Algal-bacterial Granular Sludge-based Wastewater Treatment System and Its Prospects in the Context of Circular Economy

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Abstract

Increasing waste generation and growing natural/processed resources demand from the rapid human population growth in the past 100 years are the greatest threats to environmental safety and sustainable development. Along with the increase in wastewater generation, the transition and focus of wastewater treatment varied in accordance with the needs and requirements of the society. Biological wastewater treatment systems are the most preferred alternatives due to their low-cost, environmentally friendly, easy-to-operate, and low chemical use features. The flocculent conventional activated sludge (CAS) process has been successfully applied in urban environments for the past five decades. However, its use is increasingly considered unsuitable for future demands because of its drawbacks. Aerobic granular sludge (AGS) systems, accepted as the second-generation wastewater treatment biotechnologies, are competitive alternatives to the flocculent CAS. Their characteristically dense, compact, and fast-settling granules promote rapid water-biomass separation that highlight their high efficacy and largely reduced land footprint requirements. Currently, there are two distinct AGS biotechnologies, bacterial AGS and algal-bacterial AGS; and the latter is the symbiotic granular system of microalgae and bacteria. These innovative alternatives are prospective solutions to the society's resource scarcity and pollution reduction needs in energy efficiency, climate-smart adaptability, and resource recovery. This propels a circular economy integration of wastewater treatment plants (WWTPs), which is critical to the future sustainability of WWTPs. Hence, the sustainability and resource recovery evaluation of WWTPs is expected to become an essential component of WWTPs or water and resources recovery facilities (WRRFs) in the context of circular economy.

The underlining hypothesis guiding this research is that wastewater treatment technology advance/engineering is a continuum to meet the changing needs of the society. The current value of resources recovery from wastewater has not been extensively explored in the literature, nor has a comparison of the prospects between flocculent CAS and AGS systems been reported. In this research, mainly three aspects were considered and investigated, which would contribute to a better understanding of the sustainability of biotechnologies in wastewater treatment and resource recovery, in order to successfully realize the circular economy integration and future better design/assessment.

(1) The distinctive features of each alternative were compared to establish the sustainability of the flocculent CAS, bacterial AGS, and algal-bacterial AGS biotechnologies. The choosing-by-advantage method for sustainability evaluation was applied, namely, sixteen factors from environmental, sociocultural, and technical indicators of sustainability were used. The importance of advantage scores for each alternative biotechnology was decided by reviewing peer-reviewed research articles to provide expert judgement of each alternative's peculiar differences and advantages with the maximum score for the importance of advantage

being set at 30. The results show that AGS systems are sustainable alternatives for future demands. In addition, the algal-bacterial AGS system with emphasis on climate-smart and circular economy integration of WWTPs, achieved 458 scores in comparison to 441 scores by the bacterial AGS system, indicating the former is more sustainable than the latter.

(2) The treated wastewater from flocculent CAS, bacterial AGS, and algal-bacterial AGS systems were evaluated according to ten international discharge and reuse standards to compare effluent quality. In addition, nutrient resource (P) and high-value-added resources (like alginate-like-exopolysaccharides (ALE), tryptophan, lipids, and polyhydroxyalkanoates) recovery were compared. The results show that both AGS systems can achieve effluent concentrations < 30 mg/L of chemical oxygen demand and < 1 mg/L of ammonium nitrogen and orthophosphate, which can effectively meet the ten international wastewater discharge standards and various reuse purposes for application in irrigation and non-potable uses in addition to safe disposal for surface and groundwater recharge. Moreover, bacterial AGS shows twice as much ALE and P resource recovery compared to the flocculent CAS; and algal-bacterial AGS may recover slightly higher P but an almost 100% increase in ALE and lipids recovery than bacterial AGS.

(3) The analysis of wastewater treatment investment, existing infrastructure, and potential reclaimed water, struvite, and energy resource recovery was carried out to evaluate the circular economy integration of WWTPs in Ghana. The state and available infrastructure capacity for water/struvite resources recovery was evaluated. Meanwhile, energy resource recovery from the produced sludge was estimated from annual estimates of freshwater withdrawal. As a result of low investment, there is low infrastructure capacity for wastewater collection, treatment, and resource recovery. However, the treated wastewater retail and struvite recovery can contribute over $1 million/annum and almost $ 40,000/annum from existing capacities for agricultural development. Energy recovery can contribute 1.8 to 3.2 million kWh/annum, equivalent to $1 to 2 million annually.

This study elucidates the degrees of sustainability of the flocculent CAS, bacterial AGS, and algal-bacterial AGS systems. Results show that algal-bacterial AGS system possesses higher degree for future climate-smart adaptation demands, enabling more treated water reuse, higher nutrient resource, and high-value-added products recovery for the circular economy model. Meanwhile, the treated water resource recovery from conventional WWTPs is a profitable opportunity to derive value for the sustainable financing of sanitation development in developing countries. These findings provide information for value recovery from wastewater treatment toward future sustainability applications.

Keywords: Wastewater treatment; Conventional activated sludge process; Bacterial aerobic granular sludge; Algal-bacterial granular sludge; Resource recovery; Sustainability

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List of Abbreviations

ABE	Africa Business Education
AD	Anaerobic Digestion
ADBG	African Development Bank Group
AFWR	Annual Freshwater Withdrawal
AGS	Aerobic Granular Sludge
AHP	Analytical Hierarchical Process
ALE	Alginate-Like-Exopolymers
AS	Activated Sludge
AT	Aeration Tank
BCM	Billion Cubic Meter
BOD	Biological Oxygen Demand
CAS	Conventional Activated Sludge
CBA	Choosing-by-Advantage
CE	Circular Economy
CEC	Contaminants of Emerging Concern
CECCE	Commission for the Environment Climate Change and Energy.
CFR	Continuous Flow Reactor
COD	Chemical Oxygen Demand
CWN	Canadian Water Network
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EPA	Environmental Protection Agency
EPC	European Parliament and the Council
EPS	Extracellular Polymeric Substances
EU	European Union
FAO	Food and Agriculture Organization
GAC	Granular Activated Carbon
GB	Great Britain
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GHS	Ghana Cedi
GIZ	Gesellschaft für Internationale Zusammenarbeit
GSS	Ghana Statistical Service

HRT	Hydraulic Retention Time
IEA	International Energy Agency
IMF	International Monetary Fund
ITEMG	Israel’s Trade and Economic Mission to Ghana
JICA	Japan International Cooperation Agency
JMP	Joint Monitoring Program
JST-SPRING	Japan Science and Technology Agency Support for Pioneering Research Innovation for Next Generation
LCA	Life Cycle Assessment
LWSP	Legon Waste Stabilization Pond
MCDM	Multi-Criteria Decision Making
MDG	Millennium Development Goals
MLSS	Mixed Liquor Suspended Solids
MMDA	Metropolitan, Municipal, and District Assemblies
MOFEP	Ministry of Finance and Economic Planning Ghana
NGT	Northern Territory Government
NO	Nitrous Oxide
OECD	Organization for Economic Co-operation and Development
OLR	Organic Loading Rate
PHA	Polyhydroxyalkanoates
SBR	Sequencing Batch Reactor
SDG	Sustainable Development Goal
SRT	Sludge Retention Time
SS	Suspended Solids
ST	Sedimentation Tank
SUWASA	Sustainable Water and Sanitation in Africa
SVEPA	State of Victoria Environmental Protection Agency
TF	Trickling Filter
TIN	Total Inorganic Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Bed
UK	United Kingdom
UN	United Nations

UNDESAPD	United Nations Department of Economics and Social Affairs Population Division
UNDESASD	United Nations Department of Economic and Social Affairs Statistics Division
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	The United Nations International Children's Emergency Fund
US	United States
USAID	United States Agency for International Development
USD	United State Dollar
USDCITA	United States Department of Commerce-International Trade Administration
USEPA	United States Environmental Protection Agency
VER	Volumetric Exchange Rate
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WHO	World Health Organization
WRRF	Water Resource Recovery Facility
WSP	Waste Stabilization Pond
WWAP	World Water Assessment Programme
WWTP	Wastewater Treatment Plant

Chapter 1 Introduction

1.1 Historical challenges of population growth and water use

The increasing challenge to environmental safety and sustainable development in recent years is the massive increase in waste generation from rapid population growth and growing natural/processed resource demand. Wastewater streams are products of developing societies' daily water use that has risen since the 1900s. Global water withdrawal and population increased by 630% and 340% from 1900 to 2010, respectively (FAO, 2021). The solvency of water contributes to wastewater richness in material resources that enhances microorganism growth processes. If untreated, wastewater poses water-related public health risks, alongside producing offensive odors that impact air quality, particularly in restricted urban spaces. Progressively, wastewater generation has kept pace with population growth, urbanization, industrial development, and increasing agricultural production from the late 18th and early 19th centuries to the 21st century.

Human population increase in the last 100 years is the most significant as recorded in human history. In retrospect, on the global scale, the human population tripled from 2.5 billion in 1950 to 7.9 billion in 2021(UNDESAPD, 2021). This enlightens the increased water abstraction, uses, and subsequent wastewater generation from rapid urbanization, industrial growth, and agricultural production activities. Meanwhile, the critical value of water for human sustenance in direct and indirect applications inevitably produces wastewater, transporting high organic matters, nutrients, and varying hazardous material concentrations that threaten public health and life forms in water resources and the environment. Hence, proper wastewater treatment is a prerequisite and crucial requirement for a sustainable society.

Advanced wastewater treatment technologies are imperative for public health safety, owing to population growth, high pollutant load discharge, and rising wastewater generation. Thus, the modern technological design of centralized sewage treatment plants began in the 1900s. Meanwhile, diverse environmental, public health, and social challenges have characterized the shifting focus and bioengineering advances in wastewater treatment. However, bioengineering innovations have significantly influenced the outlook of wastewater treatment within the last 100 years. Although the public health concern of wastewater treatment spans many centuries and civilizations, its advance and evolution in the last century are the most significant, especially the transversion of the flocculent conventional activated sludge (CAS) process to bacterial aerobic granular sludge (AGS) and algal-bacterial AGS systems.

1.2 Wastewater generation and the shifting focus in the past century

The pressure of increasing discharge of high pollutant load effluents in huge volumes and frequencies shortens the residence time and reduces the self-purification capacity of water resources. Before the industrialization and increased urbanization of the 18th and 19th centuries, the need for technological advancement in wastewater treatment had not drawn much attention. Most probably, sufficient pollutant load reduction could be achieved from a high dilution factor and natural water body's self-purification for safe withdrawal during that period.

The processes for domestic wastewater separation and collection through connected sewer networks for treatment began in the 1900s. Meanwhile, the first modern technological designs of wastewater treatment plants (WWTPs) to reduce pollutant loads saw the advent of centralized sewage and municipal WWTPs. This combined physical, biological, and chemical processes first in the United Kingdom (UK) and the United States (US) in the late and early 19th- 20th centuries (Ambulkar and Nathanson, 2022). Moreover, introducing tertiary treatment with chlorine disinfection as a public health strategy in 1915 reduced cholera and typhoid mortalities.

Increased wastewater generation, low collection and treatment ratio, and poor disposal are precursors to environmental pollution that have entrenched societies' view of wastewater as a nuisance. Characteristically, unsanitary conditions and contaminated water resources use have preceded repeated disease outbreaks. The first cholera epidemic of 1823 was in St. Petersburg (Barabanova, 2014), and the most recent one was in Yemen (Ng et al., 2020). Economic prosperity and advances in public health delivery on life expectancy triggered the stable population in the 1920s and rapid population growth from the 1950s to the 1970s. Moreover, intensified agricultural production, industrialization, and urbanization exposed surface water resources to high nutrient loads from agricultural runoffs, domestic sewage, and industrial effluents (Strokal et al., 2014).

High nitrogen (N) or phosphorus (P) nutrient loads discharged from wastewater into water resources influence nutrient cycling, aquatic life, and water use. The relatively shorter residence time for natural water purification through biogeochemical processes can induce massive eutrophication. Meanwhile, excess nitrate concentration in water resources causes "blue baby syndrome" in infants. Bat et al. (2018) reported that rapid population growth and rural-urban migration prompted the direct dumping of municipal and industrial effluents into the Black Sea, which subsequently influenced its fast eutrophication and degradation. Eutrophication caused the loss of almost 60 million tonnes of living marine resources and 5 million tons of fish in the Black Sea between 1973 and 1990 (Strokal et al., 2014). Similarly, several reports on coinciding eutrophication of vital lakes in various regions during the 1970s, including Lake Erie and Lake

Kasumigaura (Mizunoya et al., 2021; Scavia et al., 2014), are found in the literature.

Primarily, wastewater treatment aims to protect and promote human health and the environment from spreading water resource contamination and associated diseases (Capodaglio et al., 2017). Thus, wastewater treatment until 1970 predominantly involved the removals of colloidal/suspended solids and floatable materials. However, more stringent measures for maximal removal of biological oxygen demand (BOD) and total suspended solids (TSS), and elimination of pathogenic microorganisms were implemented in the 1970s (Tchobanoglous et al., 2014). Additionally, N and P removal began (Kehrein et al., 2020a).

While originally designed to lower BOD by heterotrophic microorganisms, modifications for N and P removal by the flocculent CAS in different redox environments necessitated the introduction of multiple process units and recirculation flows (Nancharaiah et al., 2019). Moreover, the flocculent CAS process only became the dominant biological treatment process in urban environments from the beginning of the 1970s (Wanner, 2021), although it was discovered in 1910s (Ardern and Lockett, 1914).

In recent decades, the increasing complexity of wastewater streams has entailed more stringent effluent discharge standards prospecting innovative WWTPs' design a continuum. Therefore, the conventional focus, design, and upgrading of WWTPs to meet increasingly strict discharge standards (Fernández-Arévalo et al., 2017) characterize the innovation and the engineering of emerging second-generation biotechnologies. Moreover, the needs for energy use efficiency, economic viability, technical feasibility, and social acceptance have become relevant and critical features for WWTPs' sustainability evaluation, considering the indispensable requirements for environmental sanitation and protection.

With the emerging biotechnologies, wastewater's material resource recovery potential to transform society and foster sustainable development has gained much attention from the beginning of the 21st century. This appeals to a circular economy (CE) transition in wastewater treatment systems, adopting specific indicators for resource recovery monitoring (Preisner et al., 2022). Previous researchers on CE in WWTPs focused on descriptive perspectives for energy recovery (Gherghel et al., 2019; Kundu et al., 2022; Zarei, 2020) and environmental impact from life cycle assessment (LCA) and greenhouse gases (GHGs) emission viewpoints (Pahunang et al., 2021; Rufí-Salís et al., 2022). Meanwhile, AGS rather than flocculent CAS process systems possess high potentials of dominating the next century's environmentally friendly biotechnologies for wastewater treatment in the context of CE.

1.3 Biological WWTPs

A growing preference for biological wastewater treatment technologies is becoming more apparent internationally in effluent discharge policy planning. For example, tertiary treatment requirement is recommended in European Union (EU) countries only when biological treatment processes do not meet discharge limits. However, high aeration energy cost accounting for over 50% of energy use in wastewater treatment remains a challenge for biological processes. Meanwhile, stricter treatment standards for wastewater by 2040 may contribute to over 50% increase in energy use (IEA, 2016) and substantial GHGs emission from high fossil fuel-derived energy consumption.

The high energy demands in flocculent CAS processes mainly include mechanical aeration, suspended solids mixing and recycling, solid waste dewatering, and pumping (Sid et al., 2017). Moreover, the relatively ineffective toxic substances treatment, including contaminants of emerging concern (CEC) and salinity tolerance, are critical challenges to the flocculent CAS process. Besides, waste activated sludge (WAS) disposal remains a significant drawback in urban environments with limited avenues for sludge landfills development, since sludge disposal in developed urban environments is becoming increasingly expensive and complicated (Han et al., 2021).

Innovative and competitive wastewater treatment options with comparably lower energy demand, better effluent quality, and sludge handling are quickly becoming the preferred alternatives to flocculent CAS processes. According to Abinandan et al. (2018) and Al-Jabri et al. (2020), inefficient treatment and high energy costs in conventional wastewater treatment systems are increasingly claimed for alternative treatment options, such as microalgae technologies, to maximize treatment efficiency, biomass production, and resource recovery. Moreover, AGS systems with efficient sludge separation, compact infrastructure and high energy efficiency are promising, which can become the standard for future WWTPs engineering (Nancharaiah et al., 2019; Nancharaiah and Sarvajith, 2019). These meet current requirements for optimizing WWTPs sustainability in energy use by incorporating climate-smart thinking, which promotes public health and social development.

The prospective integration of resource recovery into wastewater treatment is innovative in transforming the outlook, successfully realizing a CE model transition in the water sector. Meanwhile, a growing consensus on WWTPs' energy recovery capacity to transform them into energy neutral or net positive facilities from renewable energy production is gaining much attraction. Furthermore, there is a growing need for WWTPs to contribute to carbon neutrality in the future (Bae and Kim, 2021). Huang et al. (2022) proposed energy neutrality as primary, with the three main pathways for decarbonization: energy reduction, resource recovery, and renewable energy generation. The widespread use of flocculent CAS process, and increasingly growing interest in AGS systems, points to their critical roles in sanitation development.

1.3.1 The flocculent CAS process

Ardern and Lockett commenced sewage aeration studies in 1912 at the Manchester Sewage Works based on Dr. Fowler's observations at the Lawrence Experimental Station in Massachusetts, New York. By retaining the sludge to accumulate in the reactor after decantation from each 6-hour cycle from preliminary experiments for five weeks, they achieved complete nitrification within 6 hours with clear oxidized effluent. Thus, exploiting the 19th century theory of natural selection, the retained solid matter from prolonged aeration of sewage termed "activated sludge" intensifies the oxidation process under suitable aeration (Ardern and Lockett, 1914). Sludge build-up from several cycles could successfully purify sewage to acceptable standards in a shorter period, radically revolutionizing the dynamic advance of biological wastewater treatment and sanitation. The loosely settled microbial structures or activated sludge particles at the end of the aeration cycles were irregularly shaped flocs in the range of 100 μm in average (Nancharaiah et al., 2019). The first full-scale continuous-flow treatment system was installed at Worcester in 1916, rapidly spreading to developed countries with sewer systems.

Based on the logical concept of organic carbon (C) conversion into carbon dioxide (CO_2) and sludge to produce "clean water" after sedimentation, the flocculent CAS process has evolved over decades to incorporate nitrification/denitrification for N removal and enhanced biological P removal (Verstraete and Vlaeminck, 2011). Modification of it has produced the modified Ludzack-Ettinger system and Bardenpho process. However, considering the increasing view of flocculent CAS processes unsuitability for future demands and increasingly low environmental friendliness, the bioengineering of more competitive alternatives has gained increasing research focus in the past two decades. Culminating to the development of the second-generation WWTPs, that advance a new sustainable and climate-smart outlook tailored at current/emerging demands of wastewater treatment in the modern society.

1.3.2 Bacterial AGS

The recent discovery of bacterial AGS systems advances the prospects of addressing the society's dynamic and evolving needs in sustainable sanitation development, waste reduction and resource recovery, and recycling to a circular economy shift. Advancing the conventional focus, design, and upgrading of WWTPs is promising to meet the stringent discharge standards (Fernández-Arévalo et al., 2017).

Bacterial AGS biotechnology is considered the second generation of wastewater treatment, revolutionizing the outlook for sanitation in sustainable cities and integrating concepts of climate-smart thinking. Bacterial AGS has been over three decades since its first report (Mishima and Nakamura, 1991), in which granules of 2-8 mm in diameter were formed from aerobic activated sludge by self-immobilization in an up-flow sludge blanket reactor and exhibited more excellent settleability compared to the CAS flocs. Thereafter, the novel bacterial AGS gained much research interest and subsequently global industrial application under the tradename Nereda® (Pronk et al., 2015; Robertson et al., 2016), with over 90 full-scale treatment plants in 20 countries and a cumulative 158,152,813 kWh savings in electricity (HaskoningDHV, 2022).

Bacterial AGS's compact structure, excellent settleability, lower energy requirement, 50-75% reduction in land footprint (Bengtsson et al., 2019; Robertson et al., 2016), simultaneous nitrification and denitrification capacity, and ability to withstand toxicity and shock loadings (Jiang et al., 2020, 2021; Wu et al., 2020) are superior advantages over the century-old CAS process. Besides the sludge density enhancement of fast settling, bacterial AGS's distinctive aerobic, anoxic, and anaerobic zones advance higher effluent quality over the flocculent CAS systems (Nereda, 2022). Figure 1-1 illustrates the activated sludge flocs and aerobic granule characteristics in addition to their nutrient removal zones.

1.3.3 Algal-bacterial AGS

More recently, algal-bacterial AGS developed from the bacterial AGS concept is gaining much research attention as a promising granular sludge option. The prospective application for high effluent quality through the algal-bacterial symbiosis process has been the basis for water purification in natural resources. Comparatively, algal-bacterial AGS exhibits a more stable granular structure and great potential for fast biomass growth, and its dense biomass per unit area can reduce 76% of footprint (Wang et al., 2022). Additionally, algal-bacterial AGS has the potential to reduce aeration energy costs from microalgae respiration, resulting in 58% decrease in energy consumption (Liu et al., 2020; Wang et al., 2022; Zhao et al., 2019).

The high nutrient accumulation and bioavailability (Wang et al., 2020; Zhao et al., 2019) in algal-bacterial AGS biomass is an innovative solution to alternate P recovery from the biological wastewater treatment process. Furthermore, it provides an alternative strategy for industrial-scale, low-cost cultivation, and a less cumbersome harvesting route for microalgae production (Wang et al., 2022) and high value-added products recovery (Meng et al., 2019a, 2019b, 2019c) for industrial applications.

Given the need for resource recovery (water reuse, nutrient recycling, energy recovery, and value-added product development), AGS systems, including bacterial and algal-bacterial AGS, are the future of sustainable WWTPs. Although its operation is still laboratory-based, algal-bacterial AGS has excellent potential for future application due to its excellent effluent quality, low energy use, high biomass production and productivity for multiple value-added resource recovery, excellently competing with the flocculent CAS process (Zhang et al., 2021) and bacterial AGS biotechnology (Guo et al., 2021; Semaha et al., 2020).

Algal-bacterial AGS system shows great potential for excellent wastewater treatment, concurrently pioneering low-cost microalgae cultivation and harvesting compared to suspended microalgae systems (Wang et al., 2022). These are promising for sustainable development goals (SDGs) attainment and CE integration. Figure 1-2 summarizes the timeline of the advancements of biological wastewater treatment, highlighting the transition of WWTPs from sanitation and environmental protection to resource/energy recovery from wastewater, especially by bacterial/algal-bacterial AGS systems. Furthermore, the evolution of biotechnologies in the past eight decades show the consistent evolving of treatment options to more efficient and robust alternatives. Thus, although the pond systems are still popular and the CAS has evolved since its discovery, it is evident that in the past decade, more compact alternatives have gained much preference and consideration as sustainable and the future of sanitation development. The timeline of most significant evolutions of biotechnologies within the past century shows the progressive advancement towards more compact options of better treatment performance (Fig. 1-3).

1.4 Sustainability thinking in modern society development

Sustainability is becoming an increasingly growing consideration for rapidly developing and modernizing societies' design. To maximize the use of declining natural resource and facilitate pollution reduction, the essential contribution of WWTPs to environmental/public health safety elucidates future WWTPs sustainability in view of current environmental safety needs, and the anticipated increases in water use and wastewater generation. For modern industrial and developing economies, the challenges for sustainable economic development and environmental safety, are defining innovative strategies aimed at creating balance.

There is no single exhaustive definition for sustainability, however it is generally conceptualized as preserving the earth and its resources for continued human existence. In academia, sustainability science provides new approaches and perspectives to complex global human-induced challenges towards building a sound and safe society (UNESCO, 2019). Thus, in the past two decades, sustainability thinking into varied aspects of society and research has gained much prominence and application by year. This is observed in the progressive increase in sustainability research publications since the year 2000 and the exponential growth in the past decade that accounts for over 80% of the total research paper count (Fig. 1-4). Out of almost 200, 000 publications from 2000 to 2022, <12% were published between 2000 and 2010, >50% between 2011 and 2019. However, almost 40% of sustainability-related research are within the past three years (2020 to 2022). This trend shows society's fast-growing interest and transitionary shift, which is expected to become more evident in subsequent years.

As shown (Fig. 1-5), among the 3,000 most cited research articles on sustainability with at least 66 citations in Web of Science categories (Environmental Sciences, Green Sustainable Science Technology and Environmental Studies), the co-occurrence of keywords analysis confirms the increasing focus on CE, climate change, SDGs, carbon sequestration, and pro-environmental behavior. Thus, sustainability and CE advance continue to attract critical research focus to ensure a safe environment which is a prerequisite for a healthy planet, sustainable development, and economic growth. Hence, various actions/efforts to promote and achieve the SDGs since its adoption in September 2015 are collectively deemed relevant.

1.5 The SDGs

The SDGs comprise seventeen comprehensive goals adopted by the 193 United Nations Member States for shared growth, development, and a safe planet attainment by 2030. It is an expansion of the phased out eight millennium development goals (MDGs) agenda (2000 to 2015). SDG 6 is broadly focused on "ensuring availability and sustainable management of water and sanitation for all". More specifically, the objective of SDG 6.3 focuses on improving water quality through reduced pollution, halving the untreated wastewater stream, and substantially increasing recycling and safe reuse. Anthropogenic wastewater that receives treatment is used as an indicator for evaluation. It can be measured as the percentage of wastewater produced/generated, collected, and treated as a ratio of the populace connected to a sewer network and WWTPs (Sachs et al., 2021).

The recent evaluation of goal attainment in the various global regions (Fig. 1-6) shows significant challenges remain in Africa, Latin America, and parts of Asia and Europe, which represents almost 60% coverage. Conversely, this goal has been achieved in North America, Australia and New Zealand, most parts of Europe, and countries like Japan, South Korea, and Chile in Asia and South America, respectively. Meanwhile, SDG 6 attainment can effectively contribute to concurrent multiple SDGs. For example, clean, affordable energy (Goal 7), sustainable cities and communities (Goal 11), responsible consumption and production (Goal 12), climate action (Goal 13), and life below water (Goal 14). Hence, the overarching need for energy efficiency in WWTPs underscores the requirements for less energy-intensive biotechnologies that concurrently contribute to climate change mitigation/carbon footprint reduction and high value resource recovery. These potentially improve the opportunities for SDGs and CE development, while advancing the prospects of sustainability evaluation tools design/use in conventional/emerging WWTPs future value determination.

Predominantly, WWTPs are expected to transition to water and resource recovery facilities

(WRRFs) in the context of CE, providing more tangible value beyond the basic function of wastewater purification before discharge into the environment. Thus, the increasing development of more robust biological WWTPs to the conventional biotechnologies such as the flocculent CAS process is essential, significant, and necessary.

1.6 The CE model

The concept of CE development for a future zero-waste society has gained much research interest in the past two decades following the recent promotion by the EU, Canada, China, Japan, the UK, and multinational businesses globally (Korhonen et al., 2018). Conventionally, natural resources/materials use for daily human needs are commonplace, span several service sectors ranging from domestic to industrial processes, and generate tons of waste products that must be disposed of. The increased volume of waste material/resource generation since the second industrial revolution and stably steep population growth from the 1870s and 1920s respectively necessitated the development of standards/regulations for waste disposal which continues to increase with population growth.

As the society has advanced, further revisions for more stringent measures that ensure environmental and public health safety have become necessary for solid and liquid streams. As viable actions to reduce environmental hazard/risks. Meanwhile, the several challenges associated with increasingly stringent environmental regulatory standards, in fiscal and legal requirements make waste-to-end product disposal systems unsustainable and enforce the need for a rethink. Thus, the concept of CE in the 21st century replacing the predominantly linear ("take-make-use-dispose") economy model incepted from the first and second industrial revolutions is considered vital for planetary safety and sustainable development.

Central to the CE model is the design to maximize finite resources efficiency from extended product useful life, in a regenerative manner along the product value chain to support sustainable environmental, social, and economic development. Although material cycle recycling dates to the early 18th and 19th-century industrial developments, the business orientation of the CE model that emphasizes material reuse, product development, and waste-derived energy through the product life value chain makes CE unique (Korhonen et al., 2018). In the 1990s, CE concepts were applied on small-scale eco-industrial parks (Stahel, 2016).

In the past two decades, several ideologies, principles, viewpoints, and research disciplines have shaped the CE concept development and approach to implementation. The reduce, reuse, and recycle (3R) initiative proposed by Japan (Ministry of the Environment Government of Japan, 2008) is considered essential, while further refining of the concept has been advanced in recent years through the Ellen MacArthur Foundation, to pioneer product design and drive business model innovations (Ellen MacArthur Foundation, 2013; 2014). However, the conceptual view of the earth as a "spaceship" (closed economic system) with limited resources (Boulding, 1966) which processes can be cyclically interlinked and balanced by conscious consumer habits of material resource recycling to keep waste within the earth's regenerative/assimilative capacity (Pearce and Turner, 1989) have been foundational.

Guided by three primary principles, CE seeks to: (1) to preserve natural capital through regenerative natural systems and effective balance of non-renewable finite and renewable resource use; (2) to keep products, components, and materials for as long as possible through extended use and recirculation within the product value chain for the society's benefit; and (3) to reduce waste and pollution in the environment to the barest minimum (Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2015).

The butterfly diagram (Fig. 1-7) distinctively illustrates the broad biological and technical materials/nutrients/resources (Ellen MacArthur Foundation, 2014) and their different value chains from a CE model concept/principle application. Primarily, biological resources are the renewable elements. The CE business model is divided along recycling and reusing of turned "old goods into as-new resources", and extended service life through repair, remanufacturing, upgrade, and retrofitting materials (Stahel, 2016). Thus, through the multiple or "as long as possible" reuse and recycle of biological and technical materials/resources in the product value-chain, waste can be substantially reduced to the barest minimum while providing beneficial use to the society at a lower or higher use purpose/value. In the past five years, circular economy application research has been rising and the recent four years have been most significant with 6.3%, 10.3%, 17.5%, 28.4% and 29.8% of the cumulated research publications of the past two decades (Fig 1-8). Also, WWTPs as significant components of biological material cycles have gained growing research attention in CE concept application to wastewater treatment. Increasing the focus of resource recovery in more promising biological WWTPs such as the AGS biotechnology-based ones, as shown in Fig. 1-9. Like the progressive increase in wastewater treatment and resource recovery research in the past decade, the same trend has been observed, both in the integration of CE in wastewater treatment, and AGS resource recovery. Thus, the mass transition of WWTPs to WRRFs is certain, which can make the existing/emerging plants integration and contribution to CE, valuable for future environmental sustainability and sustainable development.

1.7 Interaction among biological WWTPs, SDGs, and CE

Principally, biological WWTPs will contribute much to multiple SDGs and CE integration than their physicochemical counterparts because of their environmentally friendly attributes, low chemical usage/presence of hazardous substances, and volume/value of sludge biomass. According to Schellenberg et al. (2020), wastewater treatment's financial viability and feasibility for rapidly increasing urban populations in the developing Asia, the Middle East, Africa, and Latin America, presents a drawback to technology adoption, improved sanitation, and the SDGs vision. While foreign donor project incentives to increase wastewater treatment in developing economies are locally unsustainable, increasingly stricter discharge standards pose challenges to treatment motivations among industrialized countries. For example, the special discharge limit policy for wastewater in China will increase operational costs and electricity consumption by 70.44% and 86.59% respectively, with a consequent 72.21% increase in GHGs emission by 2030 (Su et al., 2022).

Requisite strategies that advance the prospective direct/tangible benefits of increased wastewater treatment to environmental and socio-economic development from resource recovery are promising to maximize the trade-offs in high- and low-income countries/economies. Potentially becoming an essential determinant in the rapid adoption of emerging biotechnologies, the basis for further research aimed at optimizing WRRFs' efficiencies, and wastewater resource value chain development to substitute the society's growing material demands.

In five decades, the global material footprint increased from 26.7 billion tons in 1970 to 75.6 billion tons 2010 (UNEP, 2017). In addition, between 2010 and 2017, it recorded a 17.4% growth to become 85.9 billion metric tons, separated according to the material categories as shown in Fig. 1-10. A further increase in the global material footprint to 95.1 billion metric tons in 2019 represented over a 65% growth from the year 2000, 70% of this was attributed to Eastern/South-Eastern Asia and Europe/Northern America (UNDESASD, 2021, 2022). However, a rise to 167 billion metric tons is projected for 2060 with almost 74% from non-metallic minerals and biomass (OECD, 2019). Meanwhile, the global human population of 7.8 billion in 2020 is expected to grow to 8.5, 9.7, and 10.9 billion by 2030, 2050, and the end of the millennium (2100), respectively (UNDESAPD, 2021). Figure 1-11 shows the population growth trend from the 1950s, and projections into the end of the millennium. This impending rise would increase material resource demand/use and culminate to more waste generation, and pollution, as illustrated in Fig. 1-12, building up more waste resources with potentially negative consequences.

Sustaining a balance between a safe environment and economic growth demands less exploitation of natural resources through changing "consumer habits". This creates the ideal avenue for biological WWTPs integration into CE and resource recovery toward multiple SDGs attainment. For example, the global phosphorus (P) demand in phosphate rocks will outstrip supply by 2033 (Mehta et al., 2015). However, P recovery from wastewater is viable to supplement demand/supply, stabilize price volatility and influence on global food security (Goal 2) and industrial development, reducing the pollution of water resources (Goal 6), and preserving life below water (Goal 14) through over 50 to 90% P recovery from biological WWTP processes (Cornel and Schaum, 2009; Liu et al., 2017; Wang et al., 2022).

1.8 Challenges and strategies to environmental safety, CE advance, and SDGs

The dynamic challenges of the 21st century and the rise of a global economy present new opportunities, notably to harness material resources availability in wastewater. This underlines the recent significant focus on resource recovery from biological WWTPs. Thus, besides the fundamental functions in nutrient removal and promoting environmental safety, WWTPs are transforming into water resource recovery factories (WRRFs) (Kehrein et al., 2020b). This can facilitate treated wastewater use, and new pathways for the recovery of multiple value-added products in a CE model of wastewater treatment. As illustrated in Fig. 1-13, the varied opportunities for simultaneously wastewater treatment and resource recovery can advance the research and development (R&D) need in WWTPs, towards a safe environment, SDGs, and value creation.

In its new outlook, wastewater as a resource transforms observations of over 80% of global wastewater discharged untreated and over 95% among some least developed countries (UNEP, 2017) into a sustainable resource value to exploit. This potentially incentivize growth in sanitation investment/development for value creation especially in developing countries. More specifically, resource recovery from wastewater treatment can stabilize price volatility from disparities in global natural resources availability and distribution, such as phosphates (Reijnders, 2014). Moreover, these applications are relevant to attaining multiple SDGs (6, 7, 9, 11, 12, 13, and 14) and CE globally. This can also enable maximal material value use and a safer environment that minimizes natural resource exploitation and the pollution effects.

1.8.1 The value of biological material cycle/resources in CE model

WWTPs are essential elements in the biological material cycle of the CE model, capable of creating sustained renewable resource opportunities for renewable energy, nutrients, metal ions, bioplastics, biofuels, and other value-added products development. Notably, organic biological material cycles/resources are high in regenerative worth, with zero waste potential within a CE. For example, in the UK, organic food waste processing could generate 2 GWh of electricity, reduce 7.4 million tons of GHG emissions and 1.1 billion USD in landfill costs annually, besides the digestate use in soil nourishment (Ellen MacArthur Foundation, 2013). Furthermore, the EU Landfill Directive implementation using municipal waste as a resource has the potential to reduce 62 million tons of CO_2-equivalent in 2020 relative to 2008 (EEA, 2016).

1.8.2 Factors influencing biological WWTPs advance of CE

The nutrient, water, and energy recovery needs of the society drives the global wastewater industry (Neczaj and Grosser, 2018). However, wastewater treatment and resource recovery are predicated on wastewater generation/production, collection systems and available treatment processes. Meanwhile, the better effectiveness, economic value, and energy production potential of sludge from biological treatment systems underline their considerable preference over mechanical and chemical treatment processes (Ali et al., 2020). Consequently, the utilization and recycling of sewage sludge can vary by treatment methods and toxic metal concentrations (Ghahdarijani et al., 2022).

Influent characteristics (pollutant/nutrient load, pH), energy use efficiency, environmental conditions (temperature, heavy metal concentration, salinity, and photoperiod), operational conditions (reactor size/WWTP capacity, biomass properties, concentration, growth rate, settleability, structure), and biotechnologies can influence prospects for various wastewater resource recoveries. For example, there are variations in the amount and characteristics of alginate-like exopolymers (ALEs) from flocculent CAS, bacterial AGS and algal-bacterial AGS systems under different operational conditions (Chen et al., 2022a, 2022b; Li et al., 2021; Lin et al., 2013; Oliveira et al., 2020; Schambeck et al., 2020). In addition, resource recovery will differ by regions according to available biotechnologies, treatment capacities, and available market value-chains. Furthermore, resource recovery can be categorized by its potential value and used to establish a hierarchy towards economies of scale evaluation. The illustrative diagram in Fig. 1-14 highlights this, showing the material value chain.

Characteristically, the volume and rate of wastewater generation varies with population and water use. However, wastewater treatment among countries is greatly influenced by income and infrastructure investments. According to Sato et al. (2013), 70%, 38%, 28%, and 8% of wastewater is treated in high-income, upper middle low-income, low middle income, and low-income countries, respectively. Thus, disparities in sanitation development and available/functional WWTPs exist in regions and would influence future wastewater treatment sustainability, and resource recovery. For example, on-site and off-site collection systems impact centralized and decentralized WWTPs' wastewater collection and treatment. Traditionally, on-site treatment systems are used in low-populated areas with low-capacity or as an economically feasible alternative, to reduce pollutant concentrations to acceptable levels before direct contact with people or the water environment (Yates, 2011).

In on-site treatment systems, wastewater is predominantly accumulated in "soak away pits" to infiltrate underground soil layers for treatment and into the water table. On-site treatment systems represent a significant percentage of the wastewater collection/treatment forms for environmental safety in most developing countries but can pose hindrances to the prospects for large-scale collection, treatment, reclaimed water use and resource recovery.

While septic tanks adopt primary sedimentation and hydraulic retention time (HRT) to reduce pathogenic load, which are widely used in low-populated areas of industrialized countries but common in developing countries. Conversely, off-site treatment systems employ the use of sewerage networks in wastewater collection for onward disposal or treatment in WWTPs, which are mostly advanced in developed or high-income countries. Sewerage coverage in sub-Saharan Africa is very low (Nansubuga et al., 2016). However, a combination of on-site and off-site treatment systems to accumulate sufficient influent for treatment can compensate for the challenges from low sewerage networks coverage often observed in developing countries.

1.9 Research objectives

Although essential to environmental safety, meeting more stringent effluent discharge standards poses potential higher energy cost and increases GHGs emission from WWTPs. Hence, energy use efficiency and low carbon alternatives are preferable for future needs. AGS systems with lower energy requirement are promising for future wastewater treatment needs, compared to the flocculent CAS. Thus, energy efficiency evaluation of WWTPs in relation to effluent quality can be adopted as a measure of circularity towards reclaimed water use or discharge and potential reduction in carbon footprint. Meanwhile, impending resource scarcity needs and the outlook of WWTPs as WRRFs create the need to evaluate the potential recovery of materials and their contribution to the economy in tangible/monetary value. Furthermore, a potential for the tangible resource recovery value from wastewater treatment to trigger technology adoption exist for developed and developing countries. Meanwhile, treatment capacities in developing countries are relatively low. Hence, the objectives of this research were:

(1) To compare resource recovery from flocculent CAS, bacterial AGS, and algal-bacterial AGS, in reclaimed water use (effluent quality), nutrient recovery (P) and its contribution to supplement national or regional demands, high value-added products such as ALEs, polyhydroxyalkanoates (PHAs) and lipids (for biofuel production);

(2) To evaluate the future sustainability of the three biotechnologies in the context of the circular economy application, climate-smart adaptation, and prospective advance of wastewater treatment; and

(3) To assess the state of wastewater treatment systems in the context of developing countries,

in addition to the evaluation of the existing systems for resource recovery and the untapped potential.

1.10 Thesis framework

The thesis is divided into five parts, as shown in Fig. 1-15. Chapter 1 addresses the shifting focus of wastewater treatment in the past 100 years, underpinning the need for wastewater treatment. The author highlights the modern wastewater treatment systems development, and the technological advancement in biological wastewater treatment technologies focusing on the flocculent CAS, and AGS systems. The CE requirement for WWTPs integration toward future economic and environmental sustainability include energy use efficiency and resource recovery potential as viable sustainability indicators. Chapter 2 adopts the choosing-by-advantage method to evaluate the sustainability of flocculent CAS, bacterial AGS, and algal-bacterial AGS systems toward successful integration in CE. Chapter 3 compares the resources (treated wastewater quality, phosphorus, and high value-added products) recovery from flocculent CAS, bacterial AGS, and algal-bacterial AGS systems. Chapter 4 presents a case study on wastewater treatment in Ghana and the potential untapped values. Its contribution to the economy is hoped to be relevant for the outlook of developing countries' future investments and business modelling from resource recovery and CE value creation. Chapter 5 summarizes the main conclusions and gives directions and perspectives for future research.

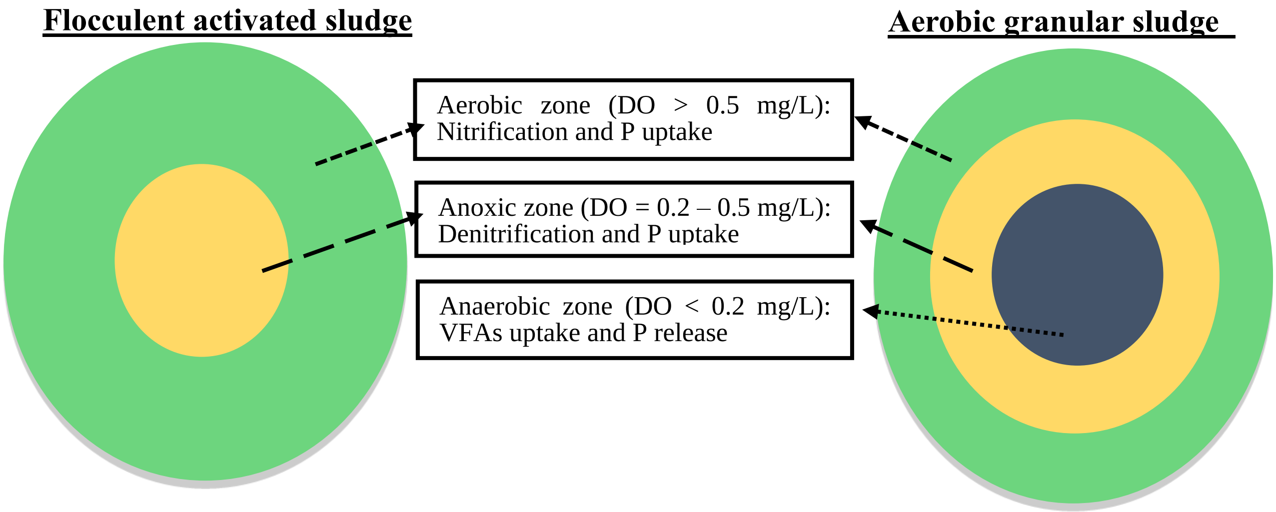

Fig. 1-1 Schematic representation and comparison of flocculent conventional activated sludge and aerobic granular sludge structures.

Modified from Gogina and Gulshin (2016) and Nereda (2022).

DO, dissolved oxygen; VFAs, volatile fatty acids.

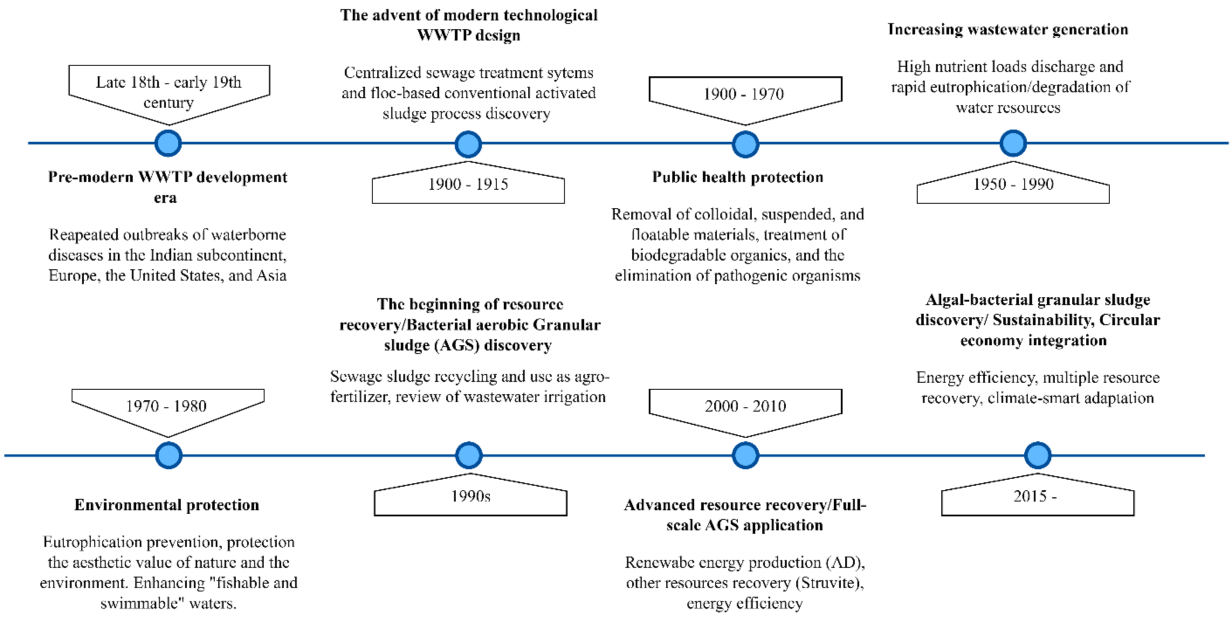

Fig. 1-2 A timeline of sanitation and environmental challenges shaping the advance of biological wastewater treatment from 19th century to 21st century.

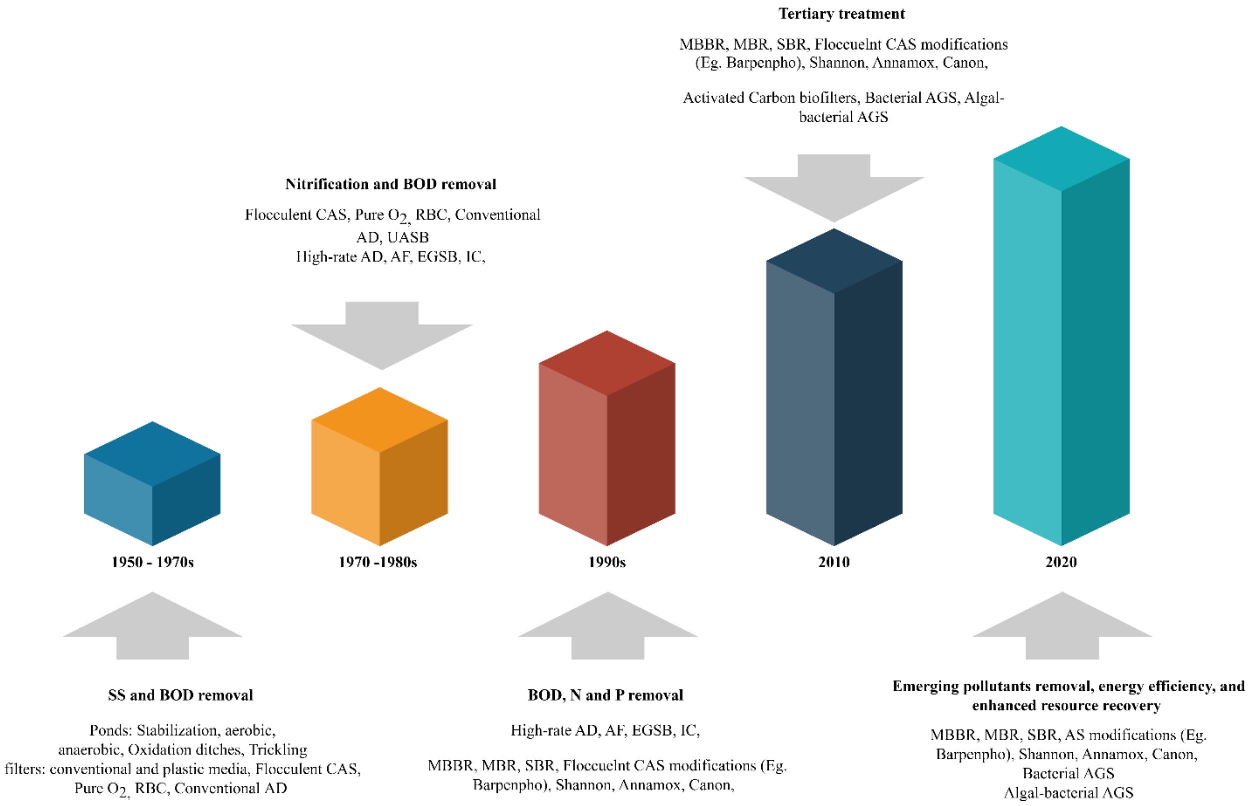

Fig. 1-3 Trends in the evolution of biotechnologies for wastewater in the past eight decades. Adapted and modified from Lippel and Dezotti (2018).

SS, suspended solids; BOD, biological oxygen demand; N, nitrogen; P, phosphorus; AS, activated sludge; AF, anaerobic filter; AD, anaerobic digestion; EGSB, expanded granular sludge bed; IC, internal circulation; MBBR, moving bed biofilm reactor; MBR, membrane bioreactor; RBC, rotating biological contractors; UASB, upflow anaerobic sludge blanket; Resources (reclaimed water, energy, nutrients (N/P), value-added-products).

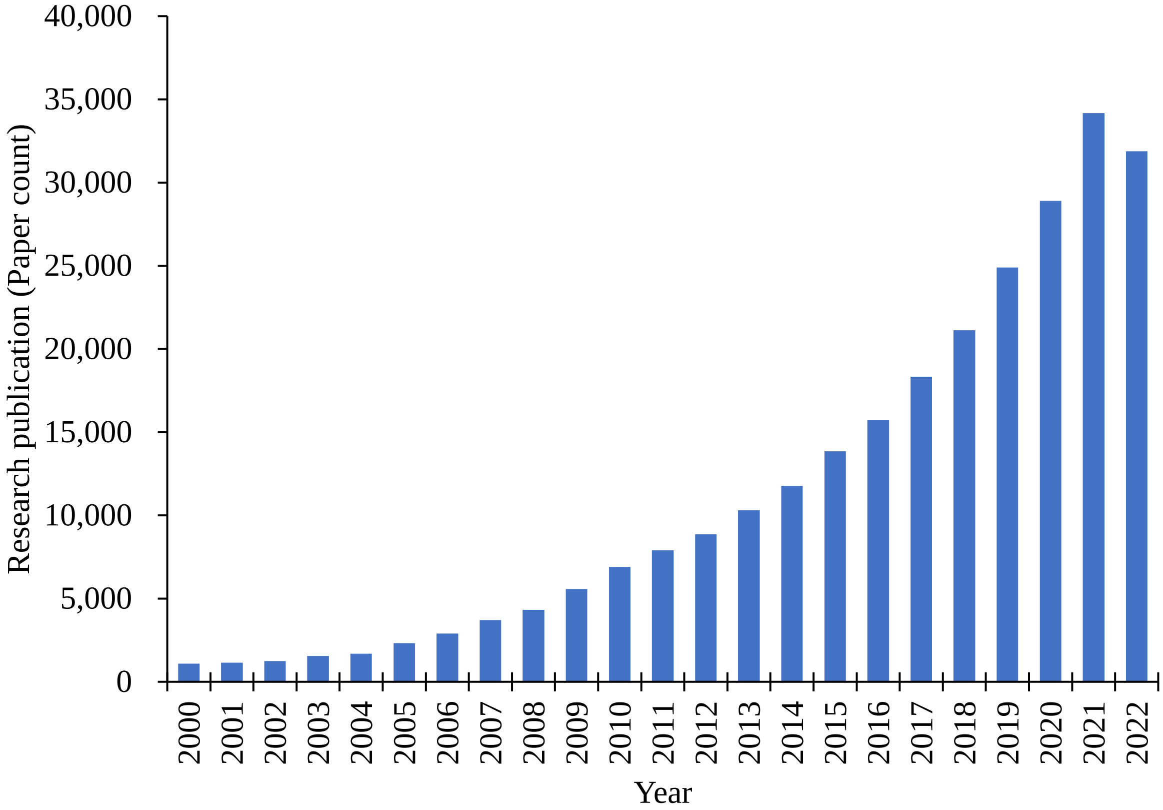

Fig. 1-4 The distribution of sustainability research by year out of 260,308 research publications

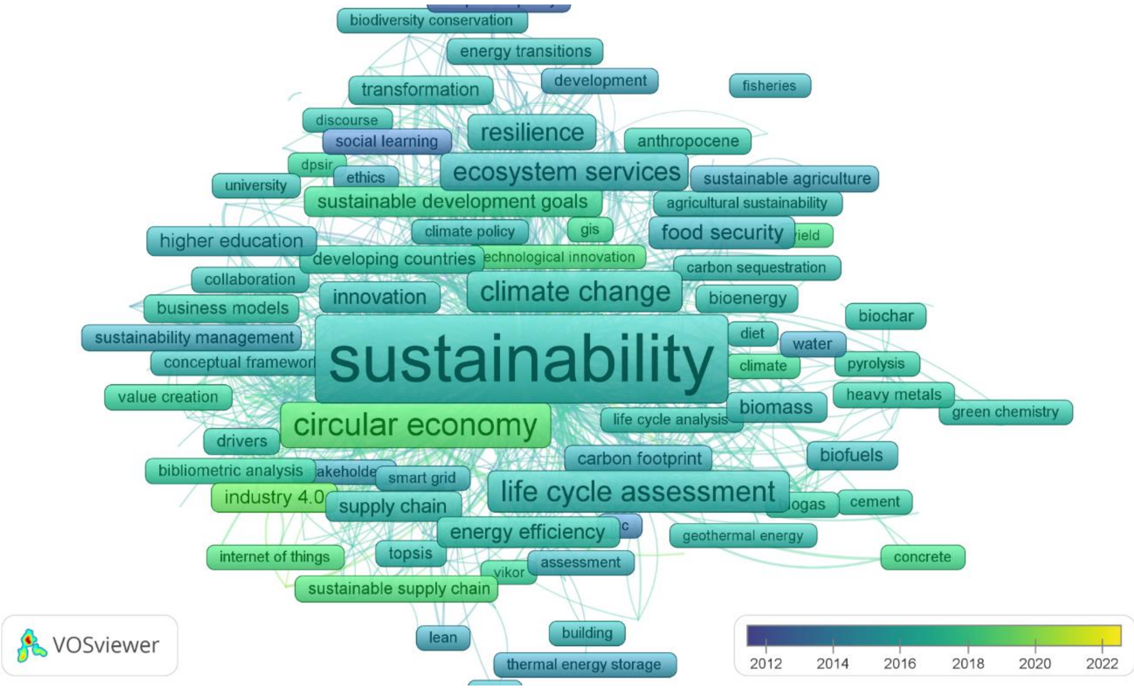

Fig. 1-5 The most common key words and period of occurrence in the past decade from the most highly cited 3,000 research articles using VOSviewer software analysis.

Search terms: Sustainability, AND 2012-01-01 – 2022-12-31.

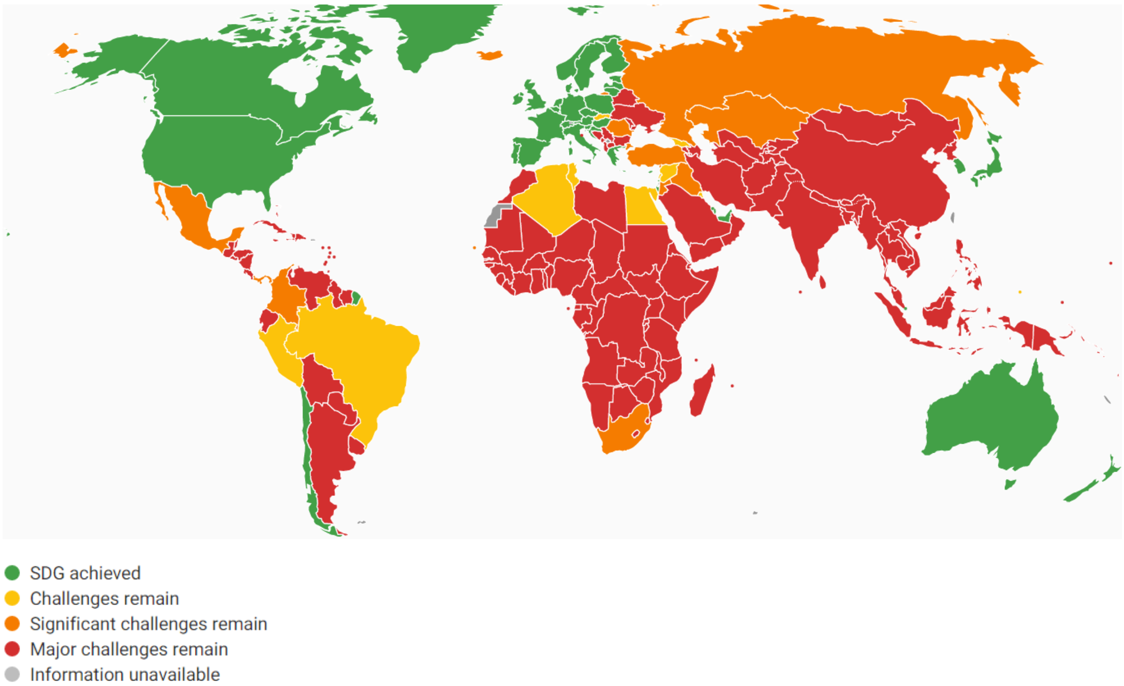

Fig. 1-6 Wastewater treatment towards SDG 6 attainment by regions.

Adapted from Sachs et al. (2021).

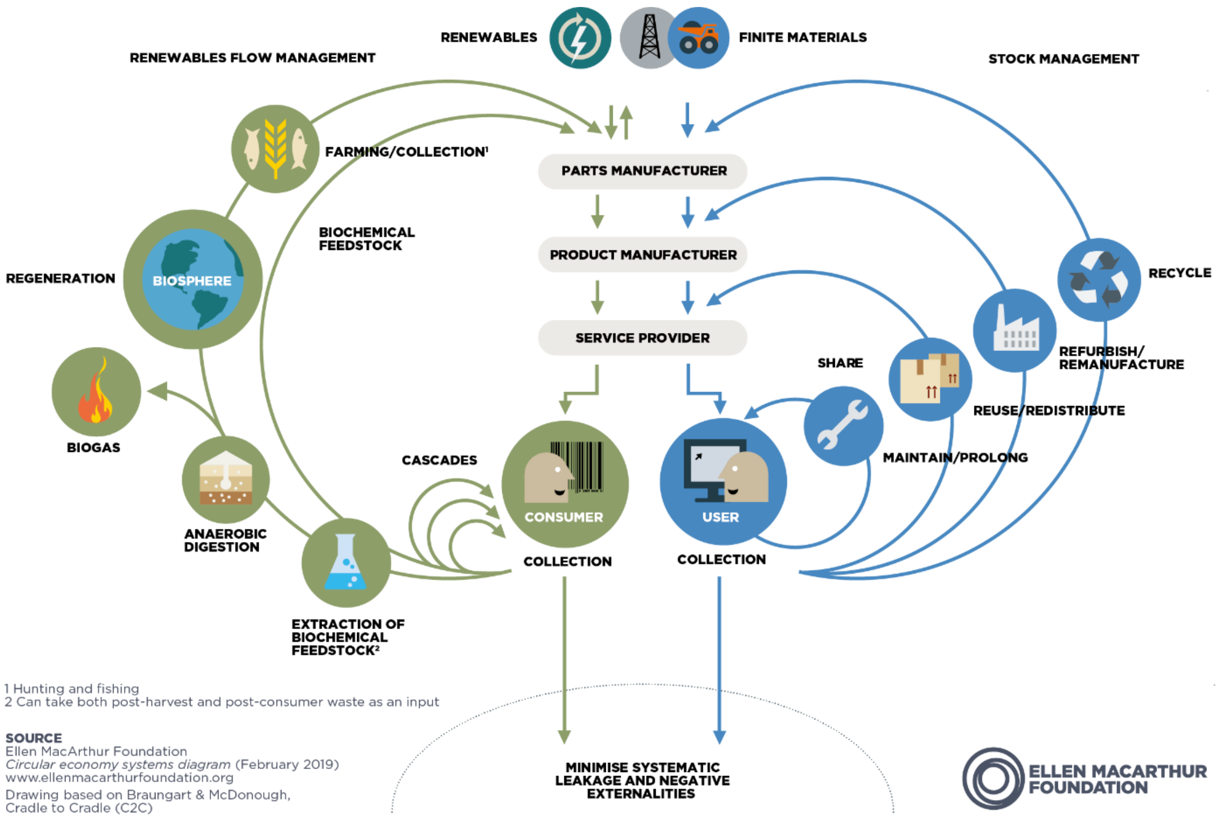

Fig. 1-7 Material cycle for biological (renewable) and technical (non-renewable) resources

Source: Ellen MacArthur Foundation (2014).

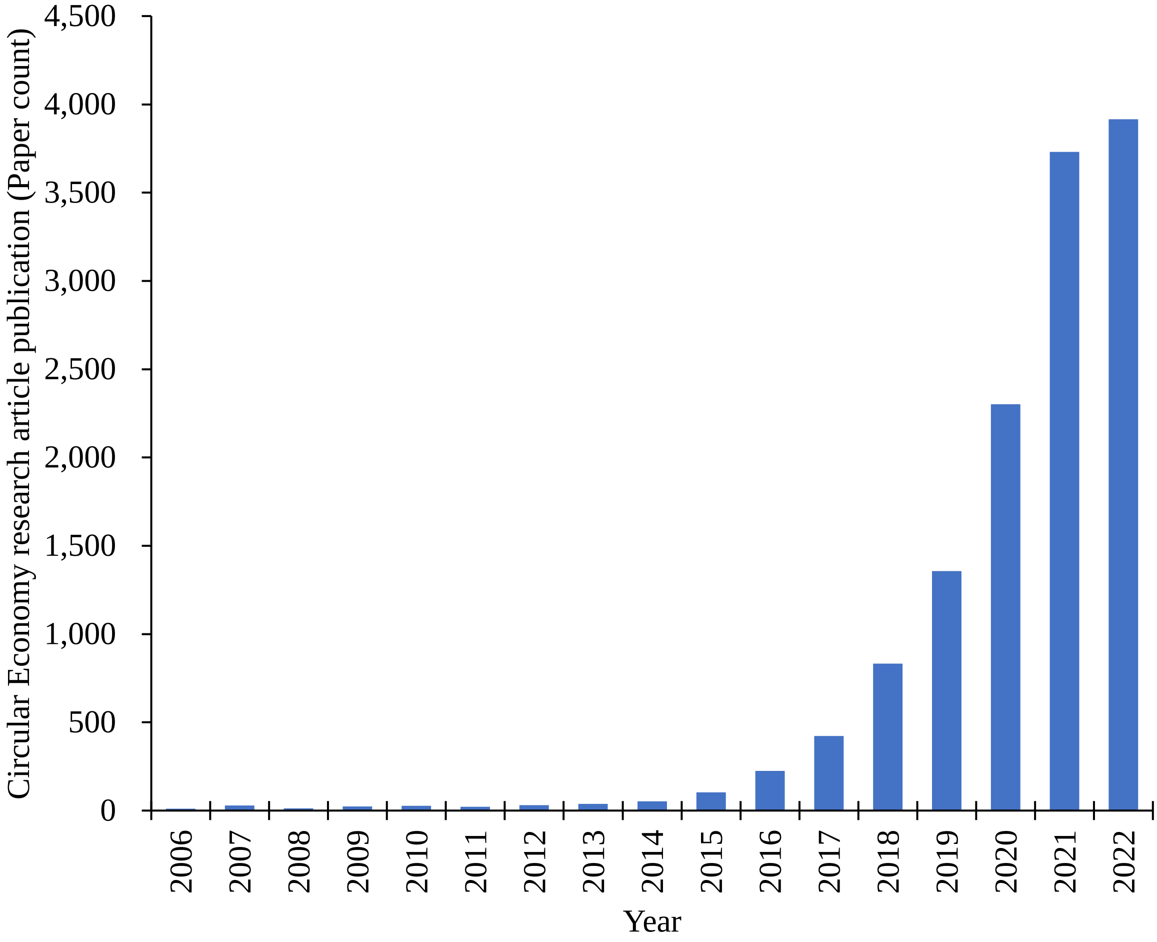

Fig. 1-8 The research trend in CE in the past two decades

Data source: Web of Science database

Search terms: Topic: Circular economy; Timespan: 2000-01-01 to 2022-12-31; Document type: Articles

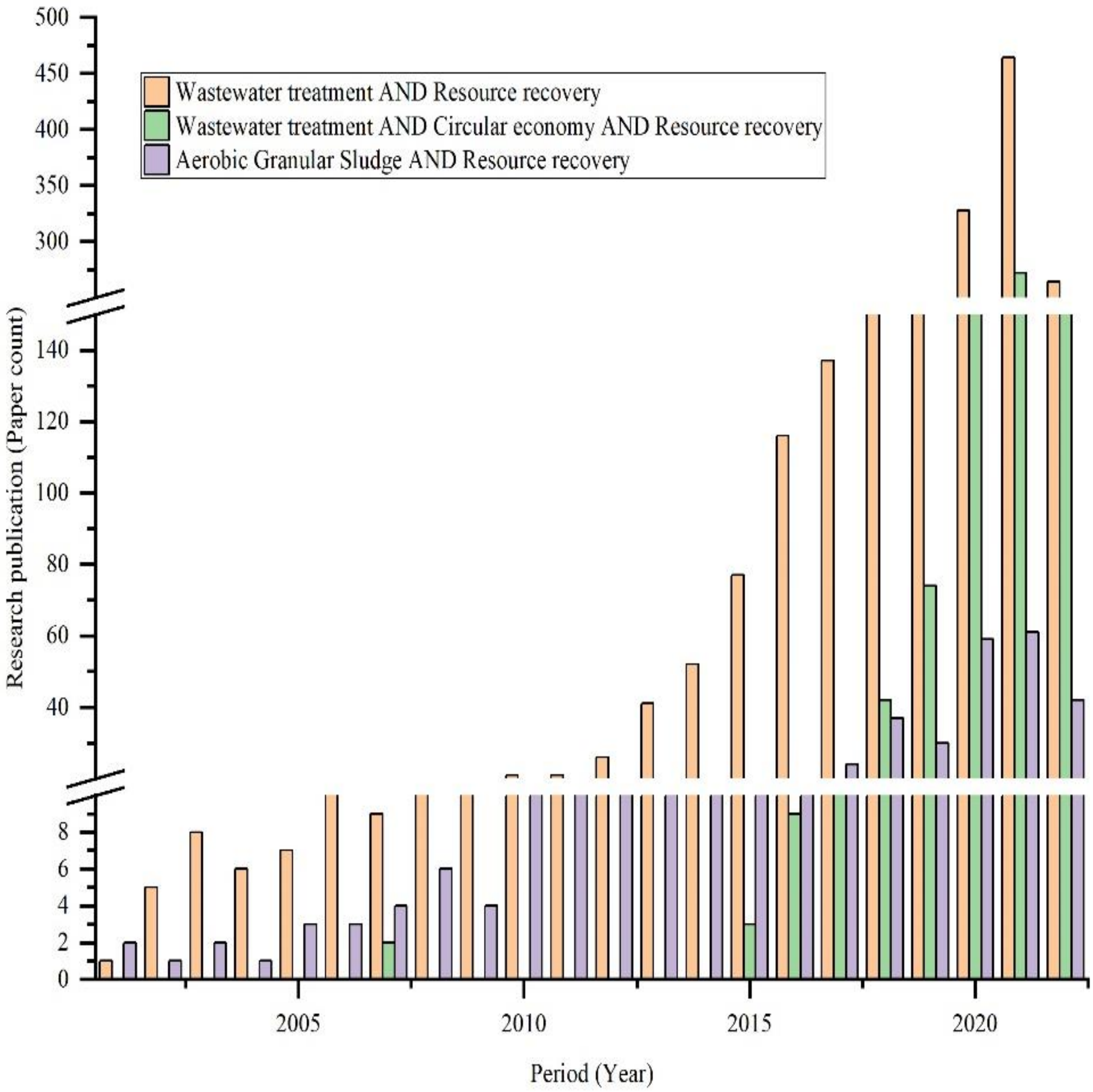

Fig. 1-9 The publications on wastewater treatment and resource recovery, AGS resource recovery, and CE application in the past two decades.

(Web of Science database search, Timespan: 2001-01-01 to 2022-09-09)
Search terms used: Wastewater treatment AND Resource recovery; Wastewater treatment AND Circular economy OR Circular bioeconomy AND Resource recovery; Aerobic granular sludge AND Bacterial aerobic granular sludge OR Algal-bacterial granular sludge AND Microalgal-bacterial granular sludge AND Resource recovery.

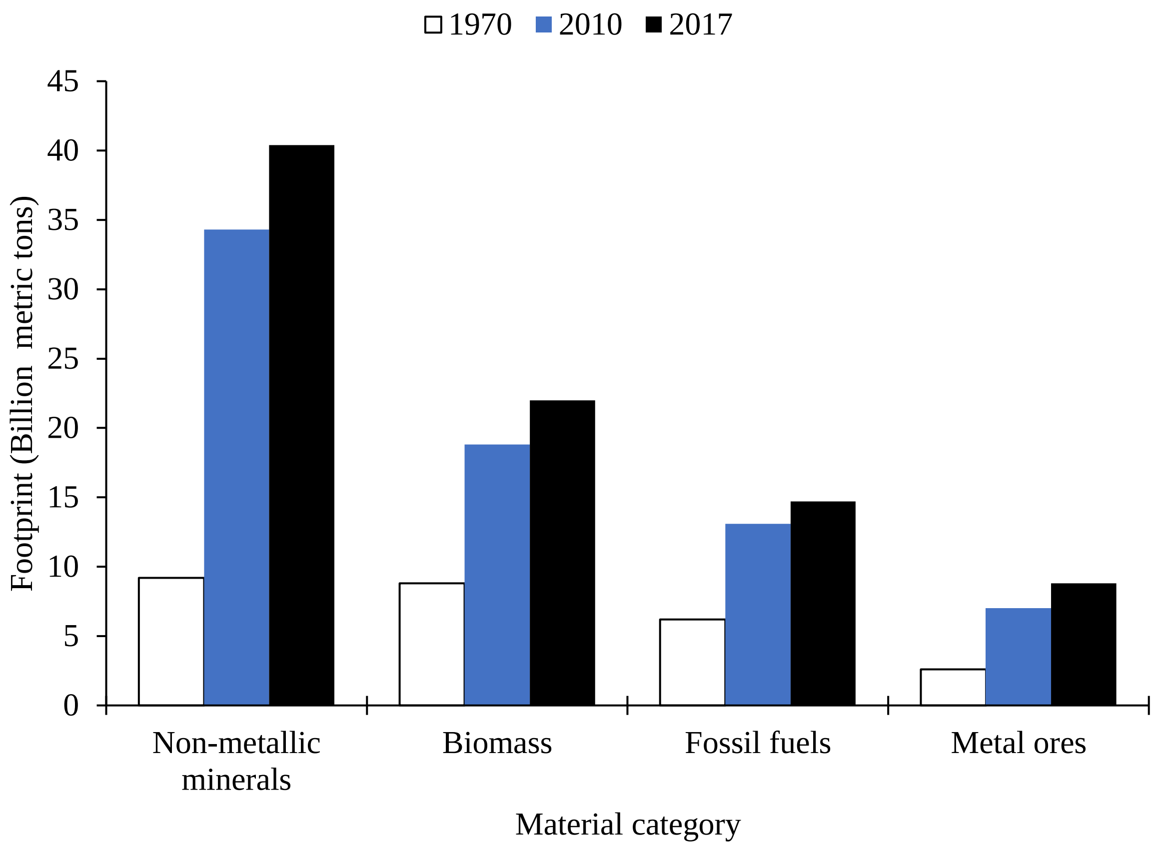

Fig. 1-10 The trend in global material extraction by categories.

Data source: UNEP/UNDESASD (2021, 2022).

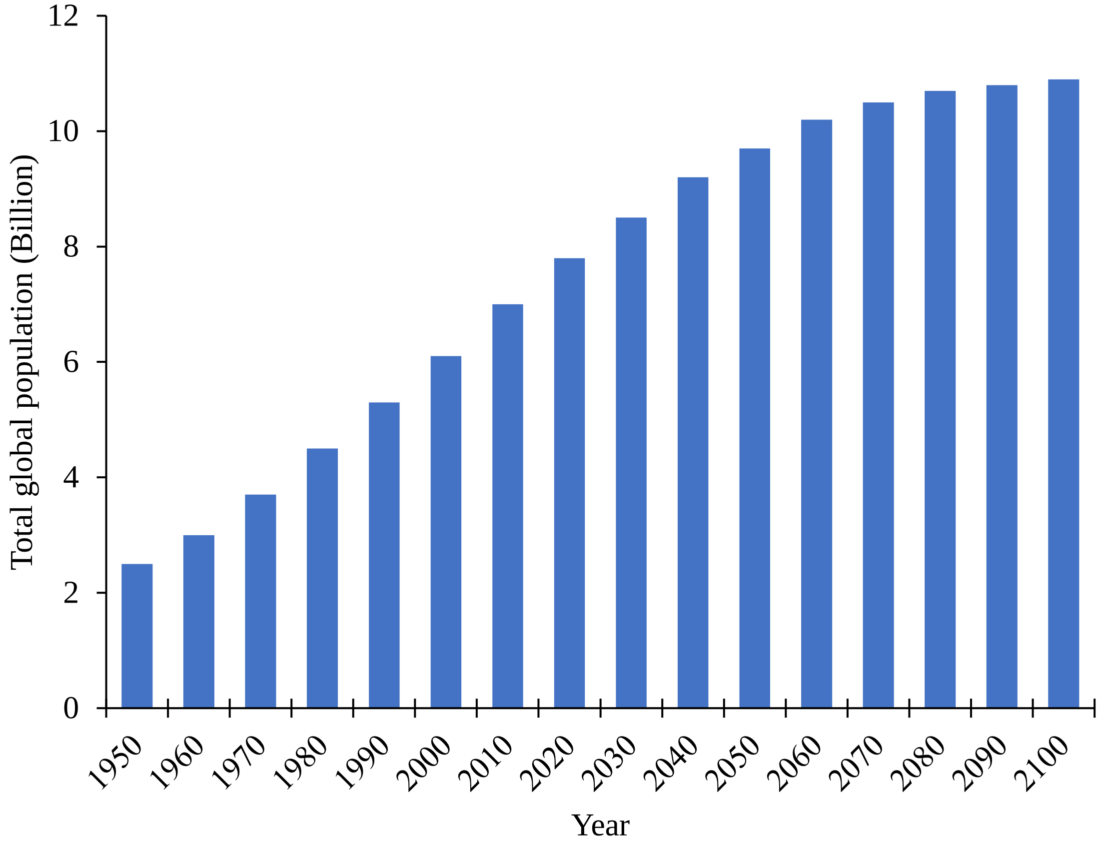

Fig. 1-11 Total global population growth since 1950, and projections to the end of the millennia. Data source: UNDESAPD (2021, 2022).

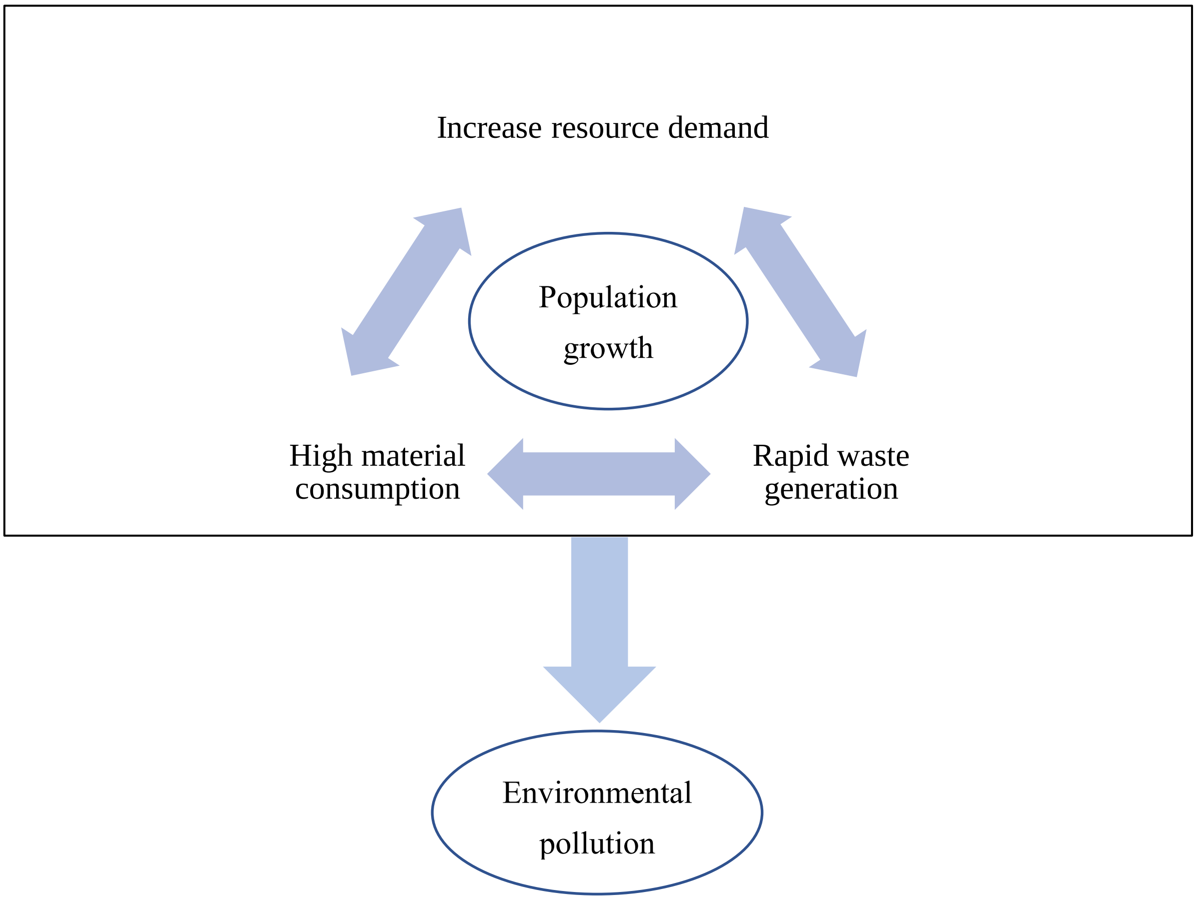

Fig. 1-12 Illustration of environmental pollution/degradation caused by the factors from population increase.

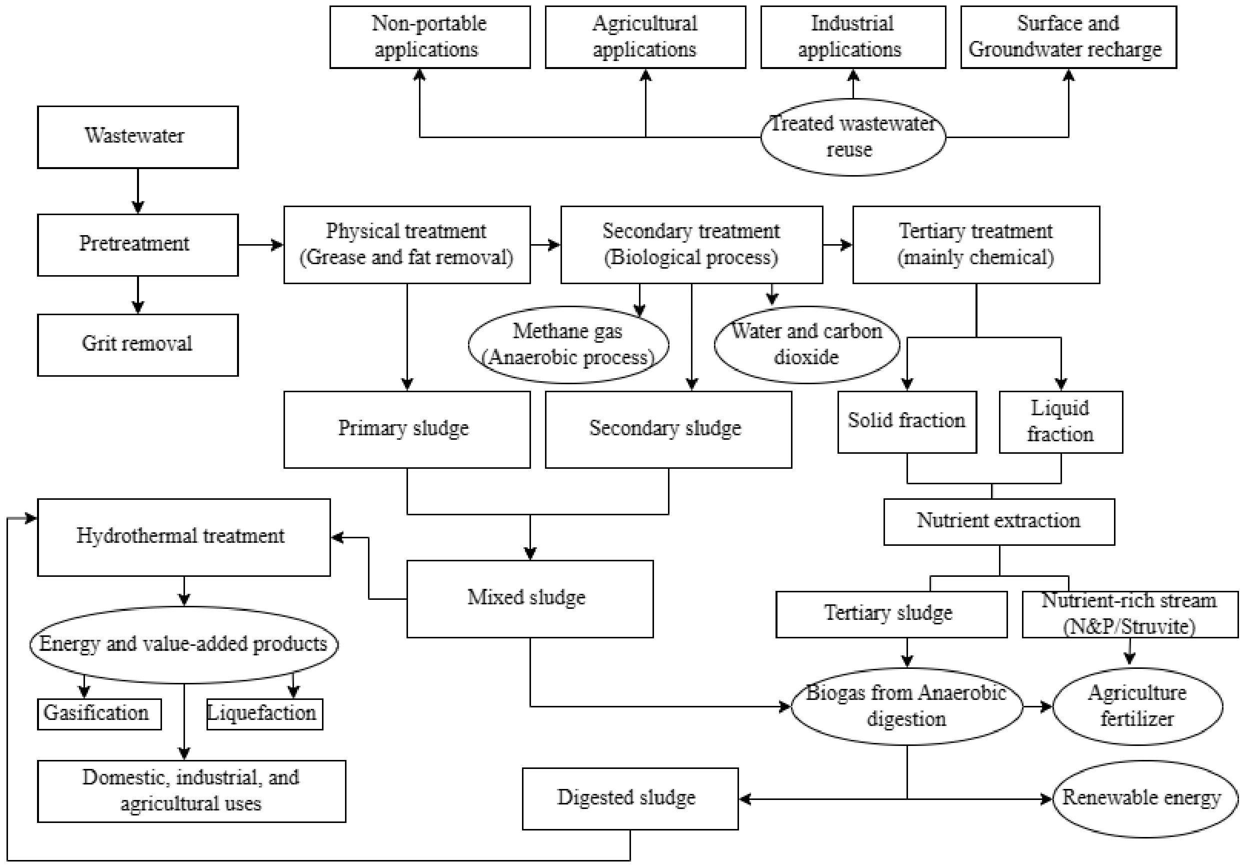

Fig. 1-13 Key steps and potential resource product recovery from the conventional wastewater treatment process and their uses.

Modified from Djandja et al. (2021) and Mbavarira and Grimm (2021)

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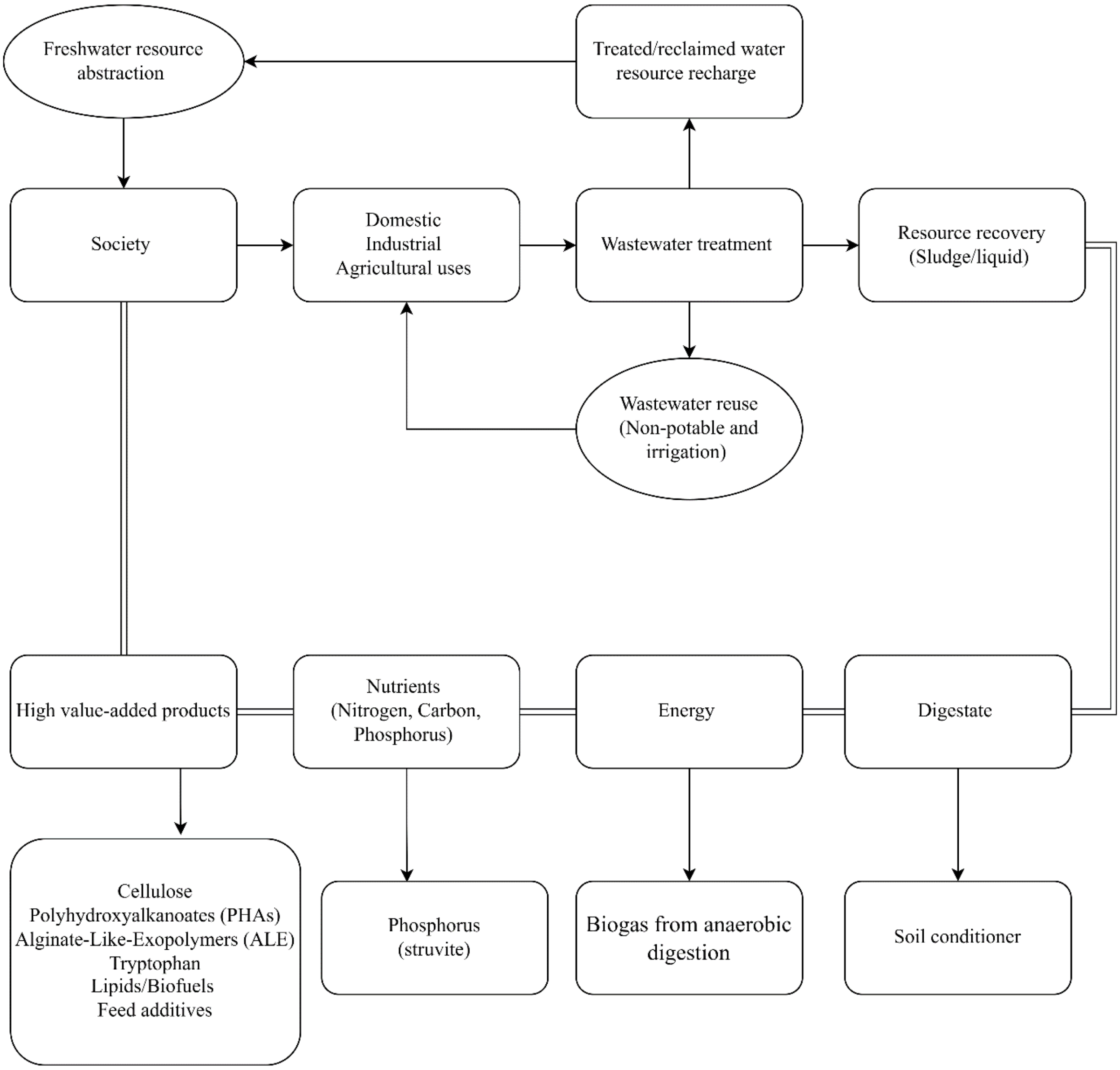

Fig. 1-14 Wastewater resources recovery characterization according to value from treatment in a CE model.

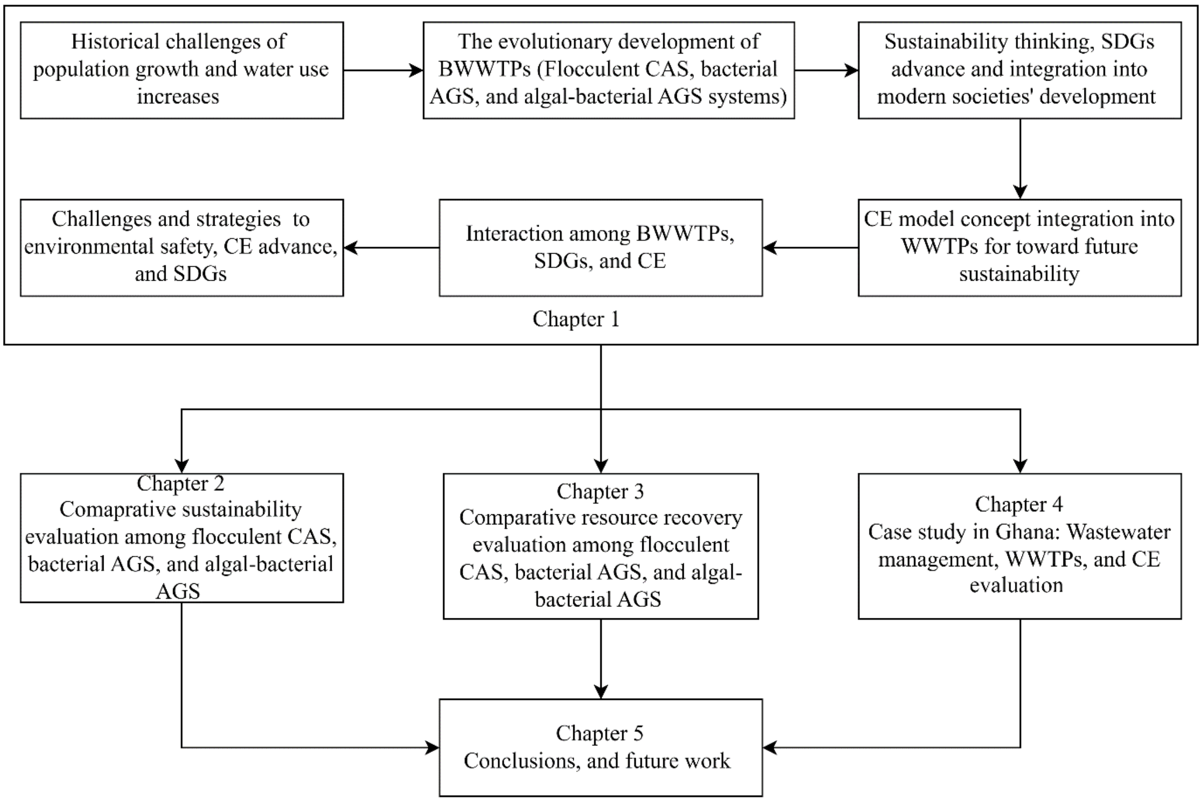

Fig. 1-15 Thesis framework

Chapter 2 Comparative sustainability evaluation among flocculent CAS, bacterial AGS, and algal-bacterial AGS systems

2.1 Introduction

Current environmental challenges, and the impending transition from a linear economy to CE rationalize the essential value of WWTPs. In the fast-growing global economy, there is an increasing demand for the evaluation of their relevance, contribution to contemporary needs, and future impact on the society. According to Molinos-Senante et al. (2014) the sustainability assessment of WWTPs is always situational, hence it can be contextualized to incorporate useful indicators toward set objectives. In the past two decades of significant increase in WWTPs sustainability-related research, the past five years accounted for almost 50% of total publications (Fig. 2-1), indicative of it becoming a critical research focus/interest. Primarily, the fundamental classifications or groups of factors for sustainability evaluation are economic, environmental, social, and technical aspects (Balkema et al., 2002; Muga and Mihelcic, 2008).

Adopting appropriate requirements for WWTPs evaluation/selection in the modern society is critical to their successful integration/transition to WRRFs. However, the contextual nature of sustainability evaluation in WWTPs makes assessments based on a defined set of indicators non-representative on a global scale (Molinos-Senante et al., 2014). Multi-criteria decision making (MCDM) techniques for structured and systematic problem-solving are applied in various decision-making processes. This applies to WWTPs selection/evaluation that requires separate tools for precise assessment (Castillo et al., 2016).

The analytical hierarchical process (AHP) is an example often used in the sustainability evaluation of WWTPs incorporating environmental, economic, and socio-economic considerations (Karimi et al., 2011; Chaisar and Garg, 2022) and AHP combination or modification with other methods is also reported (Hu et al., 2016; Ouyang and Guo, 2018). However, limitations of the AHP include the assumption of linear trade-offs without established thresholds to express satisfaction with outcomes and the balancing of poor environmental/social performance with the benefits of low cost (Arroyo and Molinos-Senante, 2018). Thus, AHP might not be the most suitable, reliable, or best alternative for the sustainability evaluation of WWTPs toward future needs on a set of indicators.

The choosing-by-advantage (CBA) alternative MCFM process proposes the adoption of the importance of advantage approach through an understanding of the differences between alternatives in each situation. The flocculent CAS, bacterial AGS, and algal-bacterial AGS systems have peculiar advantages in resource recovery, energy use efficiency, prospective future environmental safety contribution, and circular economy value creation. To advance the prospects of biotechnologies' relevance and sustainability in the modern society, the study compares the new competitive aerobic biological treatment processes employing granular sludge technology, which is superior to conventional treatment methods, to assess their sustainability prospects and relevance. This research adopts the CBA method (Arroyo and Molinos-Senante, 2018) for WWTPs evaluation, to provide a more reliable sustainability evaluation of existing conventional wastewater treatment biotechnologies and emerging competitive alternatives. Moreover, to the author's knowledge, no assessment of the three biotechnologies has been reported in the literature.

2.2 Materials and methods

The CBA method is briefly described as follows and Fig. 2-2 shows the schematic representation.

2.2.1 Procedures in the CBA evaluation method

The CBA method was conducted step by step as follows.

(1) Identify the alternatives to be assessed in the decision-making process. In this context, the flocculent CAS, bacterial AGS, and algal-bacterial AGS systems were selected.

(2) Define the factors differentiating each alternative from the other. In this study, land footprint, energy use/efficiency, climate-smartness/greenhouse gas mitigation, water reuse potential, high value-added product, and nutrient resource recovery were defined.

(3) Define the requisite criteria to evaluate the alternatives, as in "less/more is better" and (low, moderate, high).

(4) Summarize the characteristics of the alternatives. For example, in this study, the energy use value was established, with an average energy use of 0.425 kWh/m^3 for CAS).

(5) Determine the advantages of each alternative to the least preferred attribute among the alternatives based on the defined criterion. For example, alternative A consumes 0.05 kWh/m^3 less than C, which uses the most energy among all the alternatives considered.

(6) Quantify the importance of the advantages, corresponding to a preference value given each alternative, to determine the marginal performance factor that helps compare the results. The sum of the importance of advantages is the total importance of advantages for each alternative, indicating the degree of sustainability for each biotechnology.

(7) Evaluate cost vs. importance of advantage. This step develops a graph for the importance of advantage and cost. This can allow the decision-makers to make an informed decision with access to information on investment and operation/management costs to determine a choice among the alternatives.

2.2.2 Sustainability indicators' selection and considerations for adoption

Energy efficiency and resource recovery are essential for sustainable development in the circular economy transition. Water, energy, and nutrient resource recycling from wastewater can promote environmental sustainability and are essential to transition from a linear toward a resource recovery society (Capodaglio et al., 2017).

The flocculent CAS process is widespread and full-scale bacterial AGS systems are also available. However, algal-bacterial AGS systems are currently only operated on a laboratory scale (Lee and Lei, 2019; Zhang et al., 2022), which are competitively promising for the future. Hence, to evaluate the three biotechnologies, the factors for environmental, economic, socio-cultural, and technical sustainability were reviewed from the literature (Balkema et al., 2002; Muga and Mihelcic, 2008; Molinos-Senante et al., 2014).

Sixteen factors (indicators) were used. Like Arroyo and Molinos-Senante (2018) did, economic variables are not considered in this research as algal-bacterial AGS is yet to advance to full-scale application. However, technical factors (Adaptability, Shock endurance, Ease of construction) is considered, which was not reported in the previous studies (Arroyo and Molinos-Senante, 2018; Molinos-Senante et al., 2014). The other factors were environmental (Land footprint, Effluent reuse potential, Energy use/consumption, Chemical oxygen demand (COD)/BOD removal (%), Nitrogen removal (%), Phosphorus removal (%), Biomass production, Biomass, Recovery), and social indicators (Aesthetic value, Staffing requirement, Skilled labour, Public acceptance, Complexity).

The land footprint of the three biotechnologies is adopted as an environmental sustainability indicator to influence WWTPs application in urban environments constrained by high-cost lands. While biomass production and recovery are considered because of the current disposal burden and prospective influence on resource recovery potential. Secondary sewage sludge treatment and disposal cost account for approximately 50% of WWTPs operation cost in Europe (Kacprzak et al., 2017). Furthermore, nutrient removal is adopted because of its potential to influence nutrient loads (contributing to eutrophication) in receiving water resources and treated effluent reuse within a CE.

Energy demand/use is a common environmental sustainability indicator in WWTPs' evaluation (Balkema et al., 2002; Muga and Mihelcic, 2008; Capodaglio et al., 2017). Increasing stringent effluent quality standards have prospects to influence energy demand, and overall operation and maintenance (O&M) cost in WWTPs' sustainable development.

2.2.3 Protocol for sustainability evaluation scoring and analysis

In their research, Arroyo and Molinos-Senante (2018) report diverging opinions between the two groups of evaluators used, which is a common observation in subjective decision-making among varying levels of expertise.

Research impact and expert knowledge can be measured by the contribution of publications and their relevance in view of the total citations. This research adopted peer-reviewed articles as expert knowledge base for each indicator evaluated in the importance of advantage scoring. This is shown in Table 2-1. The highest score for the importance of advantage for each index was set at 30. Meanwhile, an analysis of keywords from peer-reviewed research publications on algal-bacterial AGS was conducted with VOSviewer to show the recent emphasis. VOSviewer is a computer program designed to develop bibliometric maps that can be used to observe citations/co-citation, author, and keywords co-occurrence trends (van Eck and Waltman, 2010). The most current version (VOSviewer version 1.6.18) of the software released in 2022 was used.

2.3 Results and discussion

2.3.1 Overview of the flocculent CAS, bacterial AGS, and algal-bacterial AGS

The CAS process's extensive use for wastewater treatment in urban environments spans over seven decades. Replacing the biological filtration methods like soil filtration and trickling filters, CAS became the dominant treatment alternative for BOD_5 removal and its combination with nitrification from the 1970s (Wanner, 2021). However, the demands of the modern society for low-cost, highly efficient energy use, multiple resource recovery, and small land/carbon footprints for wastewater treatment are challenging for conventional treatment processes. Hence, CAS-based WWTPs are increasingly viewed as economically and environmentally unsustainable for the future (Sheik et al., 2014).

Granular sludge systems have better treatment performance, a relatively small footprint, and great prospects for resource recovery due to their dense self-immobilized, and compact granular structure with high biopolymer contents and settling velocities (Nancharaiah and Sarvajith, 2019). In the past two decades, bacterial AGS has been patented (Heijnen and van Loosdrecht, 1998), full-scale applications reported in academic literature (Hamza et al., 2022), and has over 90 plants in operation under the tradename Nerada® in 20 countries (HaskoningDHV, 2022).

Most biological wastewater treatment processes are energy-intensive but could be low in resource recovery (Gao et al., 2014). Hence, all potentially low energy-demand options must be explored towards the future sustainability of WWTPs. Algal-bacterial relationships in wastewater treatment can reduce energy use and operational costs (Semaha et al., 2020) from microalgae oxygenation (Abdel-Raouf et al., 2012). In the United States, over USD 1.2 trillion worth of savings and 1.1 gigatons of GHGs emission reduction can be realized from energy efficiency (McKinsey and Company, 2010). Meanwhile, wastewater provides an unconventional low-cost production pathway for microalgae cultivation, reducing fertilizer and chemical input costs associated with the conventional processes (Mehrabadi et al., 2015; Ogbonna et al., 2021). This is innovative for industrial-scale microalgae cultivation toward clean energy production and other value added products recovery.

Prospecting the benefits of combined microalgae and bacterial AGS systems application in wastewater treatment, the first algal-bacterial AGS consortium was reported by Huang et al. (2015). In recent years, algal-bacterial AGS has grown with over 80% of research within the last three years (Fig. 2-3). From the review of relevant literature from Web of Science collections, nutrient removal performance, energy efficiency, lipid resource recovery, and environmental sustainability were the key focus in 2020. While 2021 focused more on toxicity tolerance, environmental sustainability, and stable treatment operation. However, process optimization, P/biopolymer resource recovery, and environmental sustainability have been the dominant research focus in 2022. Thus, the increasing focus of algal-bacterial AGS is on the realization of environmental sustainability through efficient energy use from optimized process operations and varied resource recovery. These added their potential to contribute to carbon capture and added value-product recovery (Quijano et al., 2017).

2.3.2 Sustainability of the flocculent CAS, bacterial AGS, and algal-bacterial AGS

The results of the importance of advantage for each factor for the three biotechnology alternatives are presented (Table 2-2). For the most part, bacteria AGS and algal-bacterial AGS performed similarly in the sustainability evaluation of their advantage of importance factors. The COD, ammonium nitrogen (NH_4^+-N), and P removal in bacterial AGS and algal-bacterial AGS systems were higher than the flocculent CAS, contributing to a relatively higher prospect for water reuse. The prospects for resource recovery from sludge make it beneficial for high sludge generation from wastewater treatment. Although the flocculent CAS was higher in biomass production, its poor settleability is a drawback to low-cost biomass recovery/harvesting compared to the granular sludge alternatives.

The relatively small footprint of the granular sludge alternatives and full-scale implementation of the bacterial AGS, its importance of advantage was higher for ease of construction and process complexity. This can be attributed to the need to address bottlenecks (Ji and Liu, 2021; Lee and Lei, 2019), for example, illuminance requirement and reactor depth in full-scale algal-bacterial AGS application. The urgent need to reduce the global carbon footprint is critical. Thus, algal-bacterial AGS mitigation potential is essential to environmental sustainability. In comparing the sustainability of the three biotechnologies, the algal-bacterial AGS, considering the research focus was to compare the sustainability of the three biotechnologies, the sum of the importance of advantage represents the different degrees of sustainability (Fig. 2-4).

Arroyo and Molinos-Senante (2018) proposed the development of a graph for importance of advantage by cost (total annual equivalent cost) on the y- and x-axis, respectively, to reflect economic considerations for the process. In their research, the treatment technologies adopted were already in full-scale application with relevant available information on investment and operation/management costs. Since the algal-bacterial AGS is yet to advance to full-scale application, this study does not consider prospective economic evaluation.

2.4 Summary

The sustainability evaluation of WWTPs to assess their prospective alignment/meeting of the current global emphasis on climate-smartness and CE integration was researched in this chapter. Using the choosing-by-advantage method because of the peculiar features of the flocculent CAS, fast-growing bacterial AGS, and most recent algal-bacterial AGS biotechnologies, an assessment of the treatment processes was conducted.

The following findings can be summarized.

(1) Algal-bacterial AGS and bacterial AGS are the most sustainable wastewater treatment biotechnologies from the three methods evaluated.

(2) The slight advantage of algal-bacterial AGS system over the bacterial AGS one can be attributed to their carbon mitigation potential, which also has the potential for tangible value earnings from carbon credits. Meanwhile, the lower aeration/energy demand niche for the algal-bacterial AGS systems is yet to be fully explored to realize its potential influence on cost reduction and lower operating costs.

(3) The bigger granular size, density, and higher biopolymer and nutrient bioavailability advance easy biomass harvesting and higher resource recovery from algal-bacterial AGS biomass toward successful CE application and cost-reduction from downstream processes.

Table 2-1 Relevant literature and attributes considered in importance of advantage scoring.

Item	Flocculent CAS	Bacterial AGS	Algal-bacterial AGS
Land footprint	Large land footprint Bengtsson et al. (2019)	40 – 50% smaller footprint than the flocculent CAS process Bengtsson et al. (2019)	76% reduced footprint compared to the conventional process. Wang et al. (2022)
Effluent reuse	Meets the EU Water Directive (91/271/EEC) standards. Barrios-Hernández et al. (2020)	Meets the EU Water Directive (91/271/EEC) standards. Barrios-Hernández et al. (2020)	Meets international discharge and reuse standards. Guo et al. (2021)
Energy demand	High aeration consumption 0.33 - 0.52 kWh/m^3. Gikas. (2017); Pronk et al. (2015); Wan et al. (2016)	0.17 – 0.25 kWh/m^3 23% less energy demand than CAS. Bengtsson et al. (2019); Pronk et al. (2015); Rollemberg et al. (2020)	0.34 kWh/m^3 58% less energy demand Wang et al. (2022); Ji and Liu. (2021); Zhao et al. (2019)
Carbon footprint (kg CO_2e/m^3)	High CO_2 emission 0.81. Ji and Liu. (2021)	Low CO_2 emission compared to CAS (0.36)[a]	Lower CO_2 emission than AGS (0.05)[a] Ji and Liu. (2021)
COD removal (%)	>80 Wan et al. (2016)	85 – 96 Li et al. (2014); Rollemberg et al. (2019)	93 – 98 Ji et al. (2020); Wang et al. (2021)
Nitrogen removal (%)	>95 Thwaites et al. (2018)	71–99.6 Li et al. (2014); Thwaites et al. (2018)	97– 99 Ji et al. (2020); Wang et al. (2021)
Phosphorus removal (%)	80 Rollemberg et al. (2019)	80 – 94 Rollemberg et al. (2019); Guo et al. (2021)	83 – 97 Guo et al. (2021); Ji et al. (2020)
Biomass production	High biomass production Soda et al. (2016); Zhang et al. (2022); Wan et al. (2016)	High biomass retention but low production compared to flocculent CAS. Val Del Río et al. (2014)	Higher biomass production and retention than bacterial AGS. Abouhend et al. (2018); Ji and Liu. (2021); Semaha et al. (2020); Zhang et al. (2020)
Biomass recovery potential (Fast-settling and recovery ease)	Approximately 10 m/h Low recovery. Nancharaiah et al. (2019)	50.4 m h^{-1}	High recovery (79-99%). van den Hende et al. (2014); Abouhend et al. (2018); Quijano et al. (2017); Wang et al. (2022)
High-value resource recovery	Soda et al. (2016); Zhang et al. (2022)	Amorim de Carvalho et al. (2021); Karakas et al. (2020)	Chen et al. (2022); Meng et al. (2019); Wang et al. (2022); Zhang et al. (2020); Zhao et al. (2018, 2019)

Table 2-1 (cont.)

Item	Flocculent CAS	Bacterial AGS	Algal-bacterial AGS
Adaptability	Sun et al. (2011); Wang et al. (2014)	Marques et al. (2013); Sun et al. (2011); Wang et al. (2014); Yang et al. (2021)	Hu et al. (2022); López-Serna et al. (2019); Wang et al. (2021); Yang et al. (2021); Zhao et al. (2018)
Shock endurance	Lotito et al. (2014; Wang et al. (2005)	Hou et al. (2019); Ou et al. (2018); Wu et al. (2022); Wu et al. (2020); Yao et al. (2021)	Dong et al. (2021); Meng et al. (2019); Semaha et al. (2020); Zhao et al. (2018)
Ease of construction	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review
Aesthetic value	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review
Staffing	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review
Skilled labour	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review
Public acceptance	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review
Complexity	Subjective deduction from literature review	Subjective deduction from literature review	Subjective deduction from literature review

Carbon footprint calculated on the assumption that 0.81 kg CO_2e/m^3 is the maximum (100%) emission from a WWTP (CAS) (Ji and Liu, 2021), 44.4% and 5.8% emissions for bacterial AGS and algal-bacterial AGS (Guo et al., 2021).

Table 2-2 Importance of advantage scoring by factor and sum for the three biotechnologies

Factor	Flocculent CAS process	Bacterial AGS	Algal-bacterial AGS
Land footprint	Attribute: Large footprint	Attribute: 40-50% less	Attribute: 40-50% less
Less is better	Advantage: Relatively none	Advantage: Low footprint	Advantage: Low footprint
	Importance: 0	Importance: 30	Importance: 30
Effluent reuse potential	Attribute: Moderate	Attribute: High	Attribute: High
More is better	Advantage: High water reuse potential	Advantage: Relatively higher water reuse potential	Advantage: Relatively higher water reuse potential
	Importance: 25	Importance: 30	Importance: 30
Energy demand (kWh/m^3)	Attribute: 0.425	Attribute: 0.21	Attribute: 0.34
Less is better	Advantage: High consumption	Advantage: Low energy demand	Advantage: Low energy demand
	Importance: 15	Importance: 27	Importance: 30
Carbon footprint (GHGs)	Attribute: 0.81 High carbon footprint	Attribute: 0.36 Low carbon footprint	Attribute: 0.05 Carbon mitigation
Less is better	Advantage: Comparable least advantaged	Advantage: Lower GHG emission	Advantage: Carbon mitigation
	Importance: 10	Importance: 20	Importance: 30
COD removal (%)	Attribute: >80	Attribute: >95	Attribute: >95
More is better	Advantage: High removal rate	Advantage: Higher removal rate	Advantage: Higher removal rate
	Importance: 25	Importance: 28	Importance: 30
Nitrogen removal (%)	Attribute: >95	Attribute: >99	Attribute: >99
More is better	Advantage: Moderate removal	Advantage: High removal	Advantage: High removal
	Importance: 25	Importance: 30	Importance: 30
Phosphorus removal (%)	Attribute: 80%	Attribute: 87%	Attribute: 90%
More is better	Advantage: High removal	Advantage: Higher removal	Advantage: Higher removal
	Importance: 15	Importance: 28	Importance: 30
Biomass production potential	Attribute: High	Attribute: High	Attribute: Higher
More is better	Advantage: Higher sludge generation potential	Advantage: High biomass generation potential	Advantage: High biomass generation potential
	Importance: 30	Importance: 25	Importance: 27

Table 2-2 (cont.)

Factor	Flocculent CAS process	Bacterial AGS	Algal-bacterial AGS
Adaptability	Attribute: Moderate Advantage: Low adaptability Importance: 20	Attribute: High Advantage: High adaptability Importance: 25	Attribute: High Advantage: High adaptability Importance: 30
Shock endurance potential	Attribute: Moderate Advantage: Low tolerance to shock and salinity stress Importance: 20	Attribute: High Advantage: Moderate tolerance to shock and salinity stress Importance: 25	Attribute: High Advantage: Higher tolerance to shock and salinity stress Importance: 30
Ease of construction Less is better	Attribute: High Advantage: Well-known biotechnology Importance: 20	Attribute: Low Advantage: Relatively easy construction Importance: 30	Attribute: Moderate Advantage: Considerations for large-scale still under research Eg. light requirements, and depth Importance: 24
Aesthetic value More is better	Attribute: Moderate Advantage: Good aesthetic value and contribution to urban environments Importance: 20	Attribute: High Advantage: Comparably high aesthetic value Importance: 30	Attribute: High Advantage: High aesthetic value Importance: 25
Staffing requirement Less is better	Attribute: Comparably high staffing Advantage: High staff requirement Importance: 20	Attribute: Low Advantage: Low staffing need Importance: 30	Attribute: Low Advantage: Low staffing need Importance: 30
Public acceptance	Attribute: High public acceptance Advantage: Well-known Importance: 20	Attribute: Higher public acceptance Advantage: Ideal for sustainable cities Importance: 30	Attribute: Potential high public acceptance Advantage: Potential to appeal to sustainable cities Importance: 30
Complexity	Attribute: More complex Advantage: Complex Importance: 20	Attribute: Less complex Advantage: Less complex Importance: 25	Attribute: Moderate Advantage: Moderately complex Importance: 22
Sum of importance of advantages	303	441	458

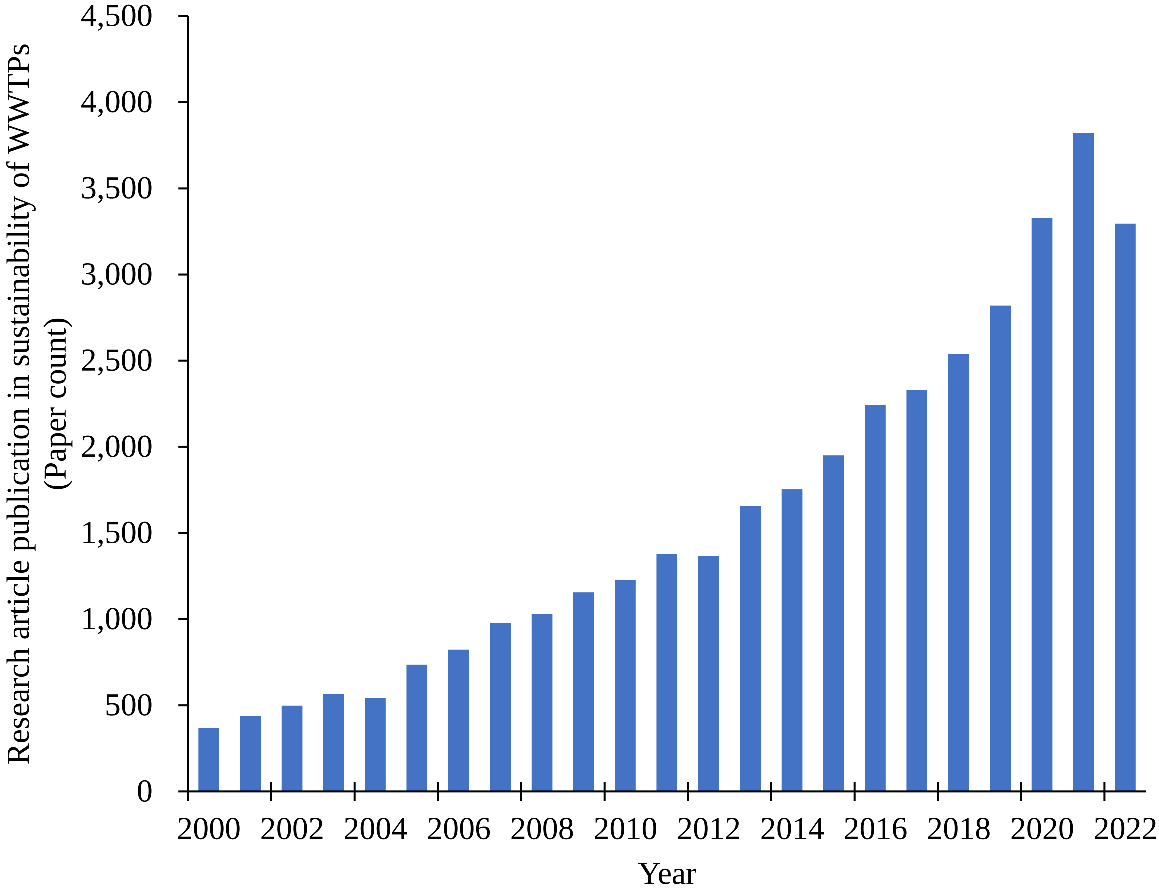

Fig. 2-1 Research publication trend in the sustainability of WWTPs in the past two decades.

Search terms used: Sustainability, AND, Wastewater treatment, OR, Wastewater treatment plant, OR WWTP. Time frame: 2000-01-01 to 2022-12-31.

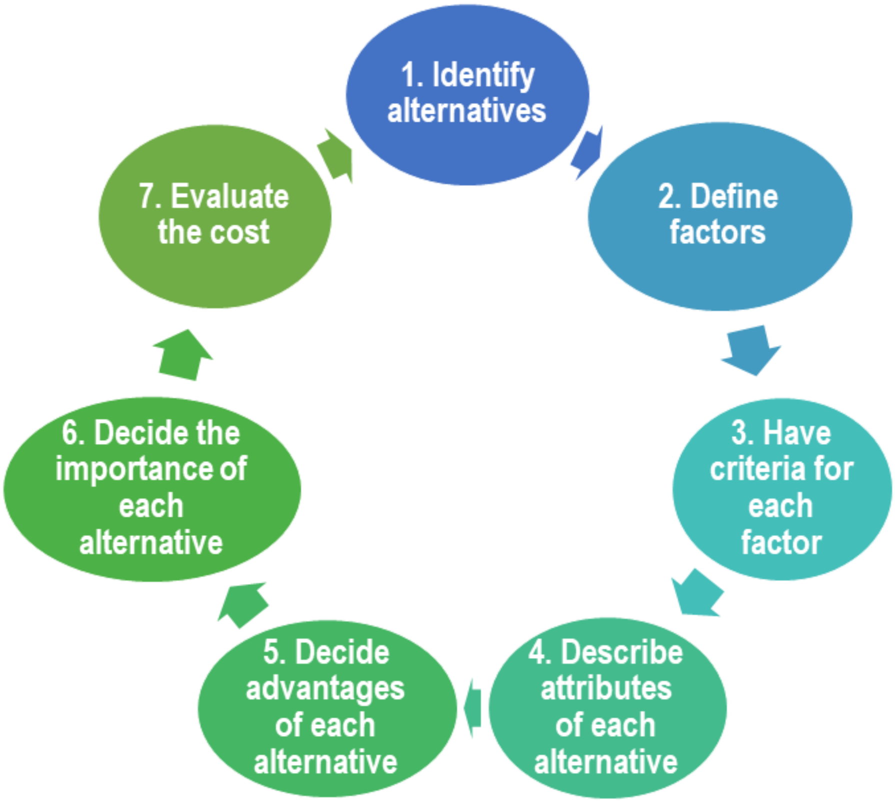

Fig. 2-2 Overview of the CBA method adopted in this study for sustainability evaluation.

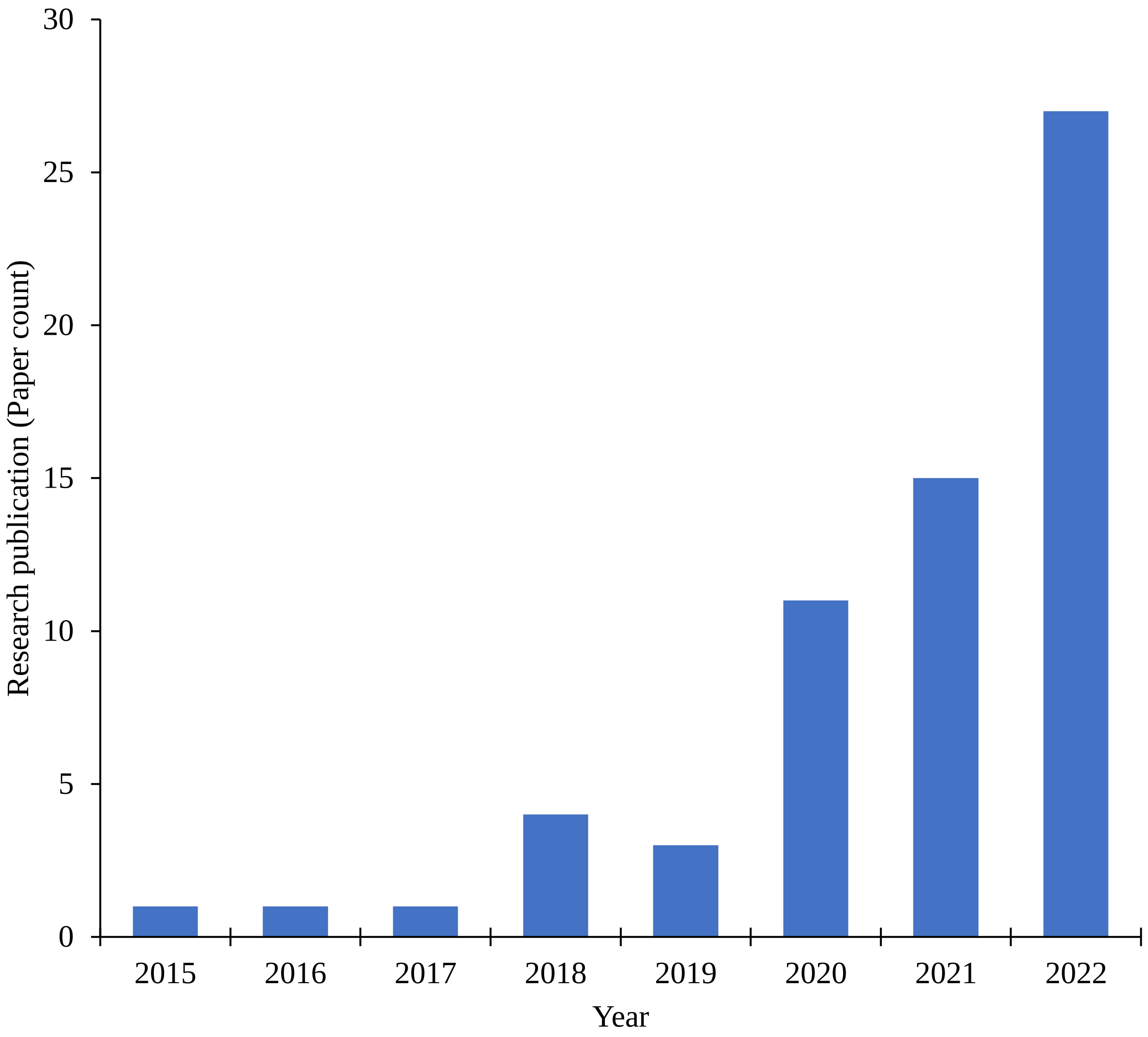

Fig. 2-3 The publication trend in algal-bacterial AGS research.

Web of Science database analysis. Search terms used were; "Algal-bacterial granular sludge" OR "Microalgal-bacterial granular sludge", AND "Wastewater treatment"

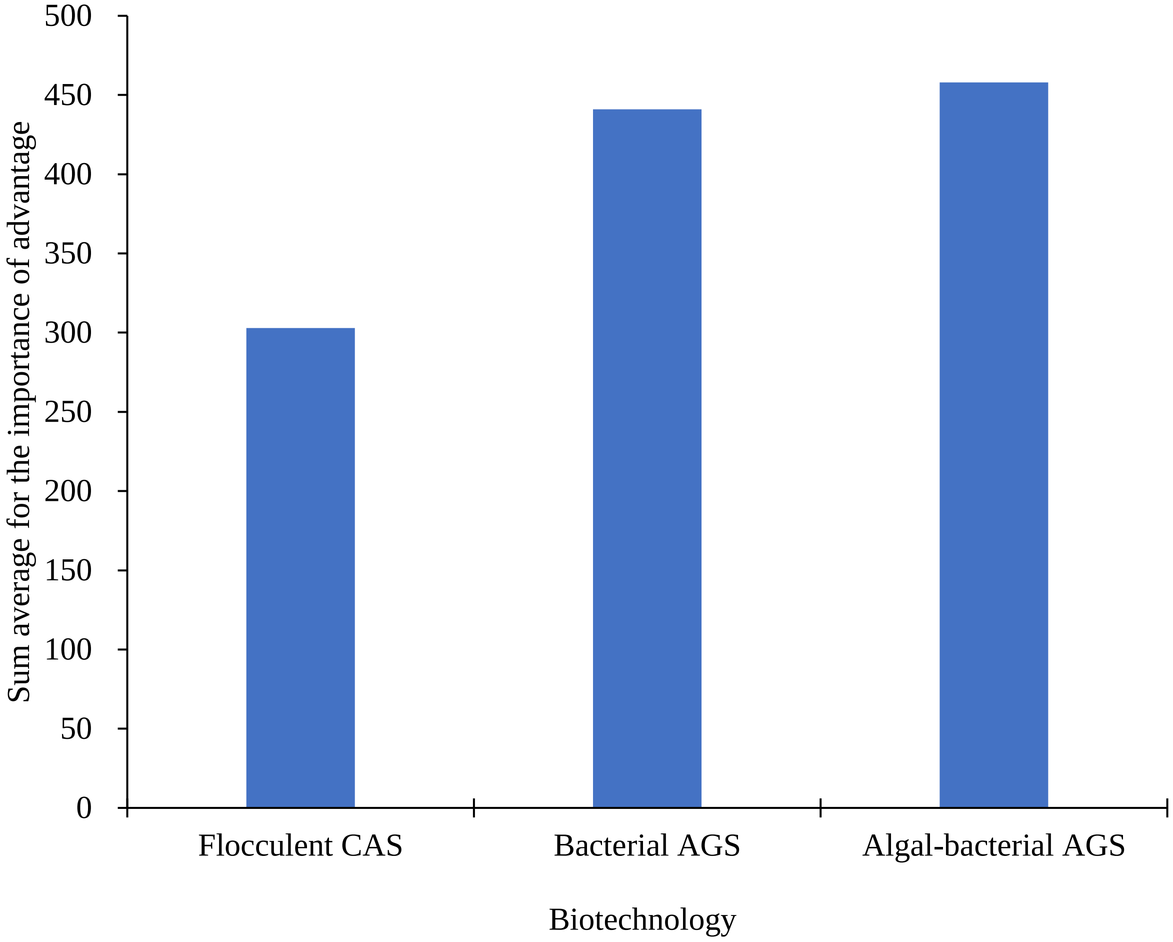

Fig. 2-4 Degrees of sustainability ranking for flocculent CAS, bacterial AGS, and algal-bacterial AGS.

Chapter 3 Comparative resource recovery evaluation among flocculent CAS, bacterial AGS, and algal-bacterial AGS

3.1 Introduction

The current focus on resource recovery and energy efficiency toward successful CE integration of WWTPs is the subject of increasing research. Thus, WWTPs to enhance environmental and public health are no longer an adequate basis for future investments/reengineering of existing infrastructures. High effluent quality for water reuse is an essential and primary function of resource recovery. Hence, future evaluation based on water reuse, other resource recovery potential, and energy use efficiency is imminent. This could entail prospective self-sustainability (economic sustainability), energy use efficiency, waste reduction, pollution control (ecological sustainability), and technical feasibility. Meanwhile, WWTP's economic affordability and improvement of the local environment are vital to socio-cultural acceptance. Although these may differ by region (Muga and Mihelcic, 2008), they can be realized through the appropriate selection of biotechnologies according to use purpose and value addition to the "community."

Two cardinal requirements for effective wastewater treatment are contaminant removal and biomass separation from the effluent. However, three dimensional sustainability of WWTPs that enhance profitability, environmental protection, and social relevance is critical to meeting future treatment demands and requirements. The key components include energy and resource recovery (Neczaj and Grosser, 2018; Zarei, 2020), environmental friendliness, ease of operation, capacity to withstand toxicity, low capital investment, and O&M costs (Ali et al., 2020) in addition to a minimized footprint (Nielsen, 2017). Besides, wastewater treatment systems are essential to the society, demanding more research on innovative strategies that adapt to climate change mitigation from anthropogenic GHGs emission.

Biological wastewater treatment systems have high resource recovery (Nielsen, 2017) potentials for energy, nutrients, biopolymers, and biofuels that can be optimized to reduce the overall operational cost while maximizing the transition of WWTPs to WRRFs (Kehrein, et al., 2020c) and increasing the prospects for more treated wastewater reuse. Resource recovery assessment design is required for the comprehensive outlook of WWTPs as WRRFs (Kehrein, et al., 2020c), particularly for emerging technologies. From the literature review, the flocculent CAS and AGS (bacterial AGS and algal-bacterial AGS) systems prospect varying opportunities for resource recovery. Meanwhile, AGS systems instead of flocculent CAS are expected to dominate the future urban wastewater treatment quality needs and concurrently provide resource recovery.

The structural differences, operational conditions, and environmental factors in flocculent CAS and AGS systems influence resource recovery potential, however this is not discussed in this research. This research adopted resource recovery from flocculent CAS process and AGS systems as an indicator toward CE implications for value recovery from wastewater treatment. To the best of the author's knowledge, no adoption of resource recovery evaluation of WWTPs is reported in the literature.

3.2 Materials and methods

This research adopted peer-reviewed articles mainly sourced from ScienceDirect. Relevant data on the differences among the three biotechnologies were collected, analyzed and discussed. Furthermore, the effluent quality of the bacterial and algal-bacterial AGS systems were compared to international discharge and reuse standards to examine the prospects, and benefits in the context of circular economy. Furthermore, other resources (high value-added products) recovery was compared due to their potential value contribution to the economy.

3.3 Results and discussion

3.3.1 Characteristic differences among flocculent CAS, bacterial AGS, and algal-bacterial AGS

Distinctive differences among the flocculent CAS and AGS systems influence their prospective wastewater treatment quality for water reuse, and resource recovery, most distinctively their biomass characteristics, growth/concentration, retention, and nutrient bioavailability. Whereas the former adopts flocculent sludge, the latter incorporates compact granular biomass. Granular sludge systems are mostly spherical, with distinctively clear structural boundaries. Aerobic granules' compact and solid mass accounts for their fast-settling, excellent biomass retention, and quick effluent-biomass separation compared to the flocculent CAS (Sarma et al., 2017).

Characteristically, CAS flocs are irregularly shaped with diameters typically ranging 50 - 100 μm (Nielsen et al., 2012). However, aerobic granules have distinctively large, and layered structures that enable simultaneous nutrient removal from different oxygen gradient zones. Thus, AGS systems' single reactor unit obsolete multiple treatment components/units for effective wastewater treatment as observed in the flocculent CAS.

Bacterial AGS and algal-bacterial AGS systems exhibit similar characteristics. However, the latter is increasingly gaining attention as a more promising and competitive alternative to the flocculent CAS (Guo et al., 2021; Ji, 2021; Ji and Liu, 2021). Enhancing more efficient stringent effluent discharge quality, resources recovery, and prospecting a climate-smart solution to mitigate anthropogenic GHGs emission. Table 3-1 shows a general comparison among the flocculent CAS, bacterial AGS, and algal-bacterial AGS systems.

3.3.2 Effluent treatment quality and potential use

Multiple use of treated wastewater is enhanced by effluent quality and can significantly contribute to increased reclaimed water use in water-stressed regions or for varied non-potable services. Agricultural reclaimed water usage in the water-scarce areas is critical to conserve/maximize freshwater abstraction for portable use. According to Liao et al. (2021), between 2015 and 2019, 398 million people were affected by drought in Asia. Meanwhile, nutrient recycling from WWTPs as fertilizer positively impacts the environment by reducing the demand and production of conventional fossil-based fertilizers, consequently reducing water and energy consumption (Mo and Zhang, 2013; Neczaj and Grosser, 2018).

AGS systems' excellent treatment performance in full and laboratory scales are promising to realize safe effluent discharge without tertiary treatment, potentially reducing cost and chemical use. Meanwhile, this also provides an avenue for agricultural irrigation use. Bacterial and algal-bacterial AGS demonstrate excellent nutrients removal that meets international discharge and effluent reuse standards (Barrios-Hernández et al., 2020; Guo et al., 2021; Ji et al., 2020). Tables 3-2 and 3-3 respectively summarize the effluent quality from full and pilot-scale bacterial AGS and lab-scale algal-bacterial AGS systems under the specific operation conditions, and the WWTP effluent discharge and reuse standards in different countries are listed in Table 3-4. Both bacterial AGS and algal-bacterial AGS systems produce high effluent quality from different types of wastewater streams and operation conditions, meeting various international discharge standards, the most stringent limits, and irrigation use (Table 3-4).

Bacterial AGS exhibit high effluent quality under lower and high temperature conditions. Thus, they can be widely applied in different regions. Meanwhile, algal-bacterial AGS systems exhibit slightly higher effluent quality than bacterial AGS alternatives and can be developed under natural sunlight conditions. Their efficiency under artificial and natural light conditions (Huang et al., 2015) expands prospects for future adoption in practice. Moreover, although sequencing batch reactor (SBR) units dominate AGS biotechnology wastewater treatment systems, the comparably good effluent quality from continuous flow reactors (CFRs) (Ahmad et al., 2017) is promising for the future investigation of algal-bacterial AGS in practice.

Besides ethical considerations, the standards for effluent discharge and reclaimed water use differ by region and local conditions. As shown in Table 3-4, secondary biological treatment is common for meeting acceptable discharge standards and non-direct consumable agriculture use in most developed economies. AGS systems with lower effluent nutrient and organics concentrations are excellent for more reclaimed water use at a lower cost. Considering high treatment cost influences reuse (Liao et al., 2021), effluent quality standards are mostly unattainable by conventional treatment processes. Meanwhile, the reclaimed waters' economic value is an entry point for resource recovery advancement, particularly in water-stressed regions.

3.3.3 Resource recovery from biomass and potential applications

Resource recovery from AGS biotechnology is promising for its future adoption and global dominance. Meanwhile, bacterial AGS is observed to have an increasing focus on ALE, PHA, tryptophan, and P recovery (Amorim de Carvalho et al., 2021). AGS-based wastewater treatment and high-value resource production can maximize waste for bioplastic development, and reduce overall operational cost. Chen et al. (2021, 2022) recently reported that algal-bacterial AGS biomass has a higher potential for simultaneous P and ALE recovery than bacterial AGS. Meanwhile, ALE has a commercial value of US$ 80–140/kg (Ferreira dos Santos et al., 2022), and could generate € 1000–2000/tonne if processing cost being excluded (Tavares Ferreira et al., 2021). Moreover, Meng et al. (2019b) reported ALE yield enhancement under moderately saline conditions for bacterial AGS. This is promising for industrial wastewater treatment and can be researched in the more saline adaptable algal-bacterial AGS (Dong et al., 2021; Semaha et al., 2020). Furthermore, the high P bioavailability in AGS (Zhao et al., 2019) is promising for phosphate biofertilizer production.

Meng et al. (2019a, 2019c) reported that algal-bacterial AGS has high lipids content and productivity for biodiesel production. Additionally, algal-bacterial AGS can accumulate higher crude protein (313.28 ± 26.67 mg/g-VSS) for animal feed production compared to suspended microalgae cells (174.10 ± 11.47 mg/g-VSS) (Wang et al., 2022). Although considerable financial investment is required to address bottlenecks and realize algal-bacterial AGS in future full-scale applications (Zhang et al., 2022a), its prospects are worthwhile. Besides, a circular economy transition will require a change of mindsets and the commitment of governments and the private sector to attain (Guerra-Rodríguez et al., 2020). This could potentially increase the economic benefits of modern wastewater treatment from varied value-chain opportunities into the end of the millennia from AGS biotechnology. Tables 3-5 and 3-6 summarizes the results of resource recovery from AGS in recent publications.

Microalgae cultivation for commercial-scale biofuel production has long been a research hotspot. Considering algal-bacterial AGS shows the higher potential for lipid production in both saline and non-saline wastewater than bacterial AGS (Table 3-5), algal-bacterial AGS can potentially become the standard for saline wastewater treatment for high lipid yield and biofuel production in practice. Moreover, the multiple industrial applications of ALE stimulate the growing interest in its extraction from AGS systems, compared to PHAs which have similar value but a relatively higher recovery cost. Thus, higher ALE recovery from algal-bacterial

AGS than bacterial AGS (Chen et al., 2022a; 2022b) implies more value can be recovered from the former.

3.4 Summary

In this chapter, the different factors form the flocculent CAS, bacterial AGS and algal-bacterial AGS systems were compared. Comparably, bacterial AGS systems outperform and exhibit significant advantages over the flocculent CAS in operation and their contribution to environment. However, algal-bacterial AGS systems show much benefit and positive contributions, and potentials to realize a carbon neutral or positive environment. Moreover, although the high value-added product recovery from algal-bacterial AGS is yet to be investigated on a full-scale level, it shows higher prospects for ALE recovery when compared to both bacterial AGS and flocculent CAS. Meanwhile, it presents a viable recovery route for future biofuel production from lipid recovery due to its high yield, which is also seen under salinity stress. Thus, algal-bacterial AGS's comparable advantage for lipids production can potentially become enormous value over low yield alternative wastewater treatment biotechnologies and high-cost conventional microalgae production systems.

Table 3-1 Comparison among flocculent CAS, bacterial AGS, and algal-bacterial AGS

No.	Parameter	Flocculent CAS	Bacterial AGS	Algal-bacterial AGS
1.	Size	50 – 100 µm [a]	>0.2 – 5 mm [b]	2.0 – 10 mm [c,d]
2.	Shape	Irregular and small [a]	Large, clearly, and well-defined boundaries, compact, and spherically shaped [b,e]	Larger, clearly, and well-defined boundaries, with sphere-shape [c,d,]
3.	Structural layers	Aerobic and anoxic [f]	Distinct aerobic, anaerobic, and anoxic layers [e,g]	Distinct aerobic, anaerobic, and anoxic layers
4.	Stability/Integrity coefficient	Low	High [d]	Higher than bacterial AGS [d]
5.	Settling velocity	Approximately 10 m h^{-1} [b]	50.4 m h^{-1} [h]	Fast-settling than bacterial AGS from denser mass and compact structure
6.	Biomass concentration	High biomass production but low retention	Lower biomass production but high retention than CAS [I]	Higher biomass production and retention than bacterial AGS [c,d,j,k]
7.	EPS production/concentration	Relatively low	High than flocculent CAS [b]	Higher than bacterial AGS [d,j,k]
8.	Nutrient bioavailability	Low	High [d]	Higher than bacterial AGS [d]
9.	Lipids recovery	Low	Low [l]	High [m,n]
10.	Salinity tolerance	Low	Higher than flocculent CAS [l]	Higher than bacterial AGS [m,n,c,o]
11.	Biosorption potential	Low	Higher than flocculent CAS	High and potential application for metal recovery from wastewater [p]
12.	Aeration energy requirement (kWh/m^3)	0.225 [q]	0.17 to 0.25	Comparably lower. Zero aeration energy requirement [t]
13.	Energy recovery from anaerobic digestion (kWh)	0.244 [q]	1.8 times lower biogas production potential than CAS [u]	0.405 [q]
14.	Greenhouse gas mitigation potential	Low	Higher than CAS, moderate compared to algal-bacterial AGS	High [d,j,v]
15.	Land footprint	Large	Reduce 50%–75% compared to flocculent CAS [w]	Comparably smaller than CAS

[a] Nielsen et al. (2012); [b] Nancharaiah and Reddy. (2018); [c] Semaha et al. (2020); [d] Zhao et al. (2018), [e] Bengtsson et al. (2018); [f] Gogina and Gulshin. (2016); [g] HaskoningDHV. (2022); [h] Lee et al. (2010); [I] Val Del Río et al. (2014); [j] (Chen, et al. (2022); [k] Wang et al. (2022), [l] Meng et al. (2019), [m] (Zhang et al. (2020a); [n] Meng et al. (2019); [o] Dong et al. (2021); [p] Yang et al. (2020); [q] Zhang et al. (2021); [r] (Pronk et al., 2015); [s] Rollemberg et al. (2020); [t] Zhao et al. (2019); [u] (Bernat et al., 2017); [v] Wang et al. (2020); [w] Bengtsson et al. (2019)

Table 3-2 Effluent quality from full- and pilot-scale AGS systems

WWTP (country)	Wastewater composition	Volumetric flowrate ($m^3\ d^{-1}$)	Operation conditions	Influent loading rate ($kg\ m^{-3}\ d^{-1}$)/ conc. (mg/L)	Effluent quality (mg/L[d])/ (Removal %[c])	Reference
Yancang WWTP (China)	Municipal wastewater (30% domestic and 70% industrial)	50,000	Filling: 40 min; Aeration: 240 min; Settling: 40 min Discharging: 30 min; (Settling/discharge: 70-80 min) Idling: 0 min Operation duration: 155 days	COD: 0.56 NH_4^+-N: 0.022	COD: 85[c] NH_4^+-N: 95.8[c] TN: 59.6[c]	Li et al. (2014)
Garmerwolde WWTP (The Netherlands)	Municipal wastewater	28,600	Sludge loading: 0.10 kg $TSS^{-1}\ d^{-1}$ HRT: 17 h SRT: 20–38 days Max. recycle ratio: 0.3 DO: 1.8- 2.5 mg/L Temp.: 20 °C SRT: 20 days HRT: 0.7 days	COD: 0.506 BOD: 0.224 TP: 0.0067 NH_4^+-N: 0.039 PO_4^{3-}-P: 0.0044 TN: 0.0494 SS: 0.236	COD: 64[d] BOD: 9.7[d] TP: 0.9[d] PO_4^{3-}-P: 0.4[d] TN: 6.9[d] SS: 20[d]	Pronk et al. (2015)
Garmerwolde (The Netherlands)	Municipal wastewater	28,600	60 min: Anaerobic feeding/simultaneous effluent withdrawal 240 min: aeration 60 min: Settling 15: Excess sludge discharge	COD: 0.528 BOD_5: 0.232 TP: 0.0072 TN: 0.053 SS: 0.247	COD: 57[d] BOD: 9.3[d] TP: 0.7[d] TN: 7.4[d] SS: 8.9[d]	Guo et al. (2020)
Garmerwolde (The Netherlands)	Municipal wastewater	20,355	SRT: >30 days HRT: 10–12 h Temp: 8 – 8.6 °C	NA	Meets EU Water Directive (91/271/EEC) standards	Barrios-Hernández et al. (2020)
Österröd WWTP (Sweden)	Municipal wastewater	1800[a] 7980[b]	5.2 h cycle VER: 50% SRT: >30 days HRT: 11.4 ± 0.7 h (average of 2 SBRs) Temp.: 13 °C	COD: 0.230 BOD_7: 0.081 NH_4^+-N: 0.019 TP: 0.0021 PO_4^{3-}-P: 0.0074 TN: 0.0177 SS: 0.102	COD:42[d] — 44[d] BOD_7: 6[d] NH_4^+-N: 0.75[d] TP: 0.06[d] PO_4^{3-}-P: 0.03[d] TN: 5.3 - 5.4[d] SS: 11- 12[d]	Burzio et al. (2022)
Frielas WWTP (Portugal)	Municipal wastewater (domestic, storm, and industrial)	55,000 - 60,000	NA	COD: 0. 310 - 0.5625 BOD: 0.1367 - 0.2825 SS: 0.1667 - 0.290	COD: 31 - 64[d] BOD: 6 - 10[d] SS: 6 - 21[d]	Oliveira et al. (2020)

Table 3-2

WWTP (Country)	Wastewater composition	Volumetric flowrate (m^3 d^{-1})	Operation conditions	Influent loading rate (kg m^{-3} d^{-1})/ conc. (mg/L[e])	Effluent quality (mg/L[d])/ (Removal %[c])	Reference
Vroomshoop (The Netherlands)	Municipal wastewater	1541	SRT: >21 HRT: 11–24 Temp.: 8.5 - 17.8 °C	NA	Meets EU Water Directive (91/271/EEC) standards	Barrios-Hernández et al. (2020)
Adelaide (South Australia) Pilot-scale	Saline Municipal wastewater	63.9 L	100% anaerobic condition 60 min: Anaerobic feeding 120 min: Aeration 8 min: Settling 2 min: Decanting Operation duration: 113 days	COD: 1.15 COD: 534.9 [e] NH_4^+-N: 35.1 [e] TN: 55.8 Sulphate: 668.6 [e] TSS: 535 Salinity: 6-7 g/L	NH_4^+-N: 77.8 – 99.7[c] TN: 16.0 – 97.5[c] PO_4^{3-}-P: 5.4 – 49.7[c]	Thwaites et al. (2018)
Adelaide (South Australia) Pilot-scale	Saline Municipal wastewater	63.9 L	33% anaerobic condition 20 min: Anaerobic feeding 40 min: Aerobic feeding 80 min: Aeration 15 min: Settling 10 min: Decanting Operation duration: 95 days	COD: 0.76	PO_4^{3-}-P: 4.3–17.3[c] NH_4^+-N: 96.1–99.8[c] TN: 27.5–94.2[c]	Thwaites et al. (2018)
Adelaide (South Australia) Pilot-scale	Saline Municipal wastewater	63.9 L	100% aerobic 54 min: Aerobic feeding 108 min: Aeration 54 min: Settling 54 min: Decant Operation duration: u	COD: 0.80	NH_4^+-N: 70.8–99.6[c] TN: 75.7–92.9[c] PO_4^{3-}-P: n.d	Thwaites et al. (2018)
Lubawa WWTP (Poland)	Low strength (30–40% from dairy industry) wastewater	3200	216 min: Aeration 20 min: Settling 40 min: Feeding/Discharge DO: 2 mg/L VER: about 25%. Superficial gas velocity: 0.18 cm/s SRT: about 30 days HRT: 1 day, Minimum settling velocity: about 1.6 m/h.	COD: 1319.5 [e] BOD_5: 1120 TP: 19.5 [e] TN: 90.5 [e] NH_4^+-N: 64.3 [e]	COD: 39.1[d] BOD_5: 20.0[d] TP: 0.9[d] TN: 11.8[d] NH_4^+-N: 0.4[d]	Świątczak and Cydzik-Kwiatkowska. (2018)

Table 3-2 (cont.)

WWTP (Country)	Wastewater composition	Volumetric flowrate (m^3 d^{-1})	Operation conditions	Influent loading rate (kg m^{-3} d^{-1})/ conc. (mg/L[e])	Effluent quality (mg/L[d])/ (Removal %[c])	Reference
Dinxperlo WWTP (Aalten, the Netherlands)	Domestic wastewater	3,100	n.d.	COD: 531 [e] BOD: 202 [e] NH_4^+-N: 54 [e] P: 6.4 [e]	COD: 28[d] BOD: 2[d] NH_4^+-N: 6[d] P: 1.1[d]	van Dijk et al. (2021)
Pilot scale test (Hangzhou, China)	Medium strength wastewater	Total working volume of 3 m^3 1 m^3 (A)	70: Feeding 120 min: Stirring 480 min: Aeration 5 min: Settling 5 min: Discharge 10 min: Idling VER: 33% Air flow rate: 3.6 m^3/h Temp: 25 ± 5 °C	COD: 447.9 [e] TN: 111.9 [e] NH_4^+-N: 95.5 [e] TP: 9.3 [e] 10 kg filling with iron shavings (filling rate: 3.3 g/L)	COD: 34.0[d] TP: 0.12[d] NH_4^+-N: 8.4[d] TN: 30.1[d] TFe: 0.30[d]	Pan et al. (2022)
Pilot scale test (Hangzhou, China)	Medium strength wastewater	1.5 m^3/cycle (B)	110 min: Stirring 400 min: Aeration: 40: Settling 40: Discharge 5 min: Idling 45 min: Feeding VER: 50% Air flow rate: 3.6 m^3/h Temp: 25 ± 5 °C	COD: 447.9 [e] TN: 111.9 [e] NH_4^+-N: 95.5 [e] TP: 9.3 [e] 10 kg filling with iron shavings (filling rate: 3.3 g/L)	COD: 21.5[d] TP: 0.07[d] NH_4^+-N: 3.7[d] TN: 19.1[d] TFe: 0.23[d]	Pan et al. (2022)

BOD, biochemical oxygen demand; COD, chemical oxygen demand; HRT, hydraulic retention time; NA, not available; SRT, solids retention time; SS, suspended solids; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids; VER, volumetric exchange ratio; [a]dry weather; [b]rainy weather, [c]removal rate (%), [d]effluent nutrient concentration (mg/L), n.d.; no data, TFe; total iron, u; undisclosed, [e]concentration.

Table 3-3 Effluent quality from lab-scale algal-bacterial AGS systems

Reactor volume and type	Operation conditions	Influent concentration (mg/L)	Effluent quality (mg/L[a]) and removal efficiency (%[b])	Reference
1.4 L Sequencing Batch reactor (SBR)	Temp.: 25 ± 2 °C Cycle: 4 h Influent filling: 2 min Non-aeration: 28 min Aeration: 185–200 min Settling: 5–20 min Effluent discharge: 5 min VER: 50% HRT: 8 h Airflow rate: 2.0 cm/s DO: 7 – 9 mg/L Natural light Operation duration: 100 days	COD: 600 PO_4^{3-}-P: 10 NH_4^+-N: 100 Ca^{2+}: 10 Mg^{2+}:5 mg Fe^{2+}: 5 mg	COD: (< 30[a]) 95.2[b] TP: (<1[a]) 44[b] TN: 43.1[b]	Huang et al. (2015)
1 L CFR	Temp.: 25 ± 2 °C Seed sludge: Mature bacterial & algal-bacterial AGS (1:1 w/w) Alternative aeration (60 min) and no-aeration (30 min) regime HRT: 6 h Airflow rate: 0.5 cm/s Av. DO: 7–8 mg/L (aeration); 2–5 mg/L (no aeration) Operation duration: 120 days Illumination: ~ 900 –1100 lux (room light; no light control)	COD: 300 – 600 PO_4^{3-}-P: 10 -20 NH_4^+-N: 100 – 200 COD/N/P = 30:10:1	COD: 43 – 50 [a] DOC: 96 – 95[b] NH_4^+-N: >99[b] TN: 29 – 80[b] TP: 44 – 50[b]	Ahmad et al. (2019)
0.25 L Shaking glass flasks	Temp.: 25 ± 2 °C Cycle: 12-h Filling: 1 min Shaking: 715 min Settling: 2 min Effluent discharge: 2 min Shaking: 150 rpm VER: 50% HRT: 24 h SRT: ~30 days Operation duration: 25 days Seed sludge: Mature algal-bacterial AGS Light on/ off period: 12h/12h Light intensity: 88–122 μmol m^{-2} s^{-1}	COD: 400 PO_4^{3-}-P: 10 NH_4^+-N: 50	DOC: (<14[a]) 94.4 – 94.8[b] TP: 55[b] TN: 71[b] NH_4^+-N: >99[b]	Zhao et al. (2019)

Table 3-3 (cont.)

Reactor volume and type	Operation conditions	Influent concentration (mg/L)	Effluent quality (mg/L[a]) and removal efficiency (%[b])	Reference
SBRs	Temp.: 23 ± 2 °C Cycle: 4 h Feeding: 2 min No aeration: 28 min of Aeration: 200 min Settling: 5 min Decanting: 3 min Idling: 2 min VER: 50% HRT: 8 SRT: 40 – 50 days Airflow rate: 3 L/min DO: 7 mg/L Light on/off: 12h/12h Light intensity: 180 μmol m^{-2} s^{-1} Seed sludge: Sewage sludge	COD: 600 PO_4^{3-}-P: 10 NH_4^+-N: 50	TOC: 97.5[b] PO_4^{3-}-P: 57 – 63[b] NH_4^+-N: > 99[b] TIN: 69.8–71.3[b]	Meng et al. (2019b)
0.92 L SBR	Temp.: 20 ± 2 °C Cycle: 4 h Feeding: 2 min No aeration: 60 min Aeration: 172 min Settling: 3 min Decanting: 2 min Idling: 1 min pH: 7.4 VER: 50% HRT: 8 h SRT: 23 days Airflow rate: 0.8 L/min Light on/off: 12h/12h Light intensity: 835 $\mu molm^{-2}s^{-1a}$ Seed sludge: Mature AB-AGS	COD: 500 PO_4^{3-}-P: 10 NH_4^+-N: 50	COD: > 98[b] PO_4^{3-}P: 71[b] NH_4^+-N: > 99[b] TN: 78[b]	Wang et al. (2021)
2 L SBRs	Temp.: 23 ± 2 °C Cycle: 4 h Feeding: 2 min No aeration: 28min Aeration: 190 – 200 min Settling: 5 – 15 min Discharge: 5 min VER: 50% HRT: 8 Airflow rate: 3 L/min DO: 7- 9 mg/L Operation duration: 120 days Light on/off: 12h/12h Light intensity: 45 – 225 μmol m^{-2} s^{-1} Seed sludge: Mature algal-bacterial AGS	COD: 600 PO_4^{3-}-P: 10 NH_4^+-N: 50	COD: 95[b] PO_4^{3-}-P: 31 – 42[b] NH_4^+-N: > 99[b] TN: 61 – 80[b]	Meng et al. (2019c)

Table 3-3 (cont.)

Reactor volume and type	Operation conditions	Influent concentration (mg/L)	Effluent quality (mg/L[a]) and removal efficiency (%[b])	Reference
0.84 L Sealed glass reactor	October – November weather in Wuhan city, China (Open terrace) Temp.: 13 – 19 °C Operation duration: 30 days Light on/off: 12-h day cycles Light intensity: 60–400 μmol m^{-2} s^{-1} CO_2: 52mL (99.9% purity) /148mL air Seed sludge: Mature bacterial AGS	COD: Glucose: 250 Peptone: 80 Urea: 15 Meat extract: 55 PO_4^{3-}-P: 3.7 NH_4^+-N: 19.2	COD: 78.3[b] TP: 95[b] PO_4^{3-}-P: 31 – 42[b] NH_4^+-N: 85.4[b] TN: 84.5[b]	Sun et al. (2022)
4 L Photo SBR	4-h cycle: Feeding: 30 min No aeration: 90 min Aeration: 190 – 204 min Settling: 15 – 1 min Discharge: 5 min VER: 50% HRT: 8 h SRT: 10 Airflow rate: 2 L/min DO: 3 – 4 mg/L Light on/off: 12h/12h Light intensity: 3000 μmol m^{-2} s^{-1} Operation duration: 100 days Static magnetic field: 5 mT Seed sludge: Sewage sludge	COD: 400 PO_4^{3-}-P: 12 NH_4^+-N: 70	COD: 91[b] TP: 95[b] PO_4^{3-}-P: 71.5 – 83.3[b] NH_4^+-N: 96.6[b] TN: 49.3[b]	Zhang et al. (2022b)
0.06 L SBR	8 cycles (3 of 8 h and 5 of 6 h, respectively). Light intensity: 200 μmol m^{-2} s^{-1} Seed sludge: Mature bacterial AGS	COD: 552.8 PO_4^{3-}-P: 13.2 NH_4^+-N: 99.4	COD: 92.69[b] TP: 87.16 [b] PO_4^{3-}-P: 71.5 – 83.3 [b] NH_4^+-N: 96.84 [b] TN: 84.10 [b]	Ji et al. (2020)
6.0 L SBR	Temp.: 22 – 28°C Cycle: 8 h Feeding: 3 min Anaerobic phase: 120 min Oxidation phase: 210 min Anoxic phase: 114–142 Precipitation: 2–30 min Settling: 2 min Discharge phase: 3 min DO: 4–5 mg/L Operation duration: 60 days VER: 50% SRT: 30 days Light intensity: 4000 lux Seed sludge: Mature bacterial AGS	COD: 320 PO_4^{3-}-P: 9 NH_4^+-N: 35	COD: 13.0 [a] TP: (0.93[a]) 97[b] PO_4^{3-}-P: 71.5 – 83.3[b] NH_4^+-N: 15.9[b] TN: 0.38[b]	Guo et al. (2021)

Table 3-3 (cont.)

Reactor volume and type	Operation conditions	Influent concentration (mg/L)	Effluent quality (mg/L[a]) and removal efficiency (%[b])	Reference
0.5 L SBR	6-h cycle Feeding: 3 min No aeration: 90 min Aeration: 262 min Settling: 2 min of settling Discharge: 3 min VER: 50% pH: 7.5 Artificial (LED) light intensity: 5500 lux Uplift air flow velocity: 0.86-0.87 cm/s Seed sludge: Matura algal-bacterial AGS Operation duration: 25 days	DOC: 150 NH_4^+-N: 50 PO_4^{3-}-P: 10	DOC: 90[b] NH_4^+-N > 99[b] TN: 75[b] NO_2^-N: 0.18[b] TP: 64[b]	Zhang et al. (2020b)
0.5 L SBR	4-h cycle Feeding: 6 min No aeration: 60 min Aeration: 161 min 2 min of Settling: 2 min Discharge: 11 min VER: 50% SRT: 30 days aeration of 0.87 cm/s and Illumination: 3600 lux	COD: 300 NH_4^+-N: 30 PO_4^{3-}-P: 5 Ca^{2+}: 10 Mg^{2+}: 5 Fe^{2+}: 5	DOC: 96.6[b] NH_4^+-N: 99.9[b] TN: 65[b] TP: 70 [b]	Dong et al. (2021)
0.5 L SBR	4-h cycle Feeding: 6 min No aeration: 60 min Aeration: 161 min 2 min of Settling: 2 min Discharge: 11 min VER: 50% SRT: 30 days aeration of 0.87 cm/s and Illumination: 3600 lux Light duration: 12 h/day Temp: 25 °C	COD: 300 NH_4^+-N: 30 PO_4^{3-}-P: 5 Ca^{2+}: 10 Mg^{2+}: 5 Fe^{2+}: 5 Salinity: 1-3 g/L	DOC: 92 – 94[b] NH_4^+-N: 99.9[b] TN: 63 – 16 [b] TP: 33 – 38[b]	Dong et al. (2021)
0.05 L	Artificial (LED) light intensity: 200 μ mol/m^2/s Light: 12 h light/12 h dark VER: 70% Temp.: 25 °C via water bath No aeration/stirring Seed sludge: Bacterial aerobic granular sludge	COD: 281 NH_4^+-N: 11 PO_4^{3-}-P: 3 Ca^{2+}: 20 Mg^{2+}: 50 Fe^{2+}: 40	COD: > 80[b] NH_4^+-N: 99[b] PO_4^{3-}-P: 92.3[b]	Hu et al. (2022)

Table 3-3 (cont.)

Reactor volume and type	Operation conditions	Influent concentration (mg/L)	Effluent quality (mg/L[a]) and removal efficiency (%[b])	
0.04 L SBR	8-h cycle Temp: 30 °C Biomass concentration: maintained at 5.7 ± 0.1 VSSg/L Illuminance: Artificial (LED) Light: intensity of about 200 μ mol/m^2/s. Operation duration: 36 continuous cycles No mixing/aeration, Seed sludge: Bacterial aerobic granules	COD: 280.91 NH_4^+-N: 11.44 NO_2^-N: 9.86 NO_3^-N: 16.61 PO_4^{3-}-P: 2.83 Ca^{2+}: 20 Mg^{2+}: 50	COD: 64.8[b] NH_4^+-N: 84.9[b] NO_2^-N: 70.8[b] NO_3^-N: 50[b] PO_4^{3-}-P: 84.2[b]	Fan et al. (2021a)
0.05 L	Reactors operated in a batch mode HRT: 8 h Artificial (LED) light intensities: 70, 140, 210 μ mol/m^2/s No mixing or aeration VSS/SS: 0.86 pH: 7.0. Temp.: about 26 °C	COD: 400 NH_4^+-N:50 PO_4^{3-}-P: 5 Ca^{2+}: 20 Mg^{2+}:50 Fe^{2+}: 40	COD: 52.1- 70.5[b] NH_4^+-N: 64.0-80.7[b] PO_4^{3-}-P: 73.9[b]	Fan et al. (2021b)

BOD, biochemical oxygen demand; COD, chemical oxygen demand; DO, dissolved oxygen; DOC, dissolved organic carbon; HRT, hydraulic retention time; TN, total nitrogen; TP, total phosphorus; SS, suspended solids; SRT, solids retention time; VER, volumetric exchange ration; mT, Millitesla; [a] effluent concentration (mg/L); [b] nutrient removal (%), u; undisclosed. DOC/TOC values were retained to ensure correlation with previous findings.

Table 3-4 WWTP effluent discharge and reuse standards in different countries/regions

Parameters	COD (mg/L)	BOD (mg/L)	NH_4^+-N (mg/L)	TN (mg/L)	TP (mg/L)	pH	TSS (mg/L)	Reference
The EU (Agricultural irrigation)	125	≤10	NA	10	1	NA	35	EPC(2020)
The UK	125	25	NA	10	1	NA	35	Oleszkiewicz et al. (2015)
The Netherlands	125	20	NA	7	1	NA	30	Pronk et al. (2015)
The United States (urban/irrigation use)	25 – 30	≤10 - ≤ 30	NA	NA	NA	6 – 9	≤ 30	USEPA (2012); Sauder (2018)
China (Class I-A)	50	10	5(8)*	15	0.5	6 – 9	10	GB18918-2002[a]
China (Class II)	100	30	25(30)*	NA	3	6 – 9	20	GB18918-2002[a]
Northern Territory and Victoria (Australia)	NA	≤ 10 - ≤ 20	NA	NA	NA	NA	≤ 10 - ≤ 30	NTG (2020)
State of Victoria (Australia) (Class A)		< 10	NA	NA	NA	6 – 9	< 5	SVEPA (2021)
State of Victoria (Australia) (Class B)		< 20	NA	NA	NA	6 – 9	< 30	SVEPA (2021)
Canada (Manitoba)	25	25	1.25	15	1	NA	25	Oleszkiewicz et al. (2015); CWN (2018)
India NGT 2019	50	10	NA	10	1	5.5 – 9	20	Schellenberg et al. (2020)
Egypt (Agricultural irrigation) Indirect reuse (Law 93/1962, 48/1982, and Decree 44/2000, 92/2013)	50 – 80	30 – 60	NA	5 – 15	1 – 3	6 – 9	30 – 50	Elbana et al. (2019)

COD, chemical oxygen demand; BOD, biochemical oxygen demand; USEPA, United States Environmental Protection Agency; EU, European Union; NA, not available; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids; UK, United Kingdom; EPA, Environment Protection Authority. *Data outside the brackets are concentrations at water temperature > 12°C; those inside the brackets are concentrations at water temperature ≤ 12°C. [a]https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/shjbh/swrwpfbz/200307/W020061027518964575034.pdf.

Table 3-5 Lipid recovery from bacterial AGS and algal-bacterial AGS systems

Wastewater type, reactor, and size	Wastewater composition	Operational condition	Lipids resource recovery (mg/g-SS)		Reference
			Bacterial AGS	Algal-bacterial AGS	
Synthetic wastewater, SBR (2.0 L)	COD: 300 NH_4^+-N: 50 to 200 PO_4^{3-}-P: 10 Fe^{2+}: 5 Ca^{2+}: 10	3-h cycle Feeding: 2 min Non-aeration: 20 min Aeration: 152 min Settling: 4 min Discharge: 2 min VER: 50% HRT: 6 h SRT: not controlled DO: 7–9 mg/L Light illuminance: 190 μmol/m^2/s Duration: Dark/light (12 h/12 h) Temp.: 20–23 °C superficial air velocity: 1.8 cm/s (3 L/min) Operation duration: 60 days	34.6	57.4	Zhang et al. (2020)
Synthetic wastewater SBR (2L)	COD: 309.4 ± 18.7 NH_4^+–N: 106.8 ± 11.2/213.6 ± 17.2 PO_4^{3-}–P: 9.7 ± 1.4	4-h cycle Feeding: 2 min Aeration: 232 min Settling: 4 min Discharge: 2 min of decanting. VER: 50.0% HRT: 8 h. SRT: Not controlled for both reactors. DO: 7.0–9.0 mg/L pH: 7.0–8.2 Superficial air velocity: 1.2 cm/s (2.0 L/min) Temp.: 18–23 °C Natural sunlight (intensity): was 1531 μmol m^{-2} s^{-1} Duration: 7h light/17h dark Operation duration: 100 days	33.4	68.7	(Huang et al., 2020)
Synthetic wastewater, SBR (2 L)	COD: 600 (50%glucose/50%acetate) NH_4^+-N: 50 PO_4^--P: 10 $NaHCO_3$: 300 Mg^{2+}: 25 Ca^{2+}: 30 Fe^{2+}: 20 NaCl (0 g/L, 10 g/L, 20 g /L, and 30 g/L)	4-h cycle Feeding: 2 min Non-aeration: 28 min Aeration: 200 min Settling: 5 min Discharge: 3 min Idling: 2 min of idling VER: 50% HRT: 8 h Temp. of 23 ± 2 °C Airflow rate: 3 L/min DO: > 7 mg/L Light intensity: 180μmol m^{-2}s^{-1} Duration: Light/dark 12 h/12 h SRT: 40–50 days Operation duration: 120 days		41.3, 48.0 - 50.7	(Meng, et al., 2019)

Table 3-5 (cont.)

Wastewater type, reactor, and size	Wastewater composition	Operational condition	Lipid resource recovery (mg/g-SS)		Reference
			Bacterial AGS	Algal-bacterial AGS	
Synthetic saline wastewater, CFR (20 L)	COD: 600 (50% glucose/ 50% sodium acetate) NH_4^+-N: 50 PO_4^{3-}-P: 10 NaCl: 10 g/L, 20 g L, 30 g/Land 40 g/L Gradual increase in salinity stress (0–50 d, 50–75 d, 75–100 d and 100–125 d) pH: 7 – 8.2 Operation duration: 125 days	Control reactor operated under no light illumination Illumination: 300 µmol m^{-2s-1} 12h/12h (Light/dark) Inflow rate: 35 mL/min by a peristaltic pump, HRT: 9.5 h. DO: 7–9 mg/L Air introduced from the bottom of the reactor (8 fine bubble diffusers) Total airflow rate: Controlled at 18 L/min, about4.5 L/min in the sludge return zone and 13.5 L/min in the aeration zone	39.5 mg/g-SS	45.9 - 80.0	Meng et al. (2020)
Synthetic wastewater, SBR (6-lab-scale identical reactors) 2 L	COD: 600 NH_4^+-N: 50 PO_4^{3-}-P: 10 Ca^{2+}: 10 Mg^{2+}: 5 Fe^{2+}: 5	4-h cycle Feeding: 2 min Non-aeration: 28 min Aeration: 190–200 min Settling: 5–15 min Discharge: 5 min VER: 50% HRT: 8 h SRT: Not controlled Superficial air velocity: 1.8 cm/s (3 L/min) DO: 7–9 mg/L Control operated without light illumination Illumination intensity: 45, 90, 135, 180 and 225 µmol m^{-2s-1} Duration: dark/light (12 h/12 h) Temp.: 23 ± 2 °C pH: 7.0–8.4 Operation duration: 120 days		31.2 - 59.6	Meng, et al. (2019)
Synthetic saline wastewater, SBR (1.2 L)	COD: 600 NH_4-N: 50 PO_4^{3-}-P: 10 $NaHCO_3$: 300 Mg^{2+}: 25 Ca^{2+}: 30 Fe_{2+}: 20 NaCl: 10, 30, 50 g/L)	No illumination for bacterial aerobic granular reactor. Illumination: 12h/12 (light/day) Intensity: 180 µmol $m^{-2}s^{-1}$ 4-h cycle Feeding: 2 min Non-aeration: 30 min Aeration: 200 min Settling: 3 min Discharge: 2 min Idling: 3 min DO: 7–9 mg/L. HRT: 8 h. Operation: 100 days	13.1	12.8 to 66.4	Cao et al. (2022)

Table 3-6 High value-added product recovery comparison among the three biotechnologies

Wastewater source	Scale and volume	Influent composition (mg/L)	Effluent quality (mg/L)[a]/ removal rate (%)[b]	Recoverable ALE/PHA/Trptophan (mg/g VSS)			Reference
				Flocculent CAS	Bacterial AGS	Algal-bacterial AGS	
Low strength wastewater	110 L SBR		NH_4^+-N: 11.48[a] TP: 4.8[a]		ALE: 236 ± 27		Schambeck et al. (2020)
Synthetic (acetate/propionate based) wastewater	Lab scale		NA		ALE: 261 ± 33		Schambeck et al. (2020b)
Municipal and 25% slaughterhouse wastewater)	Pilot-scale SBR Influent flow: 5 m^3/day	COD: 585 NH_4^+-N: 55 PO_4^{3-}-P: 6.3		72 ± 6	160 ± 4 (16% w/w VSS)		Lin et al. (2010; 2013)
Synthetic wastewater (acetate as the only carbon source two months) and brewery wastewater (added for more than four months)	Laboratory scale	N.R	N.R.	1.5-3.8%	2.2 – 6.5%		Sam and Dulekgurgen. (2015)
Synthetic (Propionate-based) wastewater	SBR (4.78 L)	COD: 1250 – 5000 Peptone: 400 Meat extract: 250 NH_4Cl: 200 KH_2PO_4: 660 $CaCl_2$: 40 $MgSO_4 \cdot 7H_2O$: 25 $FeSO_4 \cdot 5H_2O$: 20 $(NH_4)_2SO_4$: 1330 $NaHCO_3$: 13 OLR: 7.5, 9, 12 and 30 kg/m^3-d Alternating COD feed at OLR between 4.4/17.4 kg/m^3-h Constant COD at OLR of 15 kg/m^3-h	COD: 95[b]		69 – 72.5% 70.6 – 82.2% (10% w/w yield)		Yang et al. (2014)
Synthetic saline wastewater	Lab-scale SBR 2 L		TOC: 5 - 10[a] NH_4^+-N: 0[a] PO_4^{3-}-P: 0.1[a]		ALE: 26.8 – 49.8		Meng et al. (2019)

Table 3-6 (cont.)

Wastewater source	Scale and volume	Influent composition (mg/L)	Effluent quality (mg/L[a])/ removal rate (%[b])	Recoverable ALE/PHA/Trptophan (mg/g VSS)			Reference
				Flocculent CAS	Bacterial AGS	Algal-bacterial AGS	
Synthetic wastewater	5 SBRs 7.8 L		COD: 24 –80[a] NH_4^+-N: 1.4 – 6.3[a] PO_4^{3-}-P: 3.6 – 8.2		ALE: 180 – 418.7 Tryptophan: 0.9 – 4.1		Ferreira dos Santos et al. (2022)
Low strength municipal (raw and settled) wastewater	Lab-scale SBR 28 L		COD: 55 – 130[a] NH_4^+-N: 25 – 72[a] PO_4^{3-}-P: 0[a]		PHA: 10.8 and 9.3%		Karakas et al. (2020)
Synthetic wastewater	Lab-scale SBR 0.9 L		DOC: <8.97[a]		P: 0.29 kg/day	P: 0.56 kg/day ALE: 13.37 mg/g VSS	Chen et al. (2022)
Synthetic wastewater	Lab-scale SBRs 16 L		NA		TP: 33.43 ± 0.69 P: 25.10 ± 1.85	ALE: 8.81 TP: 27.54 ± 0.23 P bioavailability: 97%	Chen et al. (2021)

Chapter 4 Case study in Ghana: Wastewater management in WWTPs and CE evaluation

4.1 Introduction

Recent research estimates that almost 50% of global wastewater is treated (Edward Jones, 2021), compared to the often reported 20% (WWAP, 2017) in the literature. Although this means an increase in wastewater treatment rate, a disparity exists among high- and low-income countries. Generally, less than 40% of wastewater is treated in most low-income and developing countries. However, there has been a significant rise in global water withdrawal in the past seven decades due to population increase (FAO, 2021). Hence, the low treatment rate of wastewater treatment in developing countries has become apparent with rapid pollution of water resources (Constantine et al., 2014; Nkosi et al., 2021; Yeleliere et al., 2018).

Wastewater generation, collection, treatment, and available technologies can influence the prospects of wastewater resource recovery, which can be quantified. However, in developing countries, data on wastewater is lacking and poses challenges to quantifying the recovery of resources (treated water, nutrient, energy, and high-value-added products).

Chrispim et al. (2020) pointed out that integrating optimum resource recovery implementation in existing or new WWTPs is promising and critical for highly populated cities in developing countries because of the downward implications of water resource pollution. Considering prospects of direct surface water for potable domestic use. Meanwhile, over 90% of wastewater in some developing countries is discharged untreated (Sato et al., 2013).

The challenge to wastewater treatment in most developing countries is peculiarly comparable. It can be broadly contextualized as a rise in the human population and water use to the slow-paced development of wastewater treatment infrastructure. For example, the urban population in Africa without sanitation almost doubled from 88 million in 1990 to 175 million in 2008, further increasing to 200 million in 2012 (Mafuta et al., 2011; USAID, 2015). In contrast, improved sanitation facilities declined from 74 to 53% from 2000-2005 and 2010-2015, respectively (Armah et al., 2018). Thus, sanitation development has been relatively slow-paced, given the significant urban population growth from 14% to 43% in 1950 and 2018, respectively (UNDESAPD, 2018). However, the surging increase in urban populations further expands the infrastructure gap, estimated 11% access to a sewer connection in Sub-Saharan Africa (GIZ, 2019). Furthermore, the commonplace lack of advanced wastewater treatment alternatives, ineffective treatment performance, and general dysfunctionality is mainly attributed to poor maintenance practice and the lack of sustainable financing.

This chapter assesses WWTP's value from integration into a circular economy toward treated water, nutrients (struvite), and energy resource recovery in developing countries. The research is divided into four parts: (1) an overview of sanitation coverage and investment in Sub-Saharan Africa, (2) the state of wastewater treatment and infrastructure development, (3) an evaluation of urban wastewater treatment and sanitation investments in Ghana, and (4) analyzing the wastewater treatment resource recovery practices, and potential value in Ghana.

4.2 Materials and methods

This study adopted field surveys for the evaluation of urban WWTPs resource recovery, and effluent quality analysis in Ghana. Wastewater (influent and effluent) samples were collected from the Legon Waste Stabilization Pond (WSP) for effluent quality analysis. In addition, peer-reviewed research articles, government publications, and simulations of scenarios were used. This work is expected to serve as a basis for developing countries' exploration of circular economy applications in wastewater treatment. First, peer-reviewed research articles for resource recovery as circular economy indicators were conducted, mainly from ScienceDirect. The population equivalence was made with BOD load/person/day according to Bartram et al. (2019). Wastewater treatment coverage as a CE indicator was evaluated according to OECD (2019). This measures the population percentage within a given area connected to a WWTP through a sewer network, excluding on-site systems.

Treated wastewater resource and struvite resource recovery were evaluated according to the feasibility study estimates for WWTPs' operation proposed and value recovery by Molinos-Senante et al. (2010a, 2011a). Meanwhile, the untapped bioenergy (energy) resource recovery from wastewater treatment was evaluated based on Ghana's annual freshwater withdrawals in the past two decades (FAO-AQUASTAT, 2022). Biogas production, electricity generation, and COD derived from sludge were estimated according to Ijoma et al. (2022).

4.3 Results and discussion

4.3.1 An overview of sanitation coverage and investments in Sub-Saharan Africa

Significantly, low domestic government investments in developing countries account for the unsustainability of sanitation development projects/programs. Accordingly, most developing countries that lack an investment program show low gross domestic product (GDP) investment and donor support use from the survey of 57 countries (WHO, 2012). For example, the 2008 eThekwini commitment to sanitation required African countries to invest a minimum of 0.5% of GDP for MDGs. However, out of 30 surveyed countries, percentages of 0.1-0.5% and less than 0.1% of GDP were reported for 14 and 16 countries, respectively (Coombes et al., 2015). In comparison, a minimum of 1.2% of GDP is required for SDGs.

Urban sanitation coverage in Africa differs by region, low coverage is predominantly observed in Sub-Saharan Africa as compared to North Africa. Besides least developed countries (4% and 11%), Sub-Saharan Africa has the lowest among the twelve global region categories for sewered sanitation (7% and 16%) in national and urban coverage, respectively (WHO and UNICEF, 2021), as shown in Figs. 4-1 and 4-2. Meanwhile, a survey of sanitation coverage in the ten most urbanized African countries (Fig. 4-3) in 2018 shows Ghana has the lowest urban improved sanitation of 20%, with 27% and 31% recorded in Ethiopia, and Tanzania, respectively.

The disparity in sanitation development on the African continent shows the US$ 4 billion and US$ 35 billion per annum requirements for North and Sub-Saharan Africa, respectively, toward SDG 6 (ADBG, 2020). Almost US$ 18 billion and US$ 26.9 billion (nearly 50% and 39%, respectively, of global estimate) are required to meet basic sanitation access and safely managed sanitation targets for Sub-Saharan Africa towards SDG 6.2 by 2030 (Hutton and Varughese, 2020). Thus, sustainable sanitation financing in Sub-Saharan Africa is a critical need that requires strategies to motivate/accelerate successful wastewater treatment investment for sanitation development, SDGs, and CE transition.

4.3.2 The state of wastewater treatment and infrastructure development

As a fast-growing economy in Sub-Saharan Africa (MFG, 2019), Ghana is prided as the most stable democracy in Africa. The past four decades of economic development have also been accompanied by rapid urbanization and significant population growth (Fig. 4-4), an almost 3.5 times human population increase from 8.7 to 30 million in 1970 and 2019, respectively (UNDESAPD, 2021). Almost 60% of Ghana's 31 million population is in urban area (GSS, 2021), compared to 43.9 in 2000 (UNDESAPD, 2018). However, only 25.3% of the population has access to improved sanitation (GSS, 2021), with relatively low expansion in wastewater treatment infrastructure development since the 1970s.

WWTPs' optimum performance in developed countries is within 50 to 60 years and is influenced by process design, operation, and maintenance (Capodaglio et al., 2017). In contrast, a relatively shorter timeframe is predictable in developing countries from the lack of regular maintenance and operation. For example, most WWTPs in Ghana were built in the 1970s, and over 70% are dysfunctional (Murray and Drechsel, 2011). The more recent installations lack treatment capacity from the insufficient influent flow resulting from less than 15% national conventional sewerage network coverage. For example, Accra's Legon WSP operates at less than 50% of its treatment capacity, 8558 m^3/day. Only four out of thirty-five institutional WWTPs in Accra (Adank et al., 2011), and seven out of the national forty-four are operational

(Mbugua, 2017). Meanwhile, 72% and 43% of sludge are directly disposed of into the environment/sea in Accra and Kumasi (Mansour and Esseku, 2017). WHO/UNICEF-JMP (2015) estimate 15% and 20% for national and urban improved sanitation coverage in Ghana, which is defined as the population percentage using an improved sanitation facility such as flush/pour-flush to a piped sewer system, ventilated/pit latrines, or septic tanks.

Less than 10% of WWTPs in Ghana are fully functional, relatively small-scale, and operated in urban Ghana. 25% operate with at least one dysfunctionality, and at least 65% are completely non-functional or operational; over 25% of which are trickling filters (Murray and Drechsel, 2011). Thus, in the past decade, the Legon WSP and Mudor WWTP located in the capital Accra contribute the main capacities for wastewater treatment in Ghana. These, by extension, would account for the utmost potential evaluation of wastewater resource recovery and value creation from the existing WWTPs. Furthermore, opportunities have been created for prospective policy considerations and government/private business investments, to explore the broad economic possibilities of CE application in the context of developing countries (Wellesley, 2019). Theoretically, the direct monetary value of resource recovery in developing countries can incentivize local governments/private sector investment toward increased wastewater treatment. That contributes to a systematic transformation of the sanitation outlook, SDGs, and progressive circular economy integration.

4.3.3 Sanitation investment in Ghana

The sanitation budget allocation in developing countries is generally low. This accounts for the substantial donor agencies' sponsorship/support of sanitation development. Tayler and Salifu (2005) reported that from 1990 to 2004, the sanitation development investment in Ghana was 90% donor funded. Meanwhile, recent urban sanitation funding from the World and African Development Banks, the Dutch Embassy, UKAid, and UNICEF is expected to phase out from its lower middle-income status. However, Ghana's domestic water and sanitation investment remain below 0.5% of the GDP (approximately USD 150 million per annum) (Mansour and Esseku, 2017).

Recently, Gould (2020) reported the positive influence of prize money on liquid waste management policy planning in urban Ghana. Their research reported that 48 metropolitan, municipal, and district assemblies (MMDAs) have viable liquid waste management strategies, with 21 qualified for support and external funding from the survey of 139 (MMDAs). Thus, prospective innovative strategies approach to wastewater management at the local level of governance is viable to promote sustainable solutions in developing countries. For example, aquaculture production from treated domestic wastewater proved a successful value recovery strategy in Ghana to sustainably fund sanitation (CGIAR-RPW, 2019).

4.3.4 Wastewater treatment and resource recovery practice in urban Ghana

The waste stabilization ponds (WSPs) and flocculent CAS account for over 70% of urban wastewater treatment in Sub-Saharan Africa (Rugaimukamu et al., 2022). The WSP under good design and maintenance regimes are efficient in tropical climates and most preferred for their low-cost operation. However, they require a long hydraulic retention time and a large land footprint. Treated water quality is critical for water reuse adoption/application as a resource recovery option in developed and developing countries. Meanwhile, ethical issues regarding treated wastewater or "reclaimed" water use varies by region and application/use purpose. The Mudor WWTP and Legon WSP have design capacities of 16,000 to 18000 m^3/day (Ahmed et al., 2018) and 8558 m^3/day (although the Legon WSP operates at <50% of design capacity), respectively. These serve a population equivalence (PE) of approximately 963,000 and 435,000, respectively, calculated according to Bartram et al (2019).

The treated (effluent) quality evaluation (Table 4-1) for both WWTPs shows that they meet local treatment discharge standards (COD: 250 mg/L; ammonium nitrogen: 50 mg/L; orthophosphate: 1 mg/L) except for orthophosphate. However, they fall below international discharge standards which are competitively strict and more promising for a sustainably safe environment. For example, in the EU Directive 271/91/CEE, P discharge at 1 mg/L P is expected for >100,000 PE WWTPs (Molinos-Senante et al., 2011).

Currently, there is no reuse standard for the treated wastewater use in Ghana, although illegal wastewater irrigation of peri-urban farms is common in dry-season vegetable production. Agriculture is the economy's mainstay, constitutes over 60% of direct/indirect employment, and is mainly rainfed. However, data in the past decade shows an increase in freshwater withdrawal for irrigation by over 50% (Fig. 4-5) and significant growth in irrigated lands (Fig. 4-6), with the upsurge of informal small-holder irrigation farming from 2014 constituting the highest area coverage for irrigated use (over 180,000 hectares). According to recent estimates, almost 14,000 hectares of land are formally irrigated by public irrigation schemes and small reservoirs. Comparatively, informal irrigation by motorized pumps/buckets is almost 190,000 hectares (Dittoh, 2020), implying more agricultural water use. Meanwhile, less than 65% of Ghana's total national daily portable water demand is met, and over 40% of losses in non-revenue water are reported (ITEMG, 2020). Thus, treated wastewater use for irrigation can reduce the burden on freshwater abstraction toward meeting portable demand. Besides, 1,680 hectares of 56,000 in Ghana are irrigated with wastewater (although the source and water quality are undisclosed), and peri-urban informal irrigation accounts for 40,000 hectares; 1,200 are irrigated from unconventional sources and 26,800 from surface water resources (FAO, 2013).

Sludge recovery, treatment, and use are essential components of resource recovery from wastewater treatment processes. However, sustainable sewage sludge treatment methods are strongly influenced by local circumstances (Piippo et al., 2018), available technologies, economies of scale, and expertise. Currently, aerobic composting as a low-cost treatment option is the adopted sludge treatment method to produce organic fertilizer with the addition of sawdust and waste papers to increase the calorific value. Organic compost contributes about 1% of fertilizer demand and is underproduced in Ghana (USITA, 2022). Meanwhile, the opportunity for phosphorus recovery from wastewater treatment and commercial-scale bioenergy production has yet to be extensively explored.

4.3.5 Evaluating treated wastewater resource recovery potential from the Legon WSP and Mudor WWTP

Resource recovery from wastewater is premised on potential profitability from an economic and environmental perspective. However, the lack of tangible monetary value in quantifying environmental benefit conceals the preventive environmental damage/shadow price (Molinos-Senante et al., 2011b) consideration in evaluation/assessment. Cost-benefit-analysis from the sum of economic and environmental benefits in monetary value is more promising for WWTPs' economic feasibility evaluation in resource recovery planning. However, a project is profitable/feasible when the net profit (total income – total costs) > 0 (Molinos-Senante et al., 2010b). The operational cost of WWTPs varies by size, technology, and region. Generally, WWTPs' expenditure data in most developing countries is not public knowledge.

Molinos-Senante et al. (2010) estimated an average operational cost of € 0.22/m^3 from their evaluation of 1 million to 8 million m^3/annum WWTPs in Spain (energy = € 0.0392/m^3, staff = € 0.0712/m^3, reagents = € 0.0301/m^3, waste management = €0.0342/m^3, and maintenance = € 0.0453/m^3), and total environmental benefits/shadow price of € 0.3609/m^3. However, a lower € 0.25 ($ 0.24/ GHS 2.75) treated wastewater value was adopted instead of € 0.345/m^3 (Molinos-Senante et al., 2010) considering differences in economic conditions and prospects for easy application of water reuse in the developing countries context (at a rate of € 1 equivalent to $ 0.97). These were used to estimate the potential operation cost, environmental benefit, and treated water resource recovery value for 1.5 million m^3/annum and 6.2 million m^3/annum wastewater flow from the LWSP and MWWTP.

The operational cost was calculated according to Molinos-Senante et al. (2010) as

$$TOPC = ADF * BOC * 365 * CER \quad \text{(4-1)}$$

TOPC ($/annum), the total operational cost per annum; *ADF (m^3/day)*, average daily flowrate of influent into the WWTP; *BOC (€ 0.22/m^3)*, base operational cost estimated at an exchange rate conversion factor (*ERC) of 0.97.*

$$TEBC = ADF * ATWV * BEBV * CER \text{ .... } (4\text{-}2)$$

TEBC ($/annum), total environmental benefit-cost value; *ATWV (Million m^3/annum)*, average treated wastewater volume per annum; *BEBV (€ 0.3609/m^3)*, base environmental benefit value.

$$TWRV = ATWV * \%TR \text{ .... } (4\text{-}3)$$

TWRV ($/annum), treated water retail value; *ATWV* (Million m^3), average treated wastewater volume per annum; %TR, percentage of treated wastewater retailed.

A 50% treated wastewater use (retail) scenario was adopted for Mudor WWTP (6.2 million m^3/annum) as a base measure (to allow the opportunity for future scale-up) for use within the urban space at a relative transportation cost (not included). However, with the "high" water demand of the Legon WSP environment, 75% of the treatment capacity was adopted (1.5 million m^3/annum). In both facilities and scenarios, the total annual benefits exceed the operational cost for wastewater treatment of approximately $ 335,000 and $ 1.33 million for the Legon WSP and Mudor WWTP, respectively (Fig. 4-7). The two plants' treated wastewater retail value could contribute almost 90% and 60% of the operational cost in the Legon WSP and Mudor WWTP. However, the two plants' cumulative wastewater use and environmental benefit value amounted to $ 839,600 and $ 2,947,827. Hence, treated water resource recovery is a viable and sustainable financing strategy for developing countries in the CE concept adoption/implementation.

Strategic development planning and design locations for future WWTPs can contribute to optimum value recovery toward agriculture production in Ghana and other largely agricultural/developing economies. Meanwhile, few reports on "formally" treated wastewater irrigation or other non-potable services in developing countries is reported, while documented reuse standards are almost non-existent. Considering the high freshwater abstraction for agriculture in developing, establishing safe reuse standards for irrigation can minimize freshwater use to the essentially directly consumed fruits and vegetables. For example, Italy's general agricultural use and cereal/horticulture account for approximately 233 million m^3 and 86 million m^3/annum treated wastewater use (CECCE, 2018).

4.3.6 Evaluating nutrient (struvite) resource recovery potential from the Legon WSP and Mudor WWTP

The essential value of phosphorus (P) in fertilizers for agriculture production and varied modern industrial applications affect its high demand and potential future scarcity with geopolitical implications (van Dijk et al., 2016) and prospective influence on food security. Agro-driven developing economies are heavily reliant on annual fertilizer imports. By 2030, the P price could range from US$ 100 to 120/ton (Ashley et al., 2009), and global demands will outstrip the supply from phosphate rocks by 2033 (Mehta et al., 2015). Approximately 20 million tons of P is mined annually (Robles et al., 2020), and P was categorized in the European Union 2017/2020 list of Critical Raw Materials (European Commission, 2020). Ghana heavily depends on fertilizer imports, providing subsidies for farmers to support subsistent agriculture. The average annual imports range from 250,000 to 450,000 tons. The recent imports were valued at $ 173 million, 109 million, and 79 million for 2019, 2020, and 2021, respectively (US-ITA, 2022).

Wastewater is a P resource reservoir. Depending on consumer patterns/sources, municipal wastewater P may vary between 5 to 20 mg/L, comprising approximately 25 and 75% organic and inorganic fractions. Therefore, it is vital to recycle/recover P in wastewater where possible with practical, environmentally friendly, and sustainable strategies to sustain balance in the demand and supply curve equilibrium at a reasonable cost. Among various recovery methods, chemical dosing is the most frequently applied (Chrispim et al., 2019); meanwhile, nutrient accumulation techniques are recommended for domestic effluents (typically containing 6 to 8 mg/P/L) and P recovery applying anaerobic digestion. In conventional WWTPs, P recovery rate from the flocculent CAS process in the liquid and solid state can reach 50% and 90%, respectively (Cornel and Schaum, 2009). Meanwhile, crystallization reactors prospect better opportunities for profitability in P (struvite) recovery from wastewater (Achilleos et al., 2022).

Wastewater P recovery appeals to a CE and compliments solutions to eutrophication from excess P discharge control and the protection of life below water (SDG 14). Thus, WWTPs transitioning to WRRFs can enhance upgrading or redesign for efficiency in existing conventional systems while providing revenue for the economy. Wastewater-recovered P (struvite) and conventional fertilizers have similar properties for plant development (Montag et al., 2007), but rock P fertilizer is more economical. However, struvite recovery from wastewater under optimized conditions is viable and provides significant environmental benefits (Achilleos et al., 2022). Although the P recovery investment cost for 100,000 population equivalent is € 3,732,549, and € 1,417,739 from post-precipitation of effluent and sludge, respectively, estimated recovery from sewage sludge ash is economically unviable (Montag et al., 2009).

Based on Bartram et al. (2019), the population equivalence of the two plants was determined to be 434,641 and 962,568 for Legon WSP and Mudor WWTP. Thus, following Montag et al. (2007), the average investment cost would be $10,856,853 (Effluent = $15,736,493, sludge = $5,977,213) and $24,043,887 (Effluent = $34,850,473, and Sludge = $13,237,301) for Legon WSP and Mudor WWTP, respectively. Molinos-Senante et al. (2011) estimated 0.388 €/m^3 in cost for P recovery for 1.3 million m^3/annum WWTPs (energy = 0.088 €/m^3, staff = 0.166 €/m^3, waste management = 0.097 €/m^3, maintenance = 0.037 €/m^3). Thus, Legon WSP and Mudor WWTP can averagely gain $587,812 and $2,335,314, respectively. The price of struvite varies by region and is influenced by the use purpose.

On the assumption that 1 kg struvite/100 m^3 is recoverable from wastewater, approximately 15 and 62 tons/annum can be recovered from the two treatment plants, respectively, contributing $9,371 and $37,230 at an assumed $ 600/ton value. Previous estimates of $ 877/ton, $ 1885/ton, and $ 283/ton for struvite have been proposed for Australia, Japan, and the United Kingdom (Doyle and Parsons, 2002). However, Yetilmezsoy et al. (2017) suggest €580/ton, €600/ton, and €620/ton are reasonable under current conditions.

Meanwhile, the environmental benefit value of $330,265.63 and $1,312,109 is calculated at a rate of 0.218 €/m^3 (Molinos-Senante et al., 2011). Table 4-2 shows the total investment, operational cost, and annual benefits for struvite recovery in Ghana.

4.3.7 Evaluating CE integration and the untapped potential

Wastewater resource recovery prospects are predicated on the volume of wastewater generation and collection and are influenced by water use and sewer service coverage. According to UN categories, Ghana has Accra and Kumasi as medium-sized cities (UNDESAPD, 2018). The national average household size is 3.6 and 3.4 for the Greater Accra Region, and an urban population of approximately 5.5 million in Accra (Ghana Statistical Service, 2021). Wastewater treatment coverage as a CE indicator is estimated as

$$I_{WSC} = N_{connected}/N_{total} * 100\% \quad (4\text{-}4)$$

where $N_{connected}$ (capita/km^2) is the number of inhabitants connected to the sewerage system in an area, and N_{total} is the total number of inhabitants in the analyzed area (capita/km^2).

Less than 20% of inner-city Accra is sewered with 1100 connections (Mansour and Esseku, 2017). As assumptions of 25,000 and 50,000 sewer connections were made from a regional household size of 3.6 (Ghana Statistical Service, 2021), 4 and 10 persons/household for inner-city and urban Accra, was to determine the total coverage in Accra, Ghana. Under the best possible scenario of 50,000 sewer connections and a household size of 10, only 10% of urban Accra has sewerage coverage (Fig. 4-8). This shows the existing low prospects for domestic wastewater collection/treatment. Considering sewerage investment in developing countries is expensive and problematic, incentives to increase government and private investments are vital. Meanwhile, Ghana's national average sewerage coverage is reported to be 4.5%, with approximately 10% of municipal wastewater disposal through sewer networks connected to treatment plants (ITEMG, 2020).

4.3.8 Evaluating the reclaimed water resource recovery potential

The relative lack of reliable wastewater data (generation, collection, and treatment) is a constraint to reclaimed water use and resource recovery planning in developing countries. Relying on freshwater withdrawal and sector use can provide a reasonable basis for resource recovery estimations toward development planning in countries without adequate wastewater data resources. Moreso, international databases (The World Bank and FAO-AQUASTAT) with consistent databanks enhance trend evaluation, projections/valid inferences on water abstraction and use. Assumptive scenarios of 50, 75, and 90% wastewater treatment for abstracted water use from domestic wastewater streams were adopted. Considering the potential volume (Fig. 4-9), prospective ease of collection, low prospects for hazardous material concentrations, and high probabilities for development action through government/private sector partnerships. In the last two decades, the annual freshwater abstraction for domestic use has been approximately 6.9, 6.3, 5.9, and 6.2 billion m^3 for 2002, 2007, 2012, and 2017, respectively (average 6.3 billion m^3/annum). Averagely, municipal wastewater generation in Ghana has averaged 280 million m^3/annum over the past two decades (FAO, 2022). Conversely, water abstraction for industrial use averaged approximately 2.8, 2.5, 2.2, and 2 billion m^3 for the same period.

On the assumption of 75% domestic wastewater treatment, 5 to 10% reclaimed water use would provide approximately 232 to 465 million m^3/annum wastewater for irrigation in Ghana. At a rate of USD 0.25 (approximately 2.7 Ghana cedis) per m^3, reclaimed water from domestic sources can generate USD 58 million and USD 11.6 million annually. Reclaimed water use for agriculture is a promising avenue to exploit in dry season farming, considering perennial water shortages for agriculture water and low rainfall from increasing climate variability.

4.3.9 Evaluating the sewage sludge energy resource recovery potential

Sewage sludge, as a valuable feedstock for biogas, can provide reliable energy needs and concurrent sanitation improvement in developing countries. Moreover, its recovery, treatment, and use are essential components of the wastewater energy resource. However, sustainable sewage sludge treatment methods are strongly influenced by local circumstances (Piippo et al., 2018), available technologies, economies of scale, expertise, and climatic conditions. Arthur et al (2011) reported a potential to establish over 270,000 biogas plants (Arthur et al., 2011), significantly contributing to Ghana’s bioenergy and/or sustainable energy development.

Mohammed et al. (2017) did a cost-benefit analysis feasibility study for 9000 m^3 biogas plant installation for the Legon WSP to generate 118,912 m^3/annum biogas that provides $646,780, $17,069, and $49,806/annum earnings from electricity, fertilizer production, and non-potable reclaimed water (64,861 m^3/year) uses, respectively. Additional potentials include $29,940 contribution in carbon credit earnings, and 468,440/annum savings from cesspit emptying, with a seven-year payback on investment. Hence, energy recovery from wastewater treatment is worth exploring. In over a decade, end-use electricity tariff has almost consistently increased in Ghana, from GHS 0.2 to 0.82/kWh (Ghana Cedi (GHS), equivalent to $ 0.013 to

0.055) (Sasu, 2022). A sustainable renewable energy resource can contribute significantly to Ghana's energy mix.

Sludge is approximately 1 to 2% of the wastewater volume (Andreoli et al., 2007). On the assumption of 0.05 kg/L dewatered sludge and 1 kg COD theoretical methane value of 0.35 m^3 methane/kg, the amount of sludge generated was calculated as

$GSV = WWV \times 10^{12} \times T(\%) \times TSC$ ……………………………………………………….(4-5)

where GSV, generated sludge volume(l); WWV, water withdrawal volume (BCM); TSC, theoretical sludge concentration (1%/0.01l); T, adopted treatment percentage.

Domestic wastewater was chosen for energy resource evaluation because of the prospective ease of collection and high-volume generation from the water withdrawal data analysis over the past fifteen years, as compared to industrial wastewater or less recoverable agriculture wastewater (Fig. 4-9). Figure 4-10 shows the sludge/dewatered sludge volumes.

On the assumption of 60% biogas production and 0.002MWh/m^3 of electricity from biogas (Ijoma et al., 2022), 1807 to 3240 MWh/annum (Fig. 4-11) can be produced from domestic wastewater streams. At the current rate of end-user energy cost in Ghana, an equivalent of 1.8 million to 3.2 million kWh/annum of electricity (Fig. 4-12) can be contributed to the energy mix while providing approximately \$ 1 to 2 million to the economy from electricity energy tariff and energy recovery, and the value contribution to the economy on the assumption of GHS 1 equivalent to \$ 0.075. Thus, energy resource recovery from sewage sludge can provide an alternatively reliable source that augments hydroelectric energy dependence.

Meanwhile, considering the enormous value of algal-bacterial AGS and the possibilities for its practical scale application under natural light conditions, they can contribute to local wastewater treatment needs and have high economic value. For example, based on their estimates (Tavares Ferreira et al., 2021) and \$ 80-140/kg ALE value, a revenue of \$ 1,740 and \$ 7200/annum can be recovered from the 1.5 million m^3/annum and 6.2 million m^3/annum WWTPs in Ghana, excluding recovery expenses. Meanwhile, considering the recovery estimate (Tavares Ferreira et al., 2021b) based on bacterial AGS, a higher value is expected from more ALE recovery.

4.4 Summary

This chapter focused on exploring the opportunities that can contribute to increased infrastructure investment in developing countries. The current state shows relatively low local wastewater treatment focus and infrastructure investment across the developing African countries. The example of <1% GDP investment is abysmal to keep pace with the dynamic growth in its urban population. Meanwhile, the current investments in new WWTPs in Ghana are promising for the drive to increase wastewater treatment toward environment/public health protection. However, measures are critical to developing the sewer network for sufficient influent collection and recovery of potential resources (water, nutrients, and bioenergy). These should contribute to the future viability of sanitation development, sustainable financing, and critical environmental protection realization while providing economic benefits.

Existing WWTPs in Ghana, are potentially viable pilot opportunities for treated wastewater recovery use applications, considering the high investment cost for struvite resource recovery. This implies an urgent need for reclaimed water reuse standards incorporation in Ghana and other developing countries, to harness safety in advancing the CE benefit from wastewater as a resource.

Table 4-1 Influent concentration and effluent discharge quality from Legon WSP and Mudor WWTP

WWTP	Influent nutrient load (mg/L)						pH	References
	BOD	COD	PO_4^{3-}-P	NH_4^+-N	NO_3^--N	TSS		
Mudor	1206± 397	3173± 153	2.31 ±0.14	4.3 ±1.73	29 ± 2.82	3206± 2571	8.96 ± 1.0	Awuah and Abrokwa. (2008)
Mudor *	2095± 294	1483± 750	36.83	66.88± 4.1	354.6±50	740 ± 313	7.00 ± 0.2	Ahmed et al. (2018)
Legon WSP	156.2 ± 45	358.6 ± 73	7.14± 7.96	9.67 ± 3.6	0.184±0.2	195.5 ± 44	7.37 ± 0.3	This study
Effluent nutrient concentration (mg/L)								
Mudor	23 ± 5.74	146± 20.62	0.5 ± 0.14	2.6 ± 0.68	22.1± 0.8	958 ± 93.78	7.45±0.14	Awuah and Abrokwa. (2008)
Mudor *	23.88± 4.5	129.9 ± 53	6.71± 0.63	37.73± 4.1	253.2±356	260.3 ± 101	8.04±0.10	Ahmed et al. (2018)
Legon WSP	16.3± 1.62	195.1±15.9	1.44± 0.34	3.02 ± 1.0	0.50±0.28	44.5 ± 3.28	7.92±0.27	This study

WWTP, wastewater treatment plant; BOD, biochemical oxygen demand; COD, chemical oxygen demand; PO_4-P, orthophosphate; NH_4^+-N, ammonium nitrogen; NO_3-N, nitrate nitrogen; TSS, total suspended solids; pH, power of hydrogen; *rehabilitated

Table 4-2 Estimated P recovery cost and value for Legon WSP and Mudor WWTP

Item	Legon WSP	Mudor WWTP
Investment cost	$10,856,853	$24,043,887
Operational cost /annum	$587,812	$2,335,314
Treated wastewater retail value/annum	$284,059	$752,356
Struvite resource value/annum	$9,371	$37,230
Environmental benefit of P recovery/annum	$330,266	$1,312,109

P, phosphorus (struvite in this study); WSP, waste stabilization pond; WWTP, wastewater treatment plant

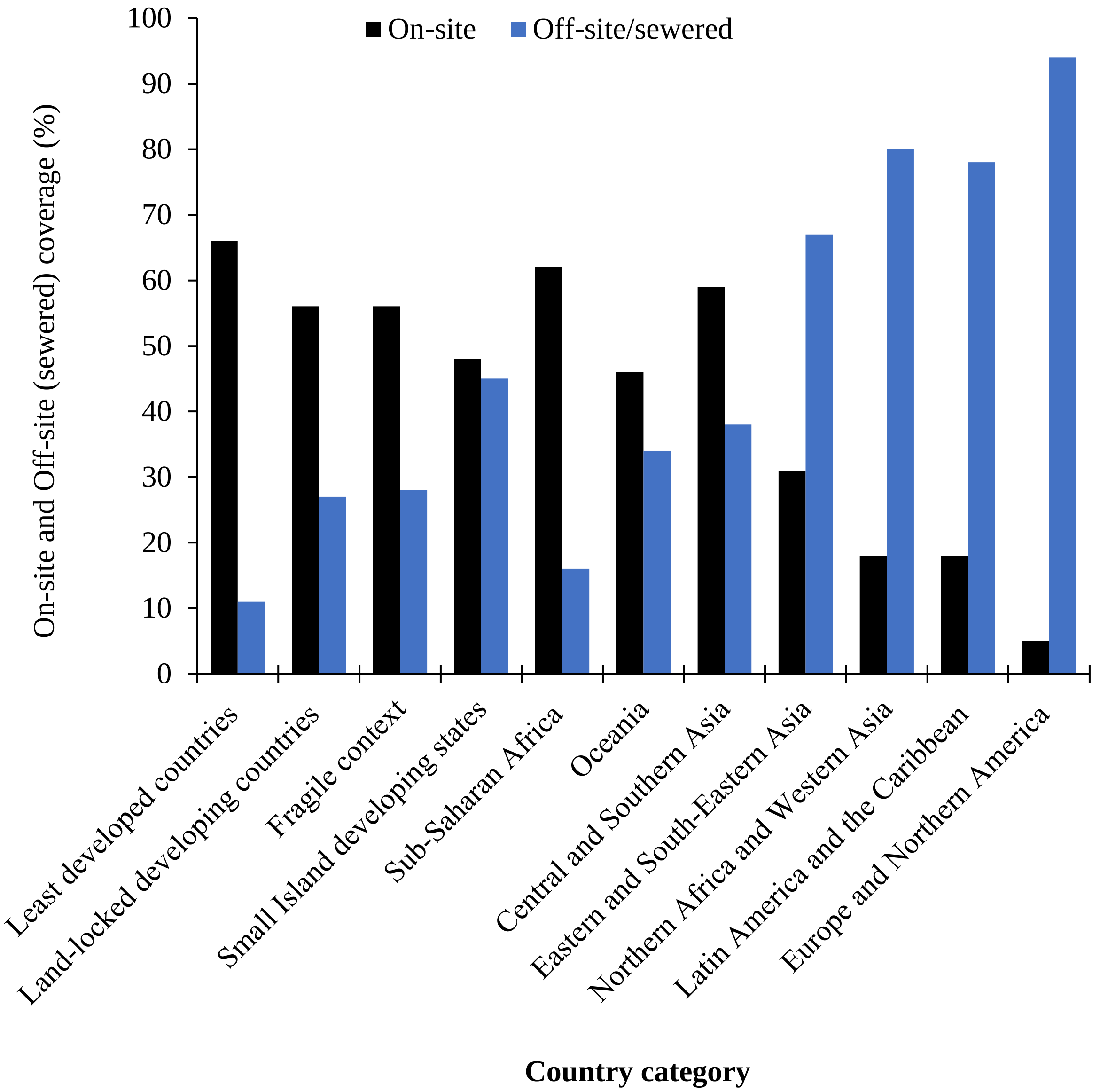

Fig. 4-1 Variation in urban onsite and off-site sewer sanitation coverage among regional categories.

Data source: WHO and UNICEF (2021).

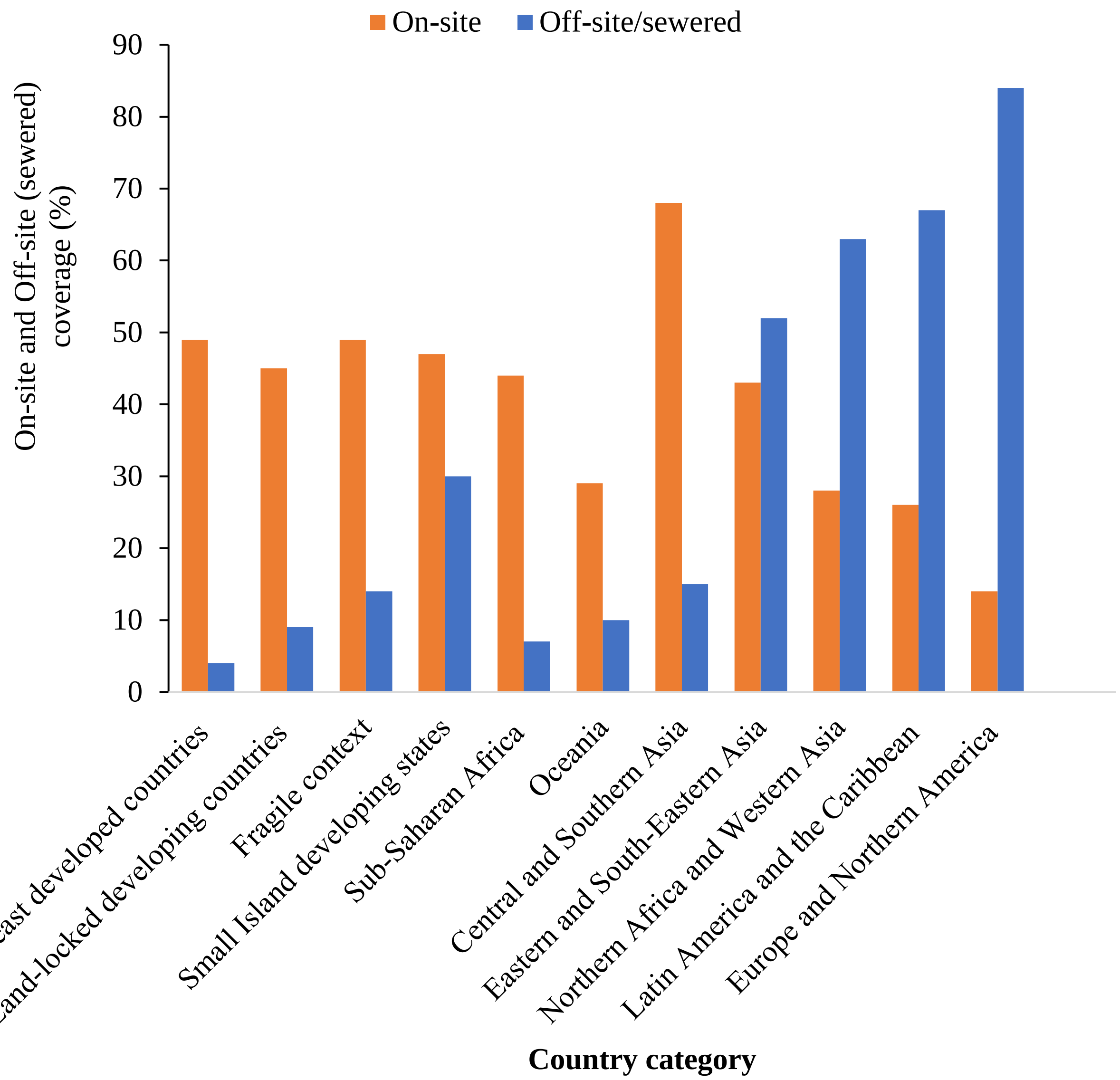

Fig. 4-2 Variation in national onsite and off-site sewer sanitation coverage among regional categories.

Data source: WHO and UNICEF (2021).

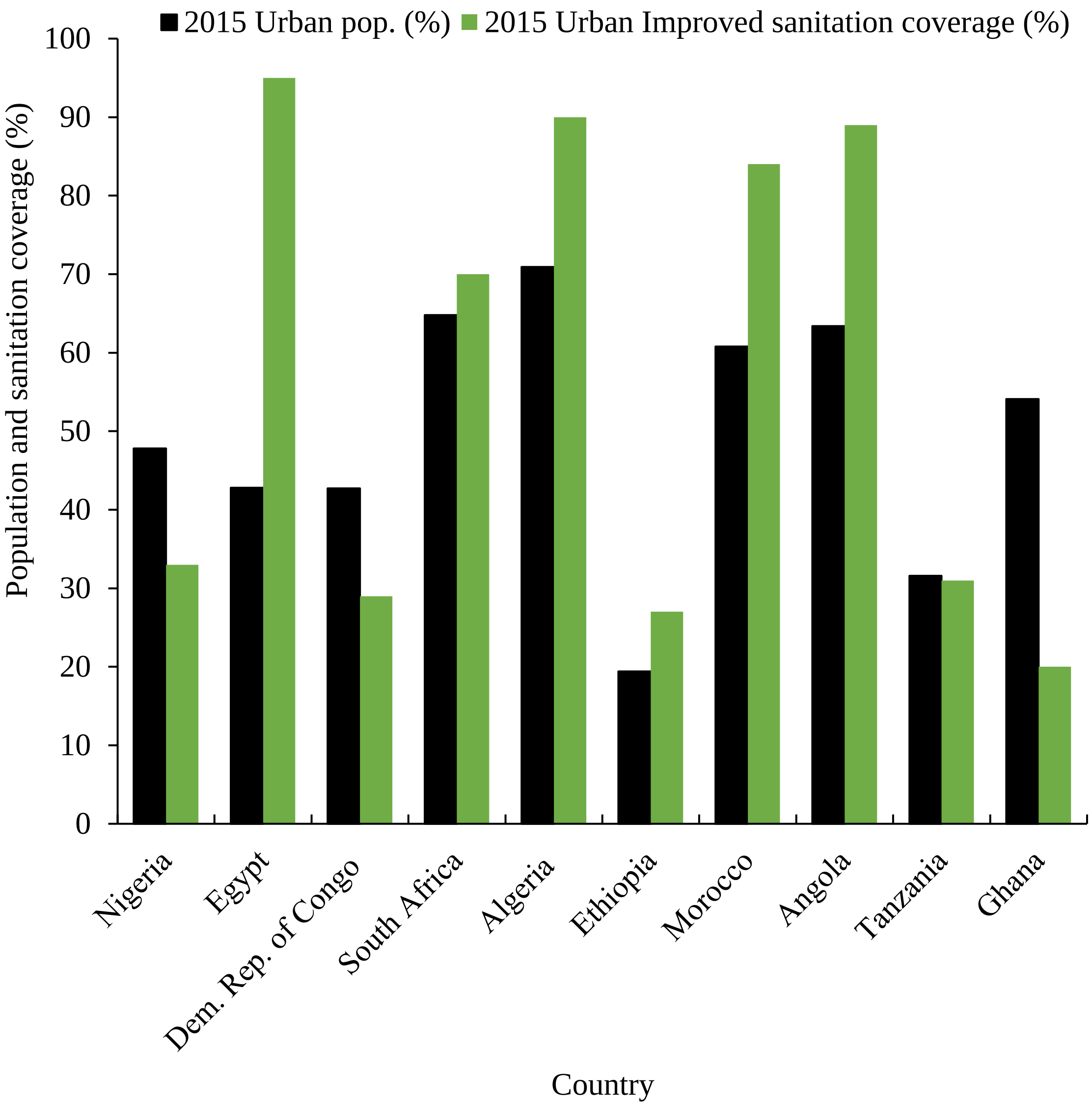

Fig. 4-3 Improved sanitation coverage in Africa's ten most urbanized countries.

Data source UNDESAPD (2018); WHO/UNICEF-JMP (2015)

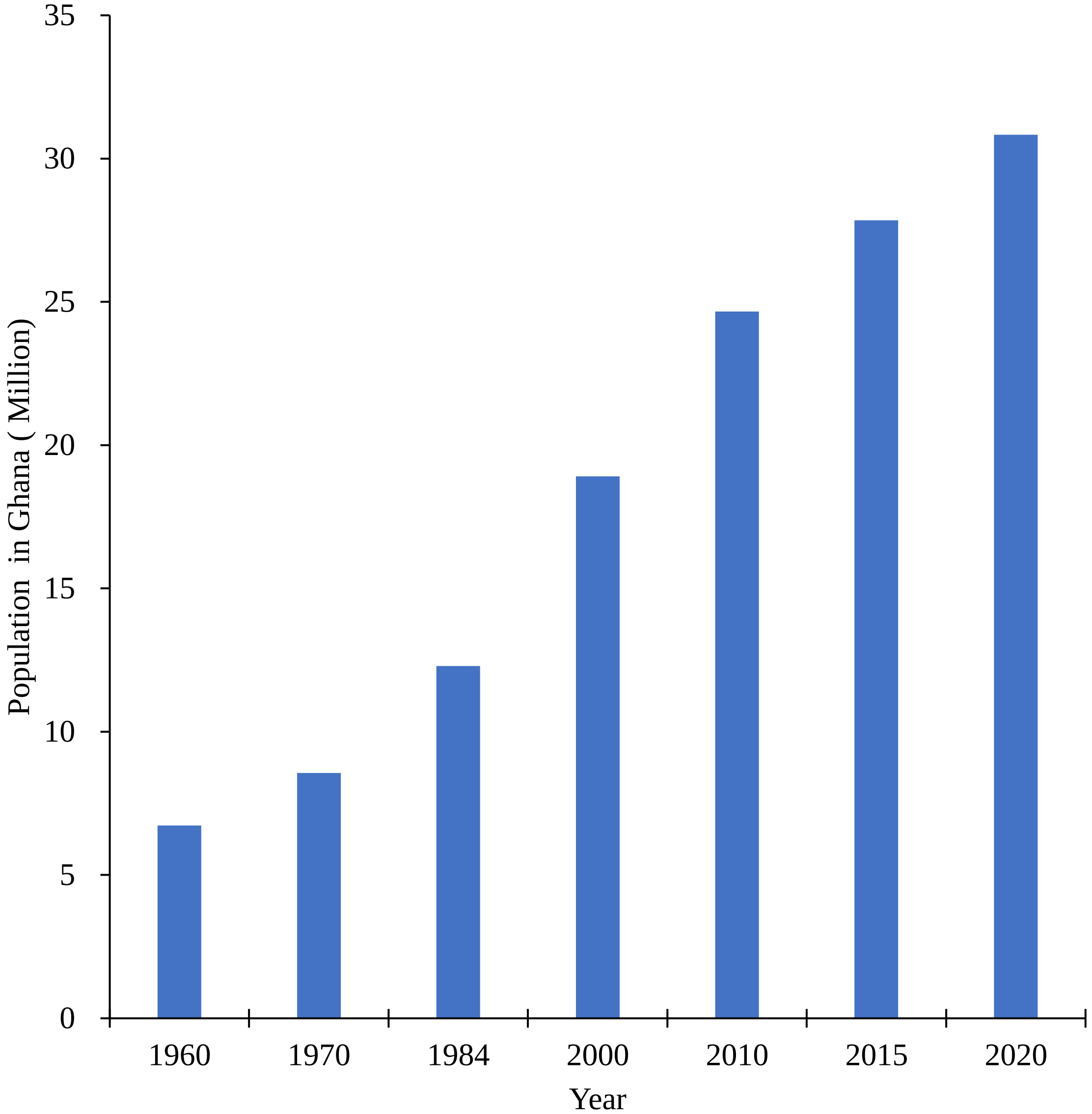

Fig. 4-4 Population growth in Ghana from 1960 to 2020.

Data source: GSS (2021)

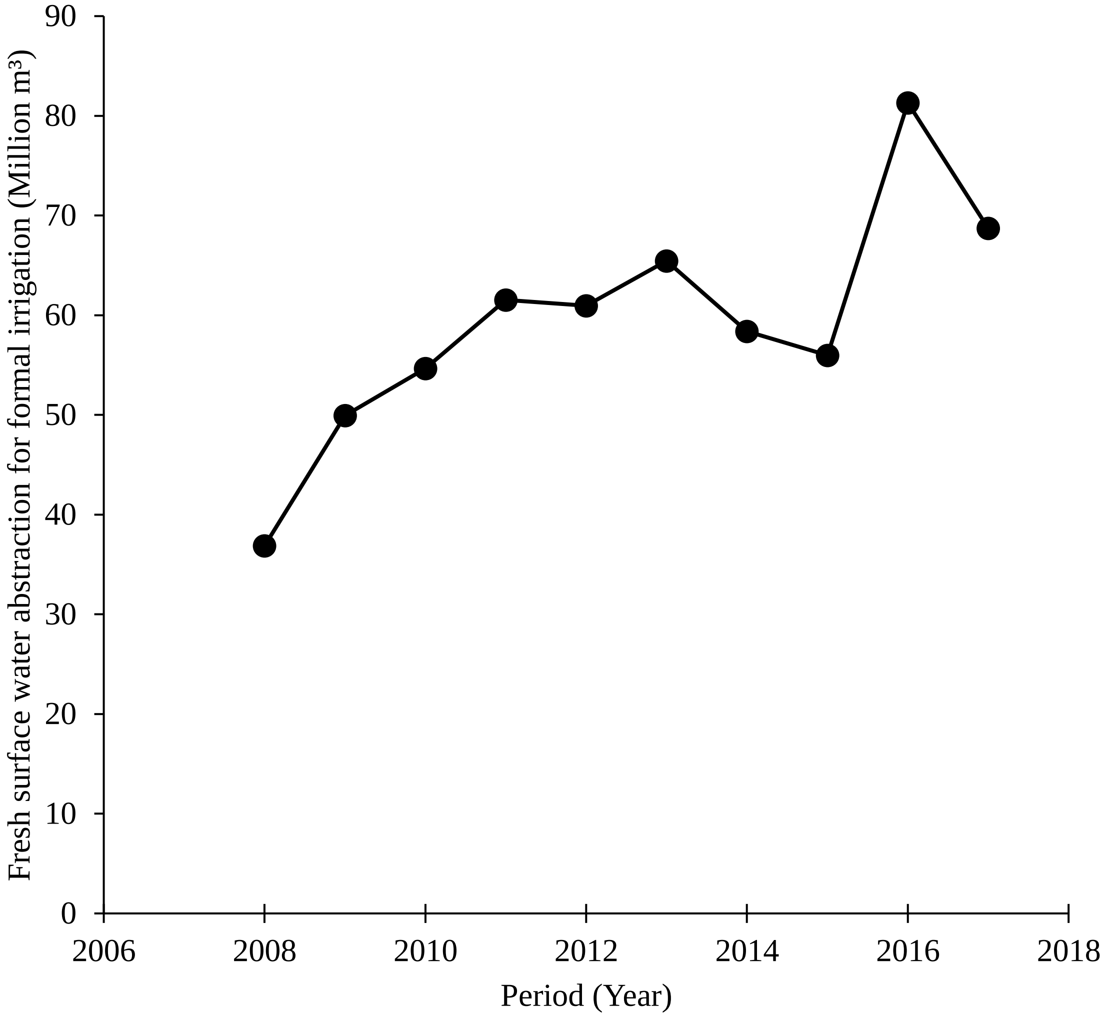

Fig. 4-5 The trend in formal irrigation water withdrawal.

Data source: GSS/EPA (2021).

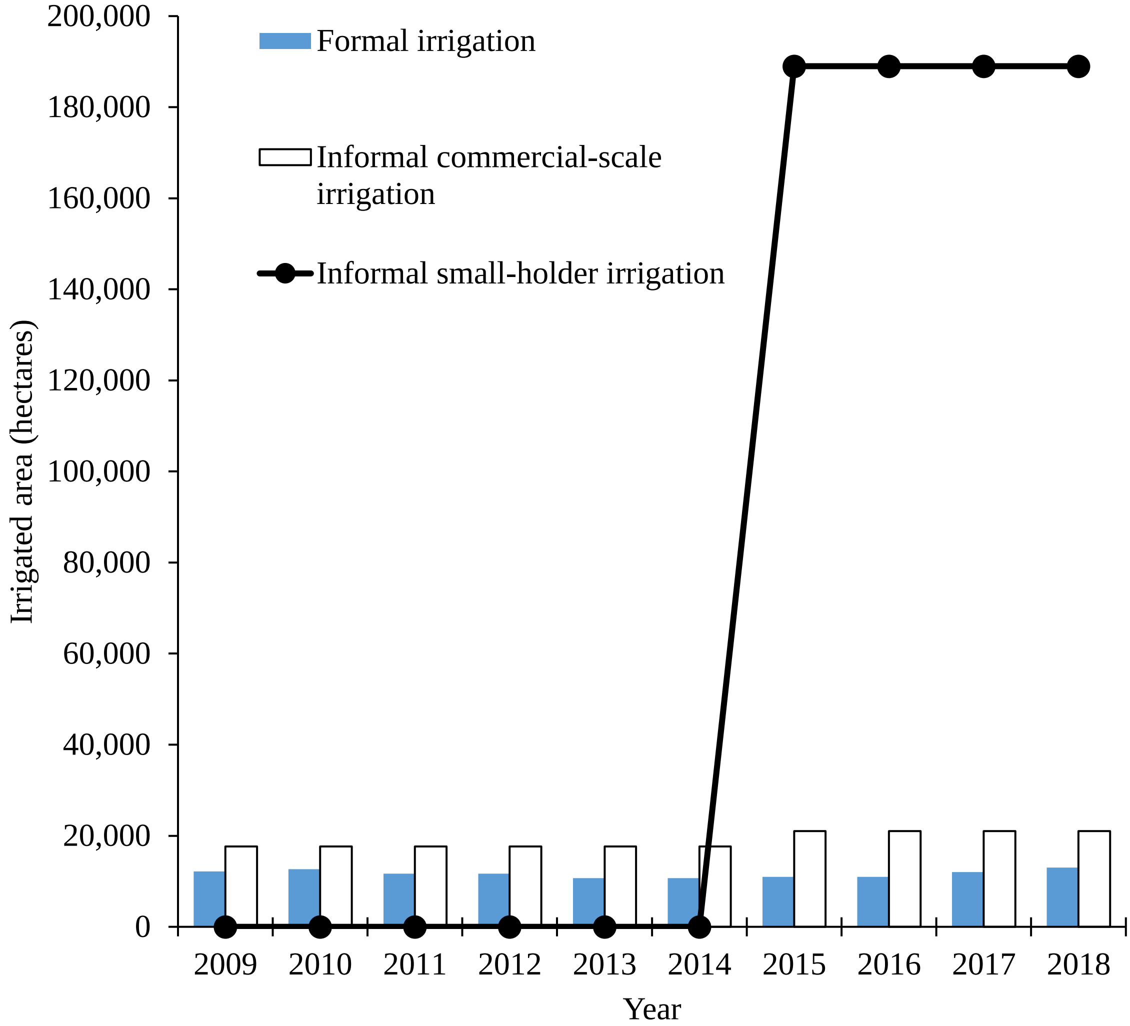

Fig. 4-6 The trend in irrigation coverage by type and scale.

Data source: Dittoh (2020).

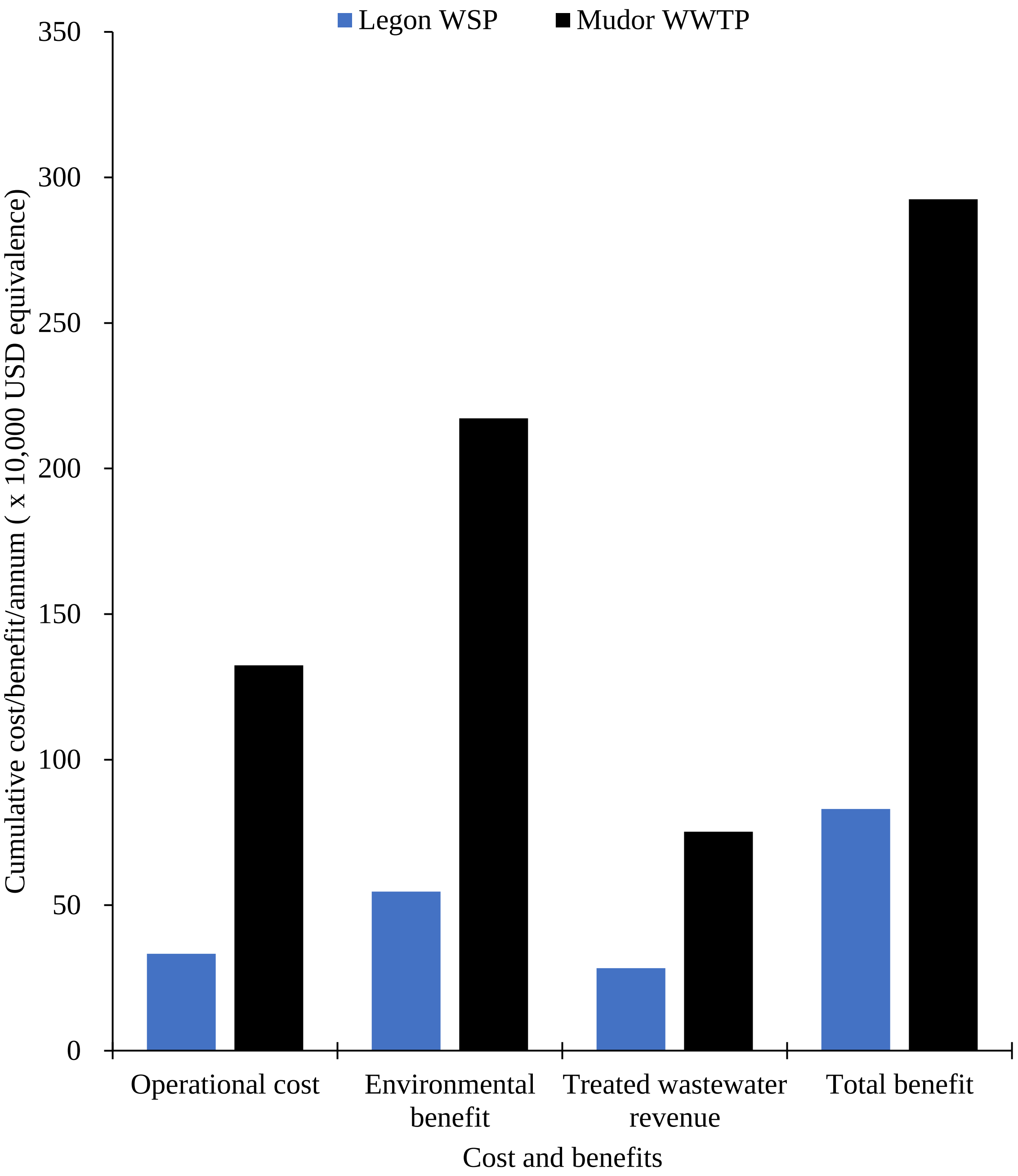

Fig. 4-7 Cost benefit analysis from environmental benefit and reclaimed value.

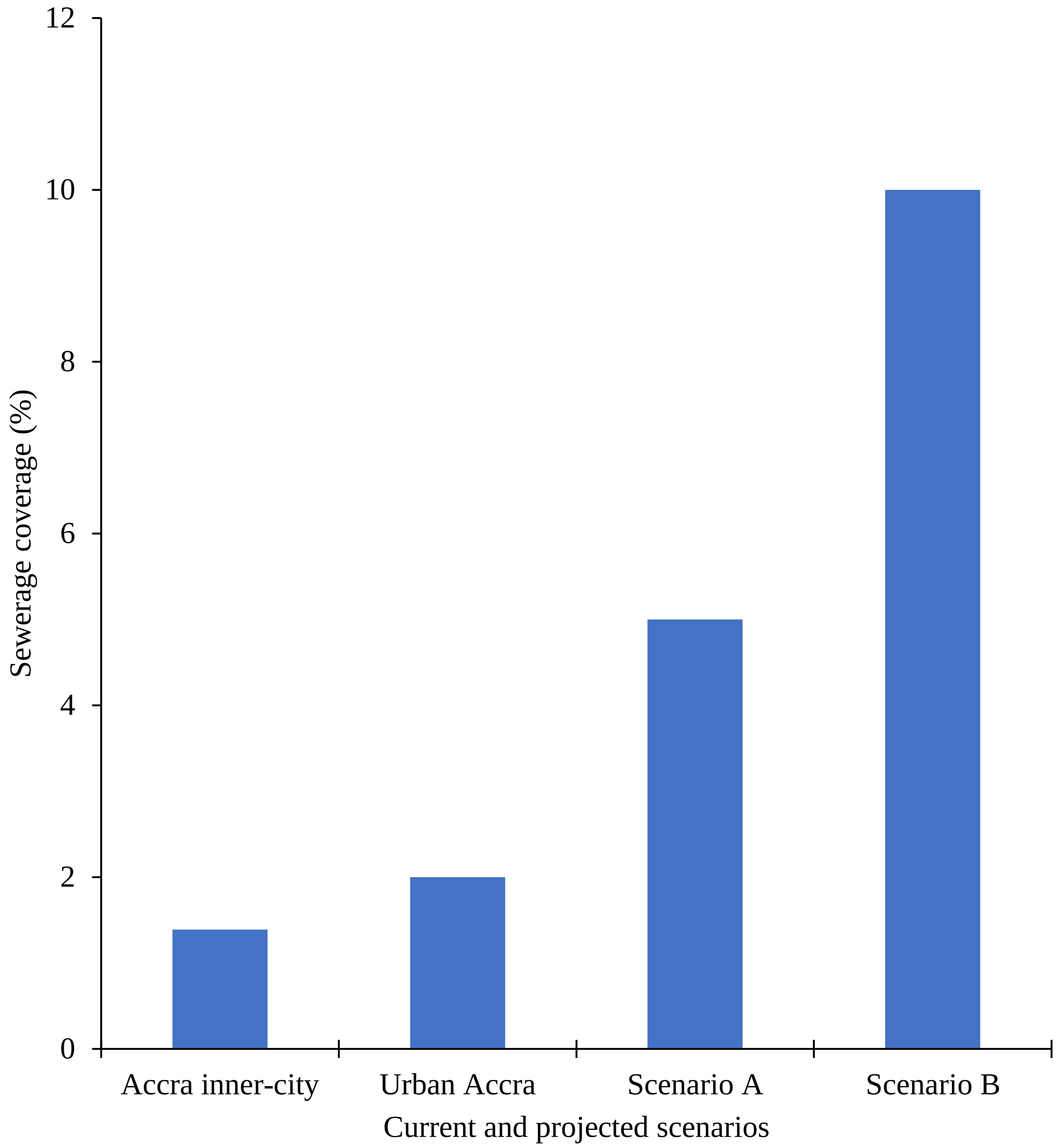

Fig. 4-8 Sewerage network coverage estimation under current and projected scenarios

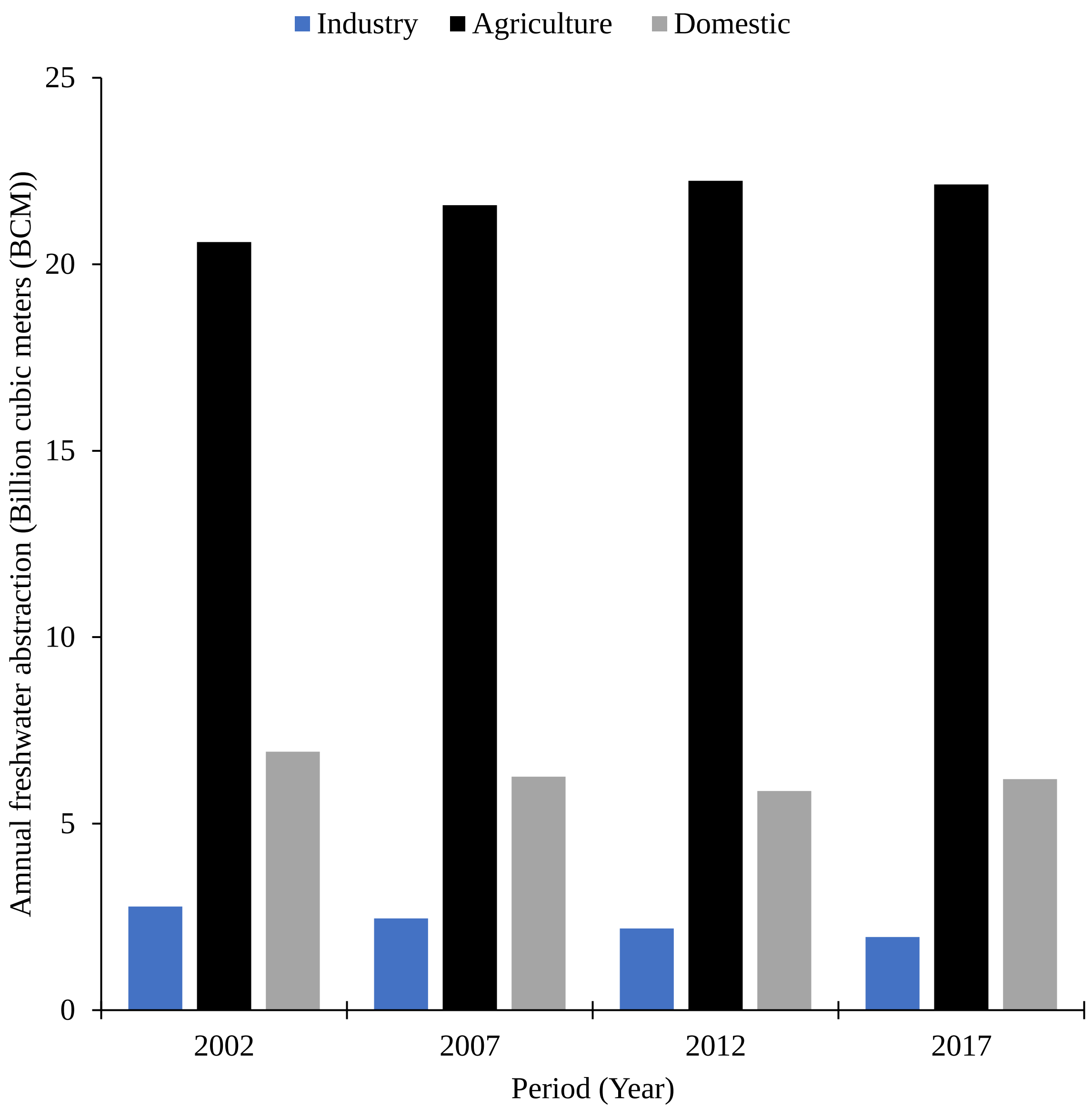

Fig. 4-9 AFWR in billion cubic meters (BCM) by sector over the past decade in Ghana.

Data source: FAO-AQUASTAT (2022)

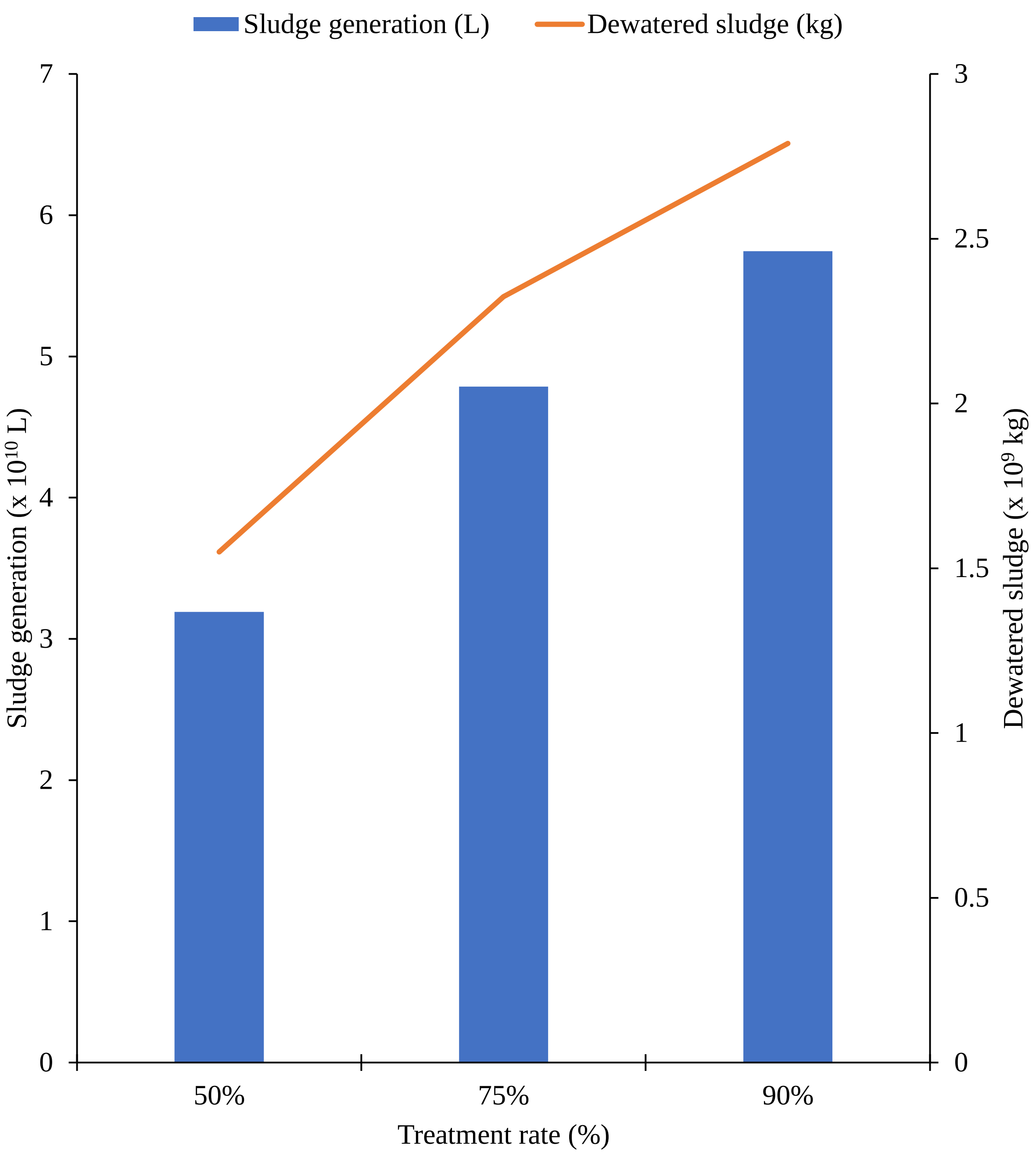

Fig. 4-10 Sludge and dewatered sludge generation/recovery potential

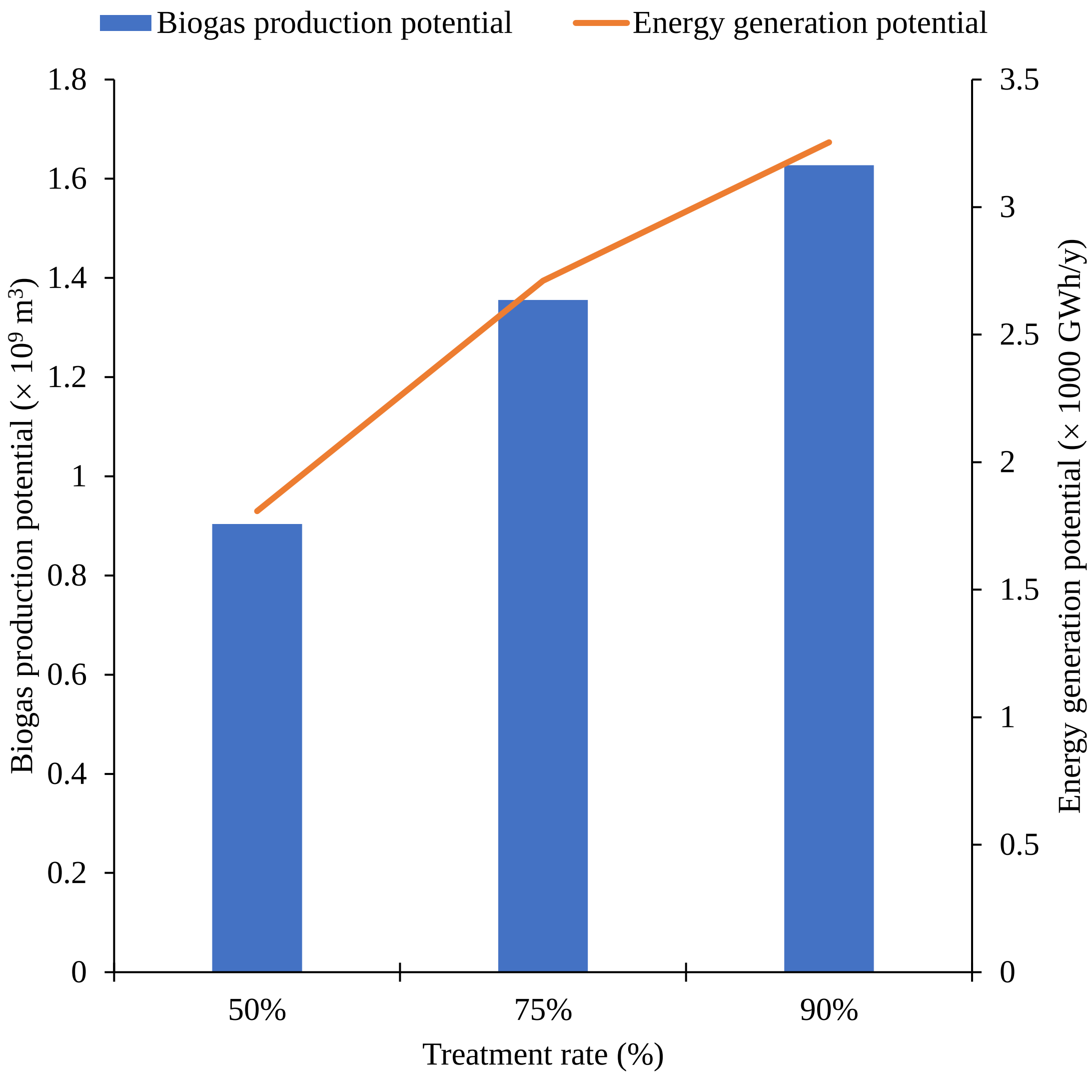

Fig. 4-11 Biogas and energy generation potential

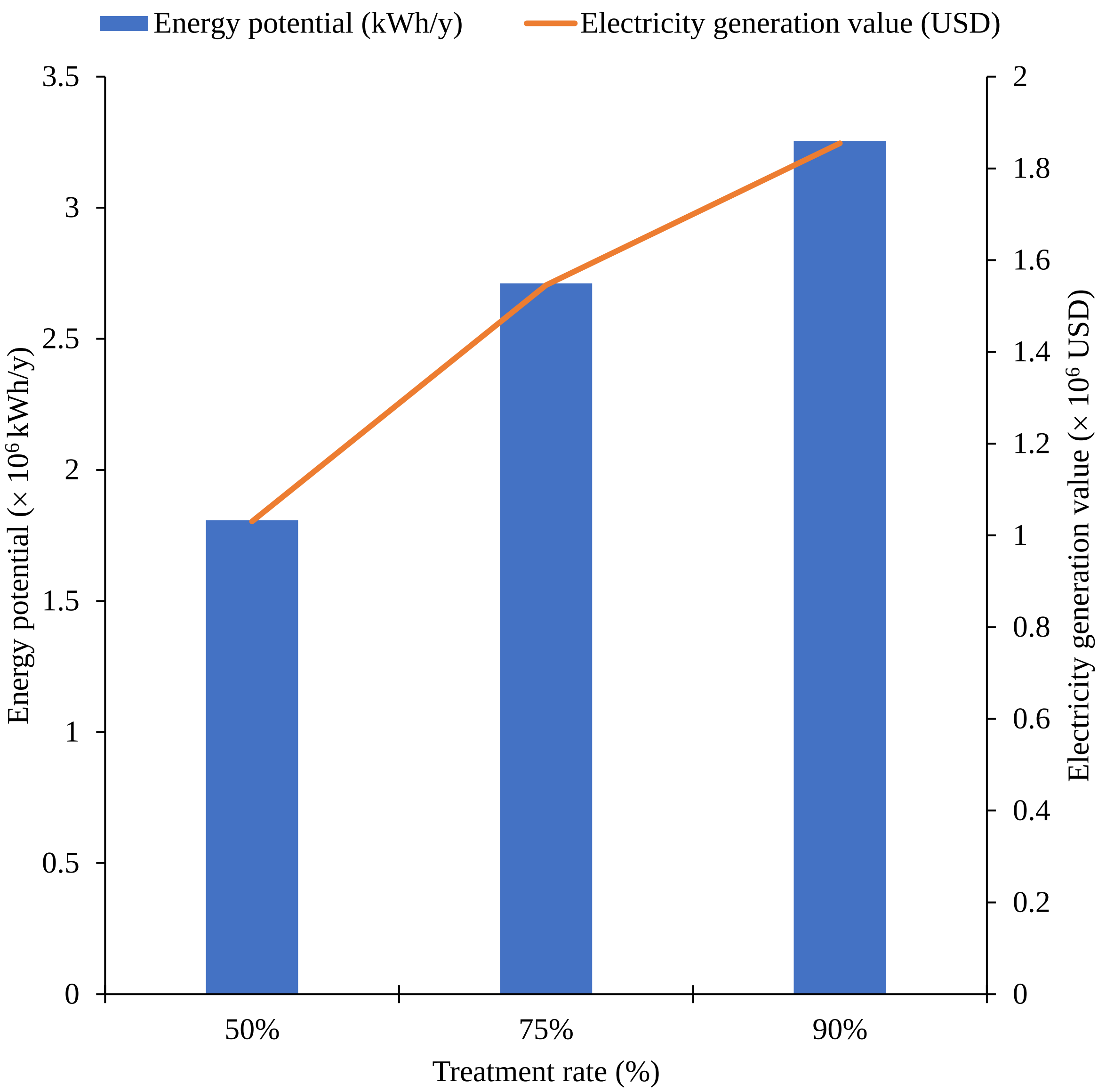

Fig. 4-12 Electricity generation potential (kWh) and value for local economy.

Chapter 5 Conclusions and future work

5.1 Conclusions

This research overviewed the importance of wastewater treatment, the development of biological WWTPs, and the changing focus in the last century by comparing the flocculent CAS and bacterial/algal-bacterial AGS systems. In addition, this study introduced the CE concept and multiple SDGs together with a systematic cross-sectional analysis of academic literature and government publications, highlighting the dominant factors in wastewater treatment transition and innovations. Furthermore, the research evaluates the prospects of developing countries' capacity to recover wastewater treatment resource value for the sustainable financing of sanitation development and increased adoption of advanced wastewater treatment biotechnologies.

The detailed conclusions can be summarized as follows.

(1) The ever-growing global human population is a critical indicator that wastewater treatment will continue to be essential for society to ensure environmental safety. Hence, strategic and innovative bioengineering inventions are expected to appeal to and meet the changing societal needs at a relatively low cost. This will require increasing research and development (R&D) investment. From the sustainability evaluation of the flocculent CAS, bacterial and algal-bacterial AGS systems, the latter is the most promising alternative biotechnology. Thus, engineering solutions to the bottlenecks for practical scale algal-bacteial AGS application can enhance its full benefit to the society. Hence, further research is necessary to optimize prospects for its future practical application. Meanwhile, their climate-smartness and superior resource recovery features make them a reliably long-term solution that can become the future gold standard in wastewater treatment.

(2) The treated wastewater resource recovery from bacterial and algal-bacterial AGS systems under various treatment conditions show their superiority to the flocculent CAS. Thus, their use prospects a safer environment from the discharge of high-quality effluent into receiving water resources which influences life below water (SDG 14). Considering almost 100%, averagely 95%, and 90% of COD, NH_4^+-N, and PO_4-P removal respectively from varying influent wastewater by both systems. While providing more opportunities for the treated wastewater use, both systems' high resource recovery can potentially reduce over 50% operational cost in multiple resources recovery from treatment processes. Based on the algal-bacterial AGS' faster and higher biomass production, retention, high resource bioavailability, and multiple resource recovery potential, it presents an innovative solution to commercial-scale biomass production and wastewater value recovery. ALE recovery can reduce sludge biomass by 35% and provide 50% of operational cost from ALE value ($ 80-140/kg). The higher ALE/P

recovery (P/struvite value is approximately \$ 600/ton), and lipids production of algal-bacterial AGS makes them the most promising biotechnology for waste sludge management in a circular economy. In addition, it is worth mentioning that algal-bacterial AGS show great potential to lower the carbon footprint of WWTPs and contribute carbon credits.

(3) The high income contribution of treated wastewater retail is a potential opportunity for sustainable sanitation financing in developing countries, with more opportunities for high value-added products recovery and viable market value chains. Meanwhile, algal-bacterial AGS wastewater treatment in Ghana can contribute \$ 6,875 and \$ 28,417, generating \$ 82,500 and \$ 341, 000 annually from 1.5 Mm^3/year and 6.2 Mm^3/year WWTPs, respectively. The treated wastewater quality from the large-scale functional WWTPs in Ghana meets local quality limits but is below international discharge and agricultural irrigation use standards. However, it is the most viable resource recovery pathway with lower investment costs. Meanwhile, the urgent need to develop and implement appropriate standards is critical in advancing increased treated wastewater reuse for agricultural purposes. More innovative strategies must be adopted to influence government and private sector investments for wastewater resource recovery in developing countries. This is the most promising pathway to circular economy application in developing countries, and the future sustenance of WWTPs and a clean environment.

5.2 Future work

The higher resource recovery from algal-bacterial AGS is a promising development to transform the outlook of wastewater treatment in the coming decades. In this research, various resource recovery opportunities and their values have been examined. However, opportunities to maximize extraction and high efficiency still exist. Several environmental and operational factors can influence the different types of resource recovery, for example, salinity contribution to lipids content. Moreover, in advancing multiple resource recovery, the optimized operating conditions are ideal.

Further research on evaluation of operation conditions for multiple resource recovery can advance future engineering of algal-bacterial AGS pilot studies in practice. Meanwhile, the energy requirement reduction in treatment process savings from algal-bacterial AGS use remains an exciting research focus to promote technology adoption.

Bacterial AGS may have a low potential for biomass growth and then lower bioenergy production from anaerobic digestion, compared to the flocculent CAS. Hence, future research on algal-bacterial AGS biomass with relatively higher biomass concentration, retention, and microbial community can influence their competitive advantage over bacterial AGS. This can advance and highlight the bright future of algal-bacterial AGS systems.

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Dedication

To God who has and remains my most dependable source of strength and hope. “For I the Lord thy God will hold thy right hand saying unto thee, fear not; I will help thee”. Isaiah 41:13.

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