for a circular economy, there is need for fundamental transition in resource recovery practices. However, while the sustainability transitions literature focuses on the transition toward a more sustainable future, practically policymakers must operationalize a goal for moving away from an unsustainable present. Historically, the United Kingdom has relied upon disposal of waste to landfill rather than viewing waste as a potential material resource and encouraging material recycling. Yet from a low base, a major successful change was made at the UK local authority level in the collection and sorting processes required to effect this sustainable transition between the then government's waste strategy appearing in 2000 and the defeat of the government in 2010. Chapter 3 discusses this change from the perspective of local authorities, who have a pivotal role in household waste management, taking a long view of the 2000s to consider the major changes in environmental policy and local government organization between 1979 and 2014. The chapter also draws on interview data from local authority waste managers in the Yorkshire and Humberside region as well as national policymakers and regulatory bodies, in addition to local authority and national waste statistics, government and industry documents. Results indicate that the historical and geographical contexts are important for understanding the ability of the local authorities to respond. It is concluded that the "landscape" level is more geographically constructed than recognized in the literature and that the regime scale, rather than being a fixture that needs to be changed, is changing continuously.

As HTL has been widely applied to obtain bioenergy and high-value chemicals from biomass at moderate to high temperature (200–550 °C) and pressure (5–25 MPa), Chapter 4 further focuses on the HTL conversion properties of lignocellulosic biomass of agricultural and forestry wastes. The history and development of HTL technology for lignocellulosic biomass are briefly introduced. The research status in HTL of agricultural and forestry wastes are critically reviewed, and the effects of HTL conditions on bio-oil yield and the decomposition mechanisms are summarized. The limitations of HTL of agricultural and forestry wastes are also addressed, and future research priorities are proposed.

The nutrients present in human faeces, such as nitrogen, phosphorous, and potassium can be recycled if a linear, non-recycling open-ended system is discarded. A better sanitation approach would be to focus on recovery of nutrients present in human excreta and considering sanitation systems as collection and processing units of those nutrients. Chapter 5 introduces the available technologies focusing on resource recovery from human waste. The potential impacts of these systems are discussed. It is concluded that ecological sanitation solutions are much cheaper and have much lower environmental impacts although the acidification potential remains a cause of concern and requires further research. These solutions are also feasible in developing countries and require low energy and capital investments. Hence, regions that do not have adequate wastewater treatment facilities from the very beginning should concentrate on implementing technologies that are resource recovery oriented.

Chapter 6 systematically outlines the current status of livestock manure production, transportation, and recycling, and proposes a future research perspective for its management from a global perspective. With the rapid development of large-size livestock farming and increasing demand of animal products, livestock and poultry farming methods have been transformed from traditional decentralized and extensive to large-scale, intensive, and specialized, as, an inevitable by-product of livestock and poultry farming, a huge quantity of animal manure (such as: pig manure, chicken manure, cow manure, duck manure, and so on) is generated all the time in each country and the resulting livestock manure has also been concentrated into the local environment, causing serious damage to the surrounding soil, groundwater, and atmosphere. Therefore, it is of great environmental and economic significance to recycle livestock and poultry manure upon a commercial model. The production, collection, transportation, and treatment of livestock and poultry manure are all currently in urgent need of research and innovation. Current treatments and technologies for livestock and poultry manure include anaerobic digestion and aerobic composting, which are all through the use different types of microorganisms under an aerobic or anaerobic environment to humify manure or convert them into natural gas, thereby achieving resource utilization. Due to the different national and economic conditions of developed and developing countries, there are some differences existing in the recycling and disposal of livestock manure. Using the theory of circular economy to recycle livestock manure has become an innovative and hot research topic, many developed countries have tried to apply the business model of circular economy to the recycling of livestock and poultry manure as well as follow the 3R principle for resource utilization. This chapter also prospects the utilization of livestock manure resources; the rational use of the theory and business model of circular economy to recycle livestock manure is an effective measure for the treatment of livestock manure in each country in the future.

There are growing concerns of fossil fuel consumption and its critical negative impact on our environment, which have driven the research and development of sustainable biofuel production in the last decades. Microalgae and thraustochytrids are promising candidates for biofuel production because of their great biomass growth rate and lipid accumulation potential. However, there are still technical and economic barriers for the commercialization of microalgae/thraustochytrids-based biofuel production. Some microalgae and thraustochytrid species have shown attractive nutraceutical application potentials, which may generate great economic values to offset the biofuel production cost. Integration of the manufacture of biofuel and nutraceutical products from microalgae/thraustochytrids could probably make the microalgae/thraustochytrids-based biofuel production economically feasible. Chapter 7 presents a review of the recent advances in the production of biofuel and nutraceutical products such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) from microalgae and thraustochytrids, including technical, economic, and environmental challenges as well as future perspectives.

Chapter 8 identifies issues related to algal energy and bioproduct formation with a perspective on market opportunities for different bio-products. Though the dilemma of cultivating algae stems around overwhelming capital and operational costs, increasing number of published studies in the past exemplify the exponential growth of microalgae bioenergy research. Currently, the main purpose of biorefinery is to integrate the production of commodity chemicals and high-value products along with fuel and energy generation, while optimizing resources and minimizing waste. Water recyclability, co-production of high-value products along with energy generation and under highly controlled process parametric conditions with specific market value analysis is the key to make the algae biorefinery logistics highly industry feasible. Furthermore, the development of cheaper novel downstream processing options would render the algae cultivation process acceptable, while helping in managing waste and simultaneously reduce carbon footprints.

The amount of sludge produced by sewage treatment is increasing rapidly, and the resource utilization of sewage sludge has been paid much attention in recent decades. Chapter 9 introduces the preparation, characteristics, and application of sludge-derived carbon for wastewater biosorption in view of influencing parameters, such as activating agent, contact time, initial pollutant concentrations and modification method. The biosorption performance and mechanism of granular sludge for direct organic pollution and heavy metal treatment are also summarized. Moreover, the role of extracellular polymeric substances (EPS) during granular sludge biosorption process and the interaction between EPS and pollutions by using various spectroscopic approaches are systematically reviewed. Additionally, due to the abundant functional groups and binding sites, the environmental applications of EPS as effective bioflocculant and adsorbent in wastewater treatment are reviewed.

As sewage sludge posed a serious environmental challenge, Chapter 10 reviews thermal-chemical processes, which have been considered as an emerging technology for sewage sludge management aiming for concurrent volume reduction, pathogens destruction, and energy and resource recovery. This chapter offers a comprehensive picture of the state of the art of energy and resource recovery from sewage sludge through thermal-chemical treatment, with the focus on process feasibility, cost, limitations, challenges, and solutions forward. The design, optimization, and operation of the thermal-chemical treatment processes of sewage sludge for long-term environmental sustainability and economic viability, with maximized energy and resources recovery, have also been addressed.

Chapter 11 introduces the treatment of sewage sludge through anaerobic sludge digestion. The state-of-the-art technologies for enhancing methane and hydrogen productions from sewage sludge are also elucidated, including physical, chemical, and biological pretreatment. Emphasis was put on their effect on methane and hydrogen production performance, with an increase of 10–340% in methane production and an increase of 20–1300% in hydrogen production. In general, thermal pretreatment, free nitrous acid pretreatment, free ammonia pretreatment, and temperature-phased anaerobic digestion show advantages over the other pretreatment technologies. In addition, ultrasonic pretreatment (< 4400 kJ/kg total solids) will also be promising if pathogen destruction is not a main concern. In the future, various pretreatment technologies should be implemented to the same sludge source in order to avoid the bias imposed by the different sludge sources.

Phosphorus (P) is a main water pollutant responsible for eutrophication and related surface water quality problems. On the other hand, P is also a limited and non-substitutable nutrient for agricultural production. The rapid depletion of natural P reserves will greatly threaten global food security. It is therefore urgent to recover and recycle P from all possible sources, including wastewater and sludge. In Chapter 12, different technologies for effective P recovery in connection to chemical P removal are introduced, including chemically enhanced primary sedimentation and chemically enhanced membrane bioreactor. The very different solubilities of Fe(III)–P and Fe(II)–P complexes and microbial transformation of Fe(III) to Fe(II) are utilized for P removal and recovery. The main pathways for P removal and recovery in chemical precipitation and acidogenic fermentation are revealed by X-ray absorption near edge structure (XANES) spectroscopy.

Although P is a nonrenewable resource, excess phosphorus inevitably enters the water environment and causes eutrophication. Compared with other technologies such as chemical precipitation and biological processes, adsorption is a favorable option for its simplicity in design, easy operation, and minimal waste production. Although various adsorbents have been developed, some drawbacks limit their application in the field. Thus, Chapter 13 introduces the novel magnetic iron-based oxide materials developed in the form of core–shell structure and composites (i.e. $ZrO_2@Fe_3O_4$, $La(OH)_3/Fe_3O_4$ and Fe^0/Fe_3O_4) for phosphorus removal and recovery, which have strong selectivity, high adsorption capacity, favorable reusability, and present easy material separation by magnetic field. The results show a high potential of using magnetic iron-based oxide materials for possible phosphorus removal and recovery applications.

Forward osmosis (FO), considered as a promising separation process for nutrient enrichment in wastewater, is attracting increasing interest in integration with chemical precipitation and other technologies for recovering nutrients in wastewater treatment. Chapter 14 highlights nutrients recovery processes via FO-based systems based on mechanisms and influencing factors. In addition, the key challenges related to the recovery systems discussed and some approaches are proposed to resolve these challenges. Future roadmap for future research and development on the nutrients recovery using FO-based systems are identified. Compared to aerobic FO-based systems, anaerobic FO-based processes need more investigations of their integrations' efficiency in the context of nutrient recovery from wastewater. Emphasis is given to carry out more economic assessment and pilot- and plant-scale evolutions of the recovery systems, which makes the nutrients recovery via FO-based technologies more sustainable in wastewater treatment.

Adsorption using low-cost adsorbent seems to be a promising technique for nutrient recovery. For the sustainability of the ecosystem and environmental protection, removal and recovery of nutrients from wastewater along with regeneration and reuse of spent adsorbent are essential. Many investigations have been carried out for the removal of nutrients from single-component systems whereas very few investigations have examined and modeled the nutrients removal in multicomponent adsorption systems. Chapter 15 covers the basic principles and potential application of low-cost adsorbent for removal and recovery of nutrients (PO_4^{3-} and NO_3^-) from single-component and multicomponent adsorption systems. Furthermore, this chapter provides an overview of adsorption capability of different low-cost adsorbents for PO_4^{3-} and NO_3^- removal, factors influencing adsorption, kinetic and equilibrium modeling, mechanism of nutrient adsorption, and management of spent adsorbent. Finally, the application of modified Langmuir model for binary adsorption system (simultaneous removal of PO_4^{3-} and NO_3^-) is discussed.

Since P must be removed from wastewater, commonly to <1 mg P/L before discharge to the environment, Chapter 16 focuses on developed biochar-based materials, produced through various approaches, which have been shown to be effective as P adsorbents. It is indicated that research now needs to demonstrate the practical ability of developed materials to recover P from wastewater, to become part of a solution to increase the sustainable use of P.

Gold is a well-known precious metal, which is reported to have been in use since 3400 BC. Since gold is precious and expensive, the recycling of gold particles from electronic devices has attracted the attention of researchers and industries. Among various conventional techniques available, biosorption is a promising method to recover gold from leachate. In Chapter 17, the need for recovery of gold to meet the ever-increasing demand for precious metal is discussed. Various technologies available for recovery of gold for secondary sources are discussed and predominantly biosorption is chosen for detailed discussion in this chapter. Different types of biomasses employed for gold recovery and their performance are critically analyzed. Furthermore, the limitations and futuristic scope of gold recovery from secondary sources have been discussed.

Due to large quantity and containing rich resources (e.g. chemical energy, metals, fresh water, and nutrients), recovery resources from municipal and industrial wastewaters can be considered where resource recovery economy can be applied. Simultaneously, resource recovery during wastewater treatment will make treatment processes more economically viable and compliant to increasingly tight environmental regulations. Bioelectrochemical systems (BESs) have emerged as a platform technology to recover resources from wastewater treatment. Chapter 18 gives a comprehensive and critical review of resource recovery via BESs. The basic information of BESs as well as the processes of resource recovery through BESs at the laboratory and plant scale are introduced. Furthermore, the current challenges related to the BES applications for the resource recovery and the possible development directions are discussed.

The textile dyeing industry has created a huge pollution problem because organic dyes are one of the largest groups of pollutants released into the environment with highly toxic and hazardous impacts on living organisms. Recently, more attention has been given to the oxidative removal of various organic pollutants by electrochemically generated hydroxyl radical including the use of high-energy radiation. In Chapter 19, dye discoloration and degradation as a result of its exposure to high-energy radiation by electron beam method are discussed in detail. The role of a variety of free radicals and ions produced during the radiolysis of water such as $\bullet$H, $\bullet$OH, and e_{aq}^- has been reported by various researchers. The results show that e_{aq}^- is very effective in decolorization but is less active in the further degradation of the products formed. The laboratory and pilot plant application of electron beam radiation for wastewater treatment are also discussed. Electron beam radiation can be an effective technique for decolorization of wastewater containing textile dyes with some advantages such as the speed, continuity, and high efficiency of the process, especially without using chemical and forming secondary sludge.

The increasing production of breeding wastewater brings environmental challenges. As breeding wastewater can be used as a valuable resource instead of a waste considering the large amounts of organic matters and nutrients in it, Chapter 20 presents the main characteristic of breeding wastewater, the potentially valuable resources in breeding wastewater and main approaches for resources recovery. Through the applications of biological, physiochemical, plant-based, and thermochemical technologies, multiple value-added products, nutrients, and renewable bioenergy can be recovered from breeding wastewater. However, the application of these technologies still has scientific and technical barriers requiring further study.

The manganese (Mn) production process generates gases, wastewater, and solid wastes, and these wastes have caused serious pollution to the environment. Chapter 21 focuses on the recovery and reuse of valuable elements in the liquid and solid wastes from Mn production industry. The chapter first introduces the production processes of electrolytic manganese metal (EMM), generation of electrolytic manganese residue (EMR), and electrolytic manganese wastewater (EMW). Then, the chapter describes laboratory tests as well as the design and performance of a pilot-scale treatment system for selective separation and recovery of Mn (in the form of $MnCO_3$) from Mn-bearing wastewater (and waste slag) using CO_2. The chapter then introduces the chemical and bioleaching methods for activating/recovering silicon from EMR. Finally, the chapter summarizes the current research and provides insight for future work and directions. For the first time, this chapter elucidates how to develop a systematic approach for the management of ore processing wastewater and solid wastes.

Eighty percent of the city's per capita daily water consumption is discharged into municipal wastewater pipes. The temperature of discharged wastewater temperature is higher than the ambient temperature in winter and lower than the ambient temperature in summer. This thermal energy stored in it can be recovered by the wastewater source heat pump to heat (area heating or hot water production) or cool the building. Chapter 22 introduces the characteristics of wastewater, the principle and application of wastewater source heat pump, wastewater heat exchanger, low-cost decontamination technology, and other key aspects of wastewater thermal energy recovery. With the continuous application of wastewater source heat pumps in the world, although the wastewater heat recovery technology is continuously developing and progressing, the application problems currently faced and its broad prospects are also presented in this chapter.

Hydrocyclone has a history of about 129 years. It has been used in various industries including mineral, chemical, coal, petroleum, papermaking, environmental protection, soil remediation, waste management, agriculture, aquaculture, food, biotechnology, nanotechnology, material science technology, and thermal energy due to its high separation efficiency, small cut size, small split ratio, lack of moving components, and low total static pressure drop. To further expand its application range in the field of resource recovery and reuse, Chapter 23 introduces the working principle of hydrocyclones, characteristic of fluid flow in hydrocyclones, parameters evaluating performance of hydrocyclones, and the applications of hydrocyclones in resource recovery and reuse. This chapter also comprehensively reviews the hydrocyclone-separation technologies developed by geometric parameters, operating parameters, and operating conditions; the challenges; and perspectives.

Every year millions of tons of wastes are deposited in landfills. Wastes in the landfills undergo a series of decomposition processes resulting in the generation of different gases. The landfill gases (LFG) pose a threat to the environment as well as human health due to their explosive nature, odor, and climate changing potential. Landfills are one of the major contributors of anthropogenic methane emissions in the world. Although LFG is considered a liability due to its harmful effects, the liability can be turned into asset by exploiting the energy potential of landfill methane.

Chapter 24 introduces the process of extracting LFG from a landfill and processing the gas to meet the end use requirements, and demonstrates that recovering landfill methane not only improves public safety and reduces environmental hazards but also provides opportunity to generate revenue and offset the use of nonrenewable sources of energy. The feasibility of the LFG recovery system is affected by various environmental and economic factors that need to be assessed for the planning and design of LFG recovery system.

The rapid growth of electronic products manufacturing and consumption has led to global concerns about the generation of electronic waste (e-waste), which poses serious threats to the environment and human health. As e-waste contains a wide range of chemicals, metals, plastics, and other substances, the appropriate management of e-waste is facing big challenges due to environmental, technical, economic, and health issues during the treatment and recycling processes. This chapter provides comprehensive information about the current status of e-waste generation, health impacts of e-waste, and the benefits of e-waste recycling. Recent advances in recycling and recovery of valuable materials such as metals, plastics, lithium-ion batteries, and waste solar PV panels have been presented. As a critical environmental problem worldwide, future perspectives and the needs of research on better e-waste management are also addressed.

References

1 Hennebel, T., Boon, N., Maes, S. et al. (2015). Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives. *New Biotechnology* 32: 121–127.

2 Daigger, G.T. (2009). Evolving urban water and residuals management paradigms: water reclamation and reuse, decentralization, and resource recovery. *Water Environment Research* 81: 809–823.

3 Dodson, J.R., Hunt, A.J., Parker, H.L. et al. (2012). Elemental sustainability: towards the total recovery of scarce metals. *Chemical Engineering and Processing* 51: 69–78.

4 Bajracharya, S., Sharma, M., Mohanakrishna, G. et al. (2016). An overview on emerging bioelectrochemical systems (BESs): technology for sustainable electricity, waste remediation, resource recovery, chemical production and beyond. *Renewable Energy* 98: 153–170.

5 Cipolla, S.S. and Maglionico, M. (2014). Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy. *Energy Procedia* 45: 288–297.

6 Mayer, B.K., Baker, L.A., Boyer, T.H. et al. (2016). Total value of phosphorus recovery. *Environmental Science & Technology* 50: 6606–6620.

7 Zhao, Y. and Zhen, G. (2017). *Pollution Control and Resource Recovery for Sewage Sludge*, 1e. Oxford: Butterworth-Heinemann.

8 Gharfalkar, M., Court, R., Campbell, C. et al. (2015). Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Management* 39: 305–313.

9 Population Matters (2020). *Population: The Numbers*, https://populationmatters.org/the-facts/the-numbers (accessed 31 January 2020).

10 Madlener, R. and Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: what can we learn for urban energy planning and urbanization management? *Sustainable Cities and Society* 1: 45–53.

11 Bilgen, S. (2014). Structure and environmental impact of global energy consumption. *Renewable and Sustainable Energy Reviews* 38: 890–902.

12 Su, B., Heshmati, A., Geng, Y. et al. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of Cleaner Production* 42: 215–227.

13 Mildner, S.A., Gitta, L., and Wiebke, W. (2011). Scarcity and abundance revisited: a literature review on natural resources and conflict. *International Journal of Conflict and Violence* 5: 155–172.

14 Chong, Z.R., Yang, S.H.B., Babu, P. et al. (2016). Review of natural gas hydrates as an energy resource: prospects and challenges. *Applied Energy* 162: 1633–1652.

15 Farhad, S., Saffar-Avval, M., and Younessi-Sinaki, M. (2008). Efficient design of feedwater heaters network in steam power plants using pinch technology and exergy analysis. *International Journal of Energy Research* 32: 1–11.

16 Panwar, N.L., Kaushik, S.C., and Kothari, S. (2011). Role of renewable energy sources in environmental protection: a review. *Renewable and Sustainable Energy Reviews* 15: 1513–1524.

17 Conley, D.J., Paerl, H.W., Howarth, R.W. et al. (2009). Controlling eutrophication: nitrogen and phosphorus. *Science* 323 (5917): 1014–1015.

18 Kroeze, C., Hofstra, N., Ivens, W. et al. (2013). The links between global carbon, water and nutrient cycles in an urbanizing world – the case of coastal eutrophication. *Current Opinion in Environmental Sustainability* 5: 566–572.

19 Panagos, P., Liedekerke, M.V., Yigini, Y. et al. (2013). Contaminated sites in Europe: review of the current situation based on data collected through a European Network. *Journal of Environmental and Public Health*: 158764. 11 pages doi:https://doi.org/10.1155/2013/158764.

20 Wu, X., Cobbina, S.J., Mao, G. et al. (2016). A review of toxicity and mechanisms of individual and mixtures of heavy metals in the environment. *Environmental Science and Pollution Research* 23: 8244–8259.

21 Zaman, A.U. (2016). A comprehensive study of the environmental and economic benefits of resource recovery from global waste management systems. *Journal of Cleaner Production* 124: 41–50.

22 Cai, T., Park, S.Y., and Li, Y. (2013). Nutrient recovery from wastewater streams by microalgae: status and prospects. *Renewable and Sustainable Energy Reviews* 19: 360–369.

23 Hoornweg, D. and Bhada-Tata, P. (2012). *What A Waste: A Global Review of Solid Waste Management*. Washington, DC: Urban Development & Local Government Unit, World Bank.

24 Jin, L., Zhang, G., and Tian, H. (2014). Current state of sewage treatment in China. *Water Research* 66: 85–98.

25 Batstone, D.J. and Virdis, B. (2014). The role of anaerobic digestion in the emerging energy economy. *Current Opinion in Biotechnology* 27: 142–149.

26 Batstone, D.J., Hülsen, T., Mehta, C.M. et al. (2015). Platforms for energy and nutrient recovery from domestic wastewater: a review. *Chemosphere* 140: 2–11.

27 Desmidt, E., Ghyselbrecht, K., Zhang, Y. et al. (2015). Global phosphorus scarcity and full-scale P-recovery techniques: a review. *Critical Reviews in Environmental Science and Technology* 45 (4): 336–384.

28 Hao, X., Liu, R., and Huang, X. (2015). Evaluation of the potential for operating carbon neutral WWTPs in China. *Water Research* 87: 424–431.

29 Khiewwijit, R., Temmink, H., Rijnaarts, H. et al. (2015). Energy and nutrient recovery for municipal wastewater treatment: how to design a feasible plant layout? *Environmental Modelling & Software* 68: 156–165.

30 Atasoy, M., Owusu-Agyeman, I., Plaza, E. et al. (2018). Bio-based volatile fatty acid production and recovery from waste streams: current status and future challenges. *Bioresource Technology* 268: 773–786.

31 Smith, K., Liu, S., Liu, Y., and Guo, S. (2018). Can China reduce energy for water? A review of energy for urban water supply and wastewater treatment and suggestions for change. *Renewable and Sustainable Energy Reviews* 91: 41–58.

32 McCarty, P.L., Bae, J., and Kim, J. (2011). Domestic wastewater treatment as a net energy producer–can this be achieved? *Environmental Science & Technology* 45: 7100–7106.

33 Kaza, S., Yao, L., Bhada-Tata, P. et al. (2018). *What a Waste 2.0 – A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank.

34 Thi, N.B.D., Kumar, G., and Lin, C.Y. (2015). An overview of food waste management in developing countries: current status and future perspective. *Journal of Environmental Management* 157: 220–229.

35 Girotto, F., Alibardi, L., and Cossu, R. (2015). Food waste generation and industrial uses: a review. *Waste Management* 45: 32–41.

36 Baiano, A. (2014). Recovery of biomolecules from food wastes – a review. *Molecules* 19: 14821–14842.

37 FAO (2012). *Current World Fertilizer Trends and Outlook to 2016*. United Nations: Food and Agriculture Organization.

38 Mulchandani, A. and Westerhoff, P. (2016). Recovery opportunities for metals and energy from sewage sludges. *Bioresource Technology* 215: 215–226.

39 Matinde, E., Simate, G.S., and Ndlovu, S. (2018). Mining and metallurgical wastes: a review of recycling and re-use practices. *Journal of the Southern African Institute of Mining and Metallurgy* 118: 825–844.

40 Cayumil, R., Khanna, R., Rajarao, R. et al. (2016). Concentration of precious metals during their recovery from electronic waste. *Waste Management* 57: 121–130.

41 Dutta, T., Kim, K.H., Deep, A. et al. (2018). Recovery of nanomaterials from battery and electronic wastes: a new paradigm of environmental waste management. *Renewable and Sustainable Energy Reviews* 82: 3694–3704.

42 Tesfaye, F., Lindberg, D., Hamuyuni, J. et al. (2017). Improving urban mining practices for optimal recovery of resources from e-waste. *Minerals Engineering* 111: 209–221.

43 Hagelüken, C. and Corti, C. (2010). Recycling of gold from electronics: cost-effective use through "Design for Recycling". *Gold Bulletin* 43: 209–220.

44 Tyagi, V.K. and Lo, S.L. (2013). Sludge: a waste or renewable source for energy and resources recovery? *Renewable and Sustainable Energy Reviews* 25: 708–728.