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A nutrient circular economy framework for wastewater treatment plants

Allan Soo, Ho Kyong Shon [*]

School of Civil and Environmental Engineering, University of Technology Sydney (UTS), New South Wales, Australia

HIGHLIGHTS

- Social, environmental and economic elements are applied to nutrient CE WWTP.
- Meso, micro and macro systems factored across different scope areas.
- Framework provides a roadmap for stakeholders towards nutrient CE WWTP.
- Drivers and enablers are identified.
- A universal nutrient CE WWTP framework model is proposed.

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ABSTRACT

Given the criticality of phosphorous and the harm eutrophication causes, wastewater treatment plants (WWTP) are undergoing circular economy (CE) conversions into becoming centres for resource recovery. This framework paper identifies the environmental, societal, political, commercial, economic, consumer, regulatory, legal, infrastructural, technological, international compliance, academic, agricultural, and plant-operator factors affecting the micro, macro and meso success and failure of nutrient CE WWTP across scope classifications. From this, nutrient CE framework is not as simplistic as it looks, given the multitude of impingers that need to be considered. The lack of technological readiness and vast selection methodologies for some nutrient recovery technologies, low private-sector investment, divisive consumer perceptions, unique economic situations, localised regulatory specifications, threats of inefficient technology lock-ins, poor acceptance among farmers and WWTP operators due to infrastructural incompatibilities, lack of efficient CE supply chains, legacy infrastructure, poor digitised solutions for nutrient CE management, low training and awareness, and integration of nutrient CE WWTPs with broader society are barriers. On the contrary, nutrient CE WWTP will mainly be driven by regulations, subsidies and consumer-WWTP-farmer nutrient CE acceptances. This framework aims to tie in and provide solutions to overcoming barriers to nutrient CE WWTPs that is universally applicable. Consequently, the framework provides a holistic structure for policy, legislative, academic, agricultural, plant operators, commercial and consumer stakeholders a roadmap for the success and difficulties of nutrient CE WWTP adoption.

1. Introduction

Nutrient consumption is touted as a growing problem for growing economies and demographics. The unsustainable consumption of nutrients, and the subsequent production of wastewater, is a two-pronged issue that governments globally are challenged to address. In 2020, 44 % of household water is not treated, 26 % of the global population do not have access to safe drinking water, 60 % of the report's assessed 89 countries have access to good quality water, while poor water quality data hampers assessment initiatives for more than 3 billion people accessing high-grade freshwater [1]. The leakage of nutrients via wastewater effluent into the environment presents significant sustainability imperatives endangering the global biodiversity and preservation of both fauna and flora. For example, the World Bank estimated that in Latin America and the Caribbean – places where wastewater treatment plant (WWTP) facilities are lacking – 80 % of wastewater is discharged without adequate treatment [2]. Wastewater production rates are forecasted to increase by 24 % by 2030 and 51 % by 2050, with 16.6 Mt nitrogen, 3.0 Mt phosphorous, and 6.3 Mt of potassium present within this supply and the potential to offset 13.4 % of global demand for

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[*] Corresponding author.
E-mail address: Hokyong.Shon-1@uts.edu.au (H.K. Shon).

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nutrients [3].

A large concentration of wastewater generation per capita is in North America at 231 m^3/capita/year [3]. Meanwhile in developing regions of the world, the capita falls to 46 m^3/capita/year as seen in Sub Saharan Africa and Latin America at 65 m^3/capita/year [3]. The low treatment rates may also present problems from lack of wastewater connectivity to populations for treatment where nutrients are disposed of into the environment, creating issues with eutrophication. Therefore, the need to recover nutrients to divert its leakage from the environment becomes one of the crucial missions WWTPs play in safeguarding environmental integrity. For instance, urine is responsible for 80 % of nitrogen and 50 % of phosphorous loads within wastewater treatment plants [4], and the recovery of nutrient loads within wastewater can help drive down operating costs and support circular economy initiatives [5] that prevent many of the environmental problems arising from nutrient loading. Presently, the European Union's (EU) CE initiatives have primarily been focused on solid wastes as opposed to wastewater and other liquid wastes, despite the huge quantities of nutrients and caloric value of liquid waste entering treatment plants on an annual basis [6]. Moreover, there is very little penetration of CE efforts globally for WWTP nutrient recovery for commercial plants. The EU recently launched the “WIDER UPTAKE” project, where fertilisers, water, soil conditioners and bioplastics formed part of the strategy to convert wastewater into valuable products [6,7]. Similar nutrient CE WWTP projects have been seen in Germany with Project SUSKULT bio-economies [8,9] and the Dutch government aims to become a fully circular economy by the year 2050 [10] through projects like DARROW [11]. NUTRIMAN is another project which aims to identify market opportunities linking industry with untapped N—P recovery sources [12], BIOREFINE [13], NUTRI2CYCLE [14], Rich Earth Institute [15], Phos4You [16], REFLOW [17], The Water Research Foundation [18,19], RePhoR [20] are some research initiatives and social programs to disseminate awareness for nutrient shortages. As another part of the EU green deal, the Circular Economy Action Plan - commissioned in 2020 - aims to recover resources from waste across a wide range of sectors including water, food, and nutrients [21]. In order to meet 2050 sustainability targets, governments are beginning to see the benefits of adopting CE across a WWTP as a way of improving self-sufficiency and sustainability from resource consumption.

CE can help alleviate water, energy and food shortages throughout the world [22].

2. Methodological approach

Popularity for circular economy studies with WWTPs and nutrients has grown over the years within academia. Keywords used were “Circular Economy” AND “Wastewater Treatment” AND “Nutrient”; “Circular Economy” AND “Wastewater Treatment”; and “Circular Economy” AND “Nutrient” for the bibliometric assessment of these recent trends (Fig. 1). Other CE framework papers have used cascading [23] approaches to transform one value-added product to the next down the process chain using the 10R principles for CE.

Authors have separated CE into two types such as sensu stricto [24] and sensu latu [25] to respectively narrowly define it within the realm of slowing and closing resource loops, or to consider the economic, environmental and societal impacts of CE frameworks [26]. In many CE framework studies, it is impossible to isolate the 10R principles for CE across all resource conservation studies, as it is ubiquitous throughout many waste management disciplines to minimise costs, material disposal and maximising product reuse and longevity. Liu et al. [27] sought to implement a digital lens towards automating, data collection and analysis for predicting the lifecycle of the product and consumer behaviours towards its use. The framework was then developed through systematic literature review, and ties in the 10R principles with that of automation, data analysis and collection. In many of these CE cases, there is an overemphasis on the product's life, which differs to that of nutrients in WWTPs. This in particular, is a challenge when the majority of CE studies have disproportionately focused on products and energy recoveries by extending the useful life of products and value-adding by upcycling and downcycling materials, while WWTP CE studies should place importance on the purity, safety and high efficiencies on nutrient resource recoveries from wastewater.

2.1. *Circular economy in wastewater*

WWTPs have orthodoxically been seen as centres for wastewater treatment and disposal into the environment, though, there is now renewed research focus and push towards retrofitting and converting current WWTPs into nutrient and energy recovery centres – closing the loop between farmlands and wastewater (Fig. 2). To a newer extent, CE is a recent area of application for WWTPs. Currently, it is possible for WWTPs to conduct nutrient recovery for fertilisers [28], energy recovery in the form of biogases [29–34] and production using microalgae [35–40], electricity from microbial fuel cells (MFC) [41–43], hydrogen generation [44–49], and even simultaneous carbon capture for biomass growth and energy through bacteria [50–52]. Renewable energy sources have also been coupled with these technologies during the nutrient and energy recovery process [53]. Other useful resources that can be recovered from wastewater include phosphorous, potassium, nitrogen and organic fatty acids [28]. Meanwhile, non-nutrient resources that are used in chemical manufacturing processes have been proposed as recoverable from wastewater such as organic solvents or acids [54] and

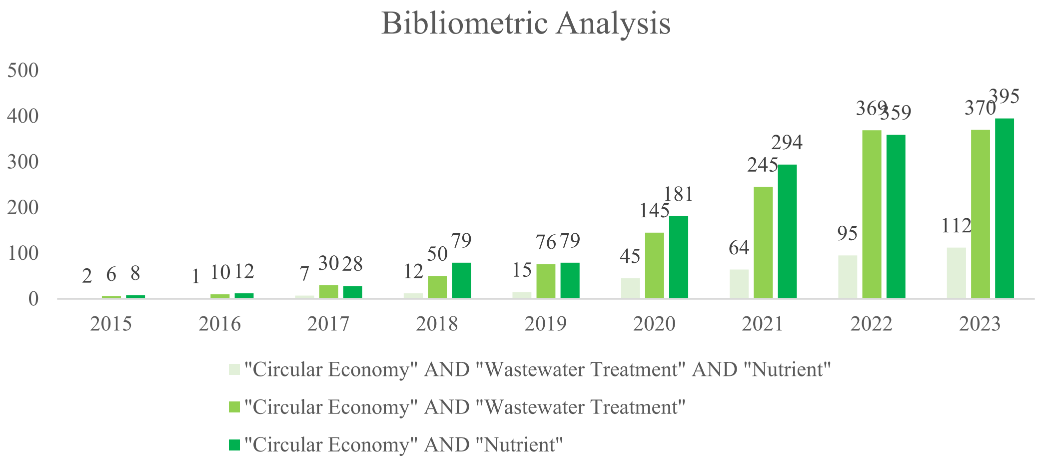

Fig. 1. Bibliometrics Assessment of the circular economy research for nutrients and wastewater using SCOPUS.

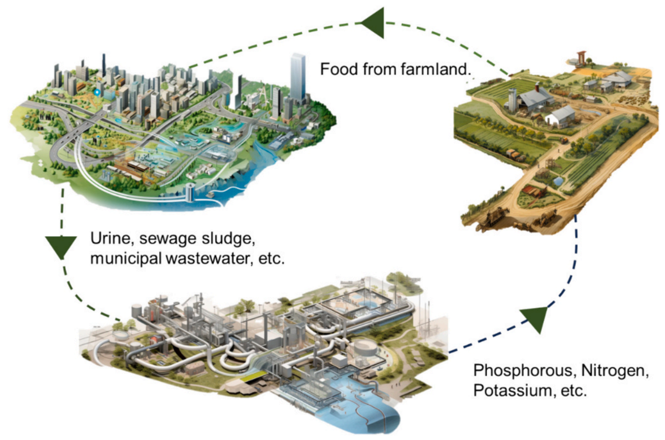

Fig. 2. The nutrient CE being closed, where society generates waste through wastewater, is collected in WWTPs which recovers the nutrients, reuses those nutrients for the growth of crops, and these crops are then sold to communities or livestock herders.

bioplastics [40,55,56]. The underpinning principles for CE WWTP are reductions in new water consumption, reclamation or removal of harmful pollutants or nutrients from the environments, reuse, recycling of water and recovery of nutrients, and public acceptance and education [57,58]. There are complementary, sustainable benefits to the use of CE besides resource and energy reuse - which is the reduction in GHG emissions [59–62] and environmental pollution from improperly treated wastewater effluent [63,64]. Studies have examined the use of microalgae carbon capture technologies to provide cost relief and value-added products [60], while microbial technologies increasingly play an important role in the recovery of nutrients, energy and minimisation of CO_2 emissions [34,65] and could be used to treat wastewater to EU Regulations [39]. The behavioural dynamics of bacteria, viruses, and other microorganisms in the AD process varies and requires high levels of genomic identification and tracking in order to reliably engage CE-metrics [65]. Larger organisms, such as wetland macrophytes, can be used to remove nutrients from water bodies before discharging into the environment – creating valuable products such as animal feed, biochar, biofuel, fertilisers and adsorbents used in the CE cycle while minimising eutrophication [66–68] and driving phytoremediation efforts of decontaminating wastewater for CE [38,69,70]. Both macro- and micro-organisms have roles to play in the conversion of wastewater elements into valuable inputs within the CE, despite the varied performances. CE WWTPs combine macro- and micro-organisms, mechanical, thermal, and chemical processes to function, however, CE systems generally require external power sources to operate and hence, renewable power sources have been studied to lower on-grid energy consumption [71,72].

2.2. Drivers and barriers to circular economy WWTP

CE WWTP introduces many opportunities for resource recovery commercialisation and there are plenty of drivers including: fertiliser and water scarcity driving prices up, policies favouring CE technologies, commercial energy demand for operation and recovery, scarcity of materials, simultaneous treatment and removal of harmful chemicals and particulates from effluents, energy and nutrient recovery to offset plant operating costs, meeting emissions targets, reducing chemical fertiliser use and Haber-Bosch nitrogen production, water reuse in droughts, retrofitting options, nutrient reapplication for agrifood, micropollutant and toxin removal, digital technologies and materials recovery [28,58,73–85]. Methodologically, lean approaches [86], sustainability weightings [87], machine learning [88] and hybridisation [63,89–95]. While technologies are a driver for the expedition of CE WWTPs, there are also institutional and governance drivers towards WWTP CE. Several directives from the EU have aimed to regulate sewage sludge management (Council Directive 86/278/EEC [96]); water treatment from WWTPs (Council Directive 91/271/EEC [97]); and phosphorous nutrient recovery (currently in force with Council Directive UWWTD 91/271 [98,99]).

Other barriers to CE implementation for WWTPs include poor policy, lack of regulation and stakeholder integration, the need for public acceptance, incompatible business models for WWTP companies, financial barriers or emphasis on short-term gains, poor education, partnerships, poor scaling up, improper market product-fit, rigidity of linear economies of operation embedded throughout WWTPs, lack of enforcement or governance, high investment and operating costs, uncertainties surrounding profit and sustainability impacts, poor governance and institutional frameworks, poor training, emerging technology status, lack of waste source separation, poorer countries prioritising water sanitation, poor CE fertiliser grade or quality, and low social acceptance [40,73–75,100–110]. While technically, P-recovery rates could reach 90 % for some processes [3], the cost of struvite for example, is generally higher than that of phosphate rock and superphosphate that is mined, which are also sensitive to changes in market commodity prices [63,76].

3. A framework for wastewater

3.1. Analysis

Articles were mined from Scopus and Web of Science for research relating to policy and framework perspectives on current CE practices across WWTPs. The duplicates were then removed by RStudio to give the list of nutrient CE WWTP articles dealing with frameworks and policies for WWTPs (Fig. 3). VOS Viewer was also used for Web of Science (Fig. 4) - given its higher quantity and saturation of articles – were able to provide a good visualisation of the CE WWTP topics connected to each other and the frequency of citations for the interrelated areas of research. The most commonly studied articles (see Table 1) show the list of journals and by citation count on research papers commencing from the year 2017. Science of the Total Environment – a journal specialising in the environmental conservation efforts for pollution prevention, climate change mitigation and water quality - had the highest WWTP citation counts for CE practices in the RStudio processed list of articles. This was then followed by the Journal for Sustainability, Journal of Environmental Management, and Bioresource Technologies. Therefore, recent CE WWTP studies have sought to advance an understanding of the impacts WWTPs have on societies and populations, and in particular from that of nutrient contamination and recovery [111]. Despite pushes from the EU to improve water circularity, only three articles from the bibliometric analysis obtained three publications in the Water journal. The assessment of key terms and their relationships from the Web of Science shows that regulatory, transitional, challenges and opportunities, and phosphorous management are highly popular in the CE WWTP nutrient space. Meanwhile, technology applications, development, nutrient recoveries remain heavily underappreciated given the criticality of fertilisers.

Table 2 considers the word counts of keywords from the research articles with the duplicates removed. The key terms circular and economy are obvious, while other areas surrounding energy, management, water, phosphorous, reuse, microalgae, AD, sustainability and assessments are other descending terms of popularity for these CE framework, regulatory and policy-driven papers. From these recent pieces of research, it is becoming paramount that CE frameworks are beginning to factor in other valuable products that are recovered along the process of nutrient wastewater recovery practices.

3.2. Indicators for a circular economy WWTP

Several metrics were considered by authors within CE framework

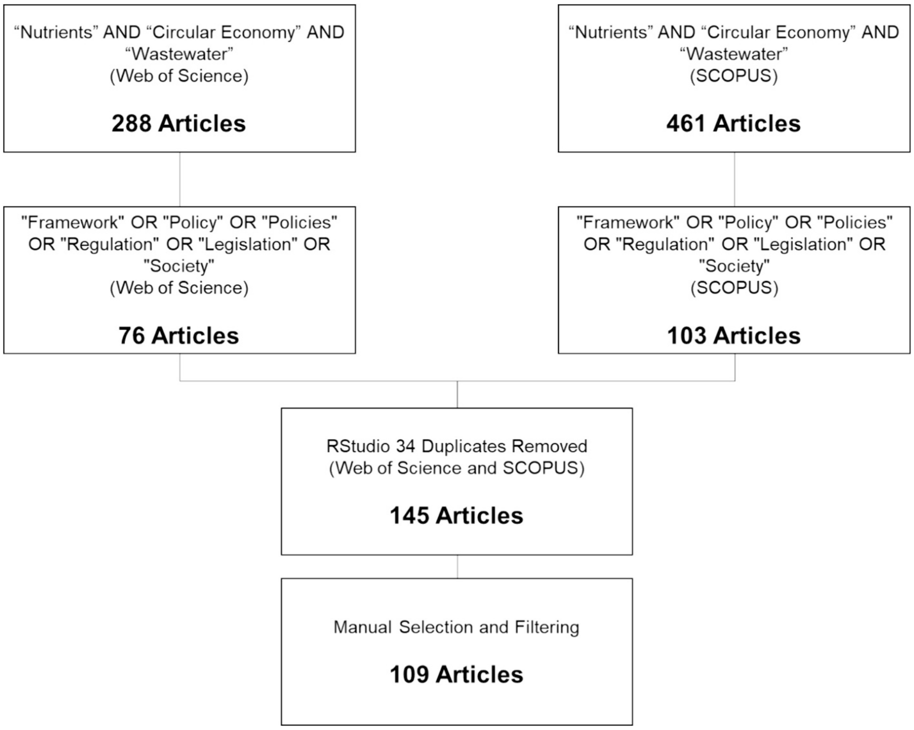

Fig. 3. Bibliometric analysis and filtering for articles relevant to policies, frameworks, circular economies and nutrients.

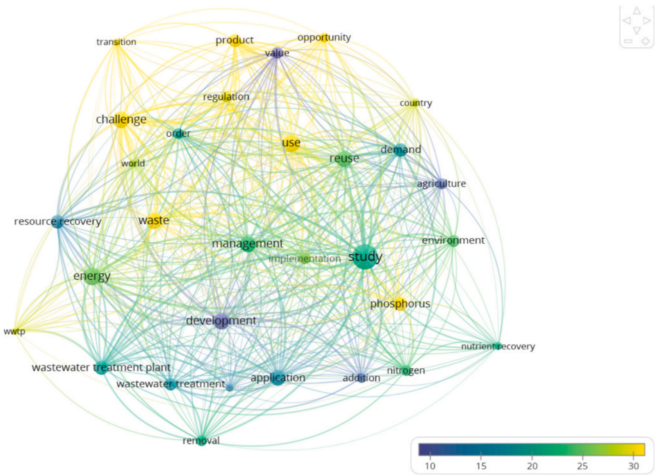

Fig. 4. Number of citations by colour code legend, articles obtained from Web of Science.

Table 1
Journal publications count through the refined keywords.

Journals	Count on publications since 2017 based on refined keywords
Science of the Total Environment	14
Sustainability	9
Journal of Environmental Management	7
Bioresource Technologies	6
Energies	3
Adv. Sci. Technol. Innov.	3
Water	3

Table 2
Keyword counts for the RStudio formatted bibliometric analysis.

Word	Keyword counts since 2017
Circular	84
Economy	83
Wastewater	83
Recovery	62
Treatment	42
Nutrient + Nutrients	39
Water	28
Sludge	27
Reuse	27
Resource	25
Waste	22
Phosphorus	22
Sewage	18
Management	17
Energy	15
Anaerobic	15
Microalgae	14
Digestion	14
Assessment	13
Sustainability	12
Nitrogen	10
Analysis	10

studies; however, these metrics are widely not applicable for the recovery of chemicals and nutrients from wastewater. For example, Number of Times of Use of a Material (NTUM) from Matsuno et al. [112], Product-Level Circularity Metric (economic value of recirculated parts/economic value of all parts) [113], longevity indicator [114], circular performance indicator (CPI, recycled mass over virgin mass material) [115], Linearity Indicator [116] and Material Circularity Indicator (MCI) [117] are all incompatible for nutrient WWTP CE given the emphasis on plastics and other material recovery efforts. Other CE indicators have considered the environmental and energetic footprints for reusability, recyclability and recoverability [118,119]. Given these studies, CE WWTP lacks considerable metrics tailored for nutrient and chemical circularity. For example, in Elia et al. [118] and the EMF

[120], the cost of manufacturing for a product with higher longevity and durability increases, by contrast, higher purities of WWTP nutrient recoveries add costs from the extra processes required to achieve these grades. For example, the addition of pretreatment [121], post-treatment [122] and post-processing technologies. Cost rises proportionally for durability in product CE, for WWTP CE, it is the purity of the recovered nutrient. Immediately, conventional product CE doctrine differs to that of WWTP CE.

Preisner et al. [87] listed a set of WWTP indicators that encompassed metal, nutrient, energy and water recoveries. The indicators for effective WWTP CE examined the use of chemicals to recover valuable nutrients, reuse rates for fertilisers and removal of toxins. The proposed final WWTP Circularity Indicator in Eq. (25) combines the recovery rates of nutrients, water, energy and organic matter. Interestingly, certain heavy metal recoveries have been experimented in other papers [123–125] which could have further expanded the indicator's coverage, but was not included in the author's paper [87]. Table 3 also combined with other relevant indicators from other works [126,127].

3.3. *Other wastewater treatment frameworks*

Smol et al. [128] proposed a framework for the CE model of WWTPs in the European Union. Directives were laid out by the European Commissions (EC) to integrate energy, nutrient, raw material, water and emissions reduction; however, this research paper lacks the emphasis on recovering nutrients from wastewater streams. The framework – while influenced by the EMF ReSOLVE framework [129,130] - focuses on the reduce, removal, reuse, recycling and recovery, but does acknowledge the recovery of nitrogen and phosphorous from sewage sludge [128]. Waste recoveries from wastewater extend to include pure urine, agricultural, industrial and greywater types; while the more nutritious waste types come from blackwater and sewage sludge. The lack of source-separation infrastructure makes the treatment of pure urine rare across the planet among WWTPs, however, there are technologies such as AD and struvite precipitation for sewage sludge which can extract valuable N-P-K [131–133], although, continuous stirring tank reactors and fluidised bed reactors were known to be effective technologies for P-precipitation of struvite [134]. These frameworks are developed to minimise the significant quantities of water wasted in the treatment and recovery processes to address the United Nations Sustainable Development Goal (UN SDG) 6, while nutrient and energy recoveries tend to act as auxiliary resources recoverable. However, the EC recently proposed a set of legislative set of principles to address nutrient critical raw material shortages by mandating that a certain quota of domestic production be met for the extraction, processing, recycling of materials and that no more than 65 % of a critical raw material be imported from a single country [135]. Given the criticality and scarcity of phosphorous across Europe, WWTP CE frameworks should be expanded beyond meeting UN SDGs, and to ensure the minimisation of phosphate rock mining. In the latest 2016/2019 review for the Fertilising Products Regulation from the EC, sourcing domestic nutrients from waste was a major focus for fertiliser CE in improving food security [136,137]. Frameworks for CE WWTPs need to tie in the recovery nutrients, energy and water with the available technologies [78,80], while the EC has yet to provide a framework that holistically integrates these resources for CE WWTP. Toxins in wastewater must also be removed such as traces of active pharmaceutical ingredients, heavy metals and other industrial chemicals that may pollute sewage waterways to ensure that the recovered resource does not harm the population.

When applying the 10R principles seen in Fig. 5, authors sought to focus on the products recovered as a litmus for the effectiveness of the CE framework, however, these studies ignore the lifecycle of the WWTP. To seriously consider CE for WWTPs: nutrients, energy, materials, water, and the plant itself must all be considered for a sustainable CE WWTP. The effective operating lifespan of a WWTP is somewhere between 15 and 20 years [138,139] limited by the equipment used, and up to 50 years before upgrades are required [140]. Given that many WWTPs have been established since the 1970s, their lifespans are nearing its end, requiring many upgrades and retrofits to make it more sustainable [141]. Therefore, the 10R principles need to be adapted to suit the upgrades of aging WWTPs. Studies have begun looking at making the plant components themselves highly sustainable such as that of membranes [142].

3.3.1. *Current directives or regulations for CE WWTPs*

The EU is pioneering the advancement of CE frameworks as part of the EU Green New Deal. Currently, the EU is proposing a Waste Management Framework geared mostly towards the recycling and reuse of food waste and textiles [143], and proposals are underway for the introduction of circular principles into the Directive 91/271/EEC concerning urban waste water treatment [144] and among others in Table 4. The reforms address the lack of harmonisation in circular recovery practices throughout the EU. Other reforms have come into focus such as the Critical Raw Materials Act 2023, Net Zero Industry Act 2023, and Soil Strategy 2030 which acknowledge the finite quantities of phosphorous and fertile soil and combining it to meet net-zero emissions. The new proposed CE Action Plan carefully considers the inclusion of businesses and civil societies in the implementation of CE frameworks across the EU [145]. According to the report [145], biomass contributes significantly to the global impact for water stress and habitat loss. Given that EU frameworks stress the need to conserve water, addressing water inefficiencies or recyclability are also key priorities coinciding with the recovery of nutrients from wastewater. The CE Action Plan acknowledges financial investment barriers and the need to expand international partnerships to countries like China, India and the continent of Africa. However, there are drawbacks to the interpretation of nutrient CE throughout the EU, for example, incineration as a destructive process once implemented, may prevent some EU nations from realising the full potential of nutrient CE [146], and different countries will have their own technologies and regulations on the interpretation and treatment of wastewater.

3.3.2. *Operating principles of the WWTP*

Conventional WWTPs remove nutrients from wastewater before it is safely discharged back into the environment. Current WWTP technologies aim to use sludge that is activated with bacteria to consume and reduce the nutrients in wastewater down to an acceptable level for discharge. Waste activated sludge and membrane bioreactors (MBR) are some of the most common ways of reducing nutrient loads within wastewater which are widely adopted throughout municipal WWTPs, and there are methods to recover nutrients from MBRs with source separated urines [161,162]. Fig. 6 shows the conventional and integrated CE pathways for municipal WWTPs. These technologies only remove and do not recover nutrients however.

The primary treatment stages of WWTPs remove grit, sediments and other large objects. The secondary treatment phases treat the wastewater streams by removing nutrients using microbes and bacteria. Sewage sludge is collected from the clarifiers which are then treated and disposed of in landfills, however, this sludge can be recovered for AD to generate biogases and recover nutrients. These nutrients exist in the form of biosolids that are generally rendered safe for agricultural land applications, however, the EU has made restrictions on its applications for edible, root-based plants [155], due to concerns regarding the presence of heavy metals and toxins in contact with the produce. The discharge of effluents into the environments presents the most wasteful, for example, the United Nations reports that only 11 % of the world's wastewater is recycled while more than 50 % is discharged into the environment [163]. Furthermore, 80 % of the world's sewage is discharged into the environment untreated [164], and within the EU-27 alone, sewage sludge production is approximately 10 million tonnes [165]. In Europe and North America, about 50 % of WWTP sewage sludge is reapplied onto farmlands [166] and 27 % is incinerated within

Table 3
List of CE WWTP indicators used by the authors.

Formula name	Formula	Description	Eqn
Wastewater service coverage indicator	$\frac{n_{connected}}{n_{total}} \cdot 100\%$	$n_{connected}$ is the number of connected households to sewage system (capita/km^2), n_{total} Number of total households (capita/km^2)	(1)
Nutrient removal efficiency indicator	$\frac{C_{iX} - C_{eX}}{C_{iX}} \cdot 100\%$	Where C_{iX} is the total nutrient content in mg/l in wastewater, C_{eX} is the total content in the treated wastewater in mg/l.	(2)
Organic matter removal efficiency indicator	$\frac{Q_w \left(COD_{inf} - COD_{eff} \right)}{10^6}$	Q_w is the wastewater flow rate in m^3/day, COD_{in} and COD_{out} is the chemical oxygen demand for influent and effluent respectively.	(3)
Sewage sludge processing indicators	–	Applied in land reclamation [Mg/year] or [%]	(4)
	–	Applied in land reclamation [Mg/year] or [%]	(5)
	–	Applied in cultivation of plants intended for compost production [Mg/year] or [%]	(6)
	–	Applied in cultivation of energy plants [Mg/year] or [%], anaerobically digested [Mg/year] or [%]	(7)
	–	Applied as an alternative fuel in cement plants [Mg/year] or [%], incinerated [Mg/year] or [%], landfilled [Mg/year] or [%], stored at the WWTPs [Mg/year] or [%].	(8)
Treated wastewater recovery indicator for irrigation	$I_{wr} = \frac{Q_{ir}}{Q_{ef}} \cdot 100\%$	Q_{ir} is the treated wastewater flow reused for irrigation [m^3/year], and Q_{ef} – total effluent flow [m^3/year].	(9)
Effluent inorganic content indicator	$I_{EIC(X)} = X_i \cdot Q_d$	Where X is the nutrient (N, P or similar) and Q_d is the daily effluent flow rate (l/day).	(10)
Nutrient recovery indicator	$I_{rec(X)} = \frac{\left(X_{initial} - X_{final} \right)}{X_{initial}} \cdot 100\%$	Where X is the nutrient (N, P or similar) content measured in Mg/year.	(11)
Biological dephosphatation potential indicator	$I_{BDP} = \frac{COD}{TP}$	COD is the chemical oxygen demand (mg/l) and TP is the total phosphorous (mg/l).	(12)
The technological nutrient performance indicator for the recovered sludge	$I_{SG,TN} = \frac{m_{sg,x}}{Q_{PMW}}$ $I_{SG,ce,p} = I_{SG,TN} \cdot \frac{m_{sg,x}}{Q_{PMW}} \cdot 100\%$	$m_{sg,x}$ is the mass of sewage sludge recovered (Mg/year), Q_{PMW} is the wastewater flowrate of a papermill (m^3/year), P_p = mass of the phosphorous product produced using recovered material (Mg/year), $I_{SG,\ ce,p}$ = is the productive sludge generation indicator.	(13)
Composting indicator for sewage sludge	$I_{c,ss} = \frac{m_{BW}}{m_{bio}} \cdot 100\%$	m_{BW} is the mass of biodegradable waste for composting (Mg/year) and m_{bio} is the total amount of biodegradable waste (Mg/year).	(14)
Pollutant content indicator for the recovered sewage sludge	$I_{b,ss} = \frac{Q_b}{m_{bio}}$	Qb is the biogas obtained from AD of sewage sludge (m^3/year) and m_{bio} is the total amount of biodegradable waste (Mg/year).	(15)
Pollutant content indicator for the recovered sewage sludge	$I_{CSUP} = \frac{\sum_{i=1}^{n} \frac{C_i}{C_i^{ref}}}{P_{concentration}}$	C_i is the concentration of heavy metal in recovered material, C_i^{ref} is the concentration of heavy metal in original reference material.	(16)
Quality indicators for SSA recovery	$I_{MER} = \frac{C_{Fe} + C_{A1} + C_{Mg}}{C_{P_2O_5}}$	C and the corresponding subscript chemical symbols are measured with mg/kg. I_{MER} is the minor element indicator. This equation can further be manipulated to compare ratios of heavy metal contents to nutrients.	(17)
Indicator for chemicals used for wastewater treatment	$I = \frac{Q_{non-chem}}{Q_W} \frac{Q_{support-chem}}{Q_W} \frac{Q_{pure-chem}}{Q_W}$	$Q_{non\text{-}chem}$ is the wastewater treated without the use of chemicals for P removal, $Q_{supp\text{-}chem}$ is the wastewater treated with partial chemicals for P removal, Qpure-chem is P removal using only chemical methods, and Qw is the total flow rate of the wastewater. All values denoted in (m^3/day).	(18)
Biobased Fertilisers (BBF)	$I_{BBF} = \frac{X_{BBF}}{X_{CF}}$	X_{BBF} is the nutrient content measured in mg/kg, and X_{CF} is the corresponding nutrient content present in conventional fertilisers mg/kg (for example, for N and P).	(19)
Hydrochar yield indicator for hydrothermal carbonization of sewage sludge	$I_{y,hydrochar} = \frac{M_{hydrochar,dry}}{M_{sludge,dry}}$	$M_{hydrochar,dry}$ is the dry mass of obtained hydrochar (Mg/year) and $M_{sludge,dry}$ is the dry mass of the used sewage sludge (Mg/year).	(20)
WWTP Circularity Indicator	$I_{CE,RR,WWTP} = \frac{I_{Nutrients} + I_{Organic\ Matter} + I_{Water} + I_{Energy}}{n}$	$I_{Nutrients}$ is the recovery rate in % recovered nutrients, $I_{Organic\ Matter}$ is the organic matter recovery rate in %, IWater is the recovery rate of water in % used for agriculture, IEnergy is the ratio percentage of energy production to energy consumption, and n is the number of indicators.	(21)
Technological nutrient performance indicator for water	$I_{W,TN} = \frac{Q_{EF}}{Q_{PMW}}$	Q_{EF} is the effluent flow rate of the treated wastewater with nutrients recovered and Q_{PMW} is the total volumetric flow rate of the wastewater. Q can also be replaced with sewage sludge.	(22)
Circular economy efficiency for water	$I_{W,CE,r} = \frac{Q_{EF}}{Q_{W,T}} \cdot 100$	Q_{EF} is the effluent flow rate of the treated wastewater with nutrients recovered and $Q_{W,T}$ is the total volume of water consumed throughout the process. Q can also be replaced with sewage sludge.	(23)
Technological nutrient performance for the recovered sludge	$I_{SG,TN} = \frac{m_{SG,R}}{Q_{PMW}}$	$m_{SG,R}$ is the mass flow rate of the recovered sewage sludge.	(24)
Circular economy efficiency for sludge	$I_{SG,CE,r} = \frac{m_{SG,R}}{m_{SG,T}} \cdot 100$	$m_{SG,T}$ is the mass flow generated by the sewage sludge in the production process. $I_{SG,\ CE,\ r}$ is the sewage sludge recovered during the production process compared to the total sludge produced throughout.	(25)
	$I_{SG,CE,P} = I_{SG,TN} \cdot \frac{Q_{PMW}}{P_P}$	$I_{SG,\ CE,\ P}$ is the sewage sludge recovered during the production process.	(26)
Circular economy efficiency for water	$I_{W,CE,P} = I_{W,TN} \cdot \frac{Q_{PMW}}{P_P}$	$I_{W,\ CE,\ P}$ is the water recovered during the production process.	(27)
Biofertiliser efficiencies	$I_{Biofertiliser} = \frac{\sum m_{biofertiliser}}{m_{slurry}}$	$M_{biofertiliser}$ is the mass of the recovered and generated fertiliser from the sludge (grams), and m_{slurry} is the mass of recovered slurry (grams). $I_{Biofertiliser}$ is the performance of the biofertiliser recovery system.	(28)
Recovery rates of nutrients	$R(\%) = \frac{1 - C_f}{C_0} \cdot 100$	C_f is the final concentration of the nutrient and C_0 is the initial concentration of the nutrient.	(29)
Fertiliser requirements	$\frac{Recommended\ dose}{\%Nutrient\ content\ in\ fertiliser} \cdot 100 \cdot Area$	Measures the grade of the fertiliser, within the CE context, this is the nutrient concentration of the recovered sludge. Area is in km^2.	(30)

Nutrients	Refuse	Refuse WWTP technologies that do not recover nutrients.
	Rethink	Rethink WWTPs as resource recovery centres.
	Reduce	Reduce the consumption of virgin nutrients.
	Reuse	Reuse nutrients and human waste for further applications.
WWTP	Repair	Repair WWTP components and processes.
	Refurbish	Refurbish plant components to extend operating life.
	Remanufacture	Remanufacture technologies for better nutrient recoveries.
	Repurpose	Repurpose existing WWTP technologies for recoveries.
Nutrients	Recycle	Recycle WWTP and nutritious influents for other applications.
	Recover	Recover nutrients and complimentary useful products (i.e. energy).

Fig. 5. 10R principles for CE adapted to CE WWTP.

the EU [167]. The application of CE AD processes for the pig farming industry in one study saw water and natural gas consumptions reduced by 47.01 % and 5.33 % respectively [168]. There is therefore, potential for WWTPs to provide nutrient, water and energy savings. Given that the housing sector worldwide accounts for 50 % of wastewater generation, 50 % of energy consumption, and a third of all global waste [169], connecting residential properties to CE WWTPs is a challenge given the legacy infrastructure which makes it impossible to integrate urine source-separation and other technologies incompatible with current hardwired plumbing systems [170].

3.3.3. *CE framework for WWTPs*

Currently, the EU plans on achieving full circularity on material consumption [209] in line with its climate neutrality goals. There are material, waste and energy considerations for WWTP CE [210]. Currently, the Netherlands, Switzerland and Germany have more than 95 % of its domestic wastewater safely treated by WWTPs [211]. Even within the Netherlands, struvite adoption as fertiliser was primarily hampered by its legislative classification as waste rather than a valuable fertiliser – only now making up less than 1 % of the total fertiliser market domestically [171]. It was only recently that the EU began adding struvite as an acceptable fertiliser from July 2022 with amendments to Regulation 2019/1009 [172], and definitions to what constitutes as ‘waste’ is still ongoing [146]. The barriers for nutrient CE are primarily legal, political, technological, economic and social, given the widespread doctrine of using WWTPs for treating and removing human waste rather than as resource recovery centres. The emerging status of converting current infrastructure through pilot programs are also evident [173], especially throughout the EU such as HOUSEFUL [169], Phos4You [174], SUSKULT WWTP NEWtrient®-Center [9]; INFEWS in the United States [175]; Singapore's Phos4SG PUB Project Challenge [176] and NEWater [177]; councils such as the Phosphorus Recycling Promotion Council of Japan [178], and so on.

Microalgae and macroalgae have been explored for energy, nutrient and materials recovery while cutting down emissions and plastics using wastewater [56,68,179–183], however, microalgae was found to be unsustainable in the production of biofuels [67] but on the contrary, quite efficient in the production of bioplastics [184]. Meanwhile, there is potential for reuse of wastewater from WWTP for urban hydroponic farming applications [185], however these studies have found that there are still nutrient deficiencies in the CE-grown produce [185,186]. This is one of the prevailing barriers to the commercialisation of CE fertiliser among the agribusiness space, as technology development alone will not suffice without including investors and beneficiaries to the CE program who can monetise and consume commercially acceptable products [187].

Bottom-up approaches have been proposed for the success in CE adoption given the localised, participatory nature of this framework for all stakeholders, and that centralised approaches are prone to exclusion against small communities [9,188,189]. Participation by communities, particularly through urine-reuse reclamation programs, ring paradoxically with both cynicism and support in closing the nutrient loop [175], ranging from harm to human health and the detriment that urine-derived nutrients have on perceptions of farmers and consumers who consume it.

Environmental impacts that WWTPs have on the broader environments with P-eutrophication needs to be addressed [190]. It costs approximately $222.9 billion globally to repair damages caused by nutrient leakages into the environment from improper wastewater treatment [191]. The removal of nutrients is highly cost, energetic,

Table 4
List of directives and regulations from the EU for WWTP and waste management.

European Union CE Motions		
Regulation/Directive/Legislation	Description	Source
Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products (EU) 2019/1009 Amends: (EC) No 1069/2009 and (EC) No 1107/2009. Repealed: (EC) No 2003/2003	Standards on contaminants, pathogens, minimum nutrient concentrations, inhibitors, polymers, bio stimulants, assigned tolerances on contaminants and nutrients, labelling and documentation, detonation tests, and compost regulating. Repeal (EC) No 2003/2003 as it did not prevent the spread of non-harmonised CE fertilisers.	[147]
Council Directive 91/271/EEC concerning urban waste water treatment	Regulates effluent discharge into the environment.	[148]
Recast Urban Wastewater Treatment Directive adopted from April 2024	Introduce circularity into wastewater practices, with a focus on water reuse.	[144]
Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption Amended by: Commission Directive (EU) 2015/1787 of 6 October 2015	Governs the quality of water for human consumption.	[149] Amended by: [150]
Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources Amended by: Regulation (EC) No 1137/2008 Regulation (EC) No 1882/2003	Regulates nitrate pollution being leaked out into the environment.	[151]
Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy	Conservation of groundwater and surface water acknowledging its scarcity and need for conservation.	[152]
Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Amended by: (EU) Commission Directive 2017/845 from 17th of May 2017	Protection of marine environment to preserve biodiversity and prevent eutrophication.	[153]
Critical Raw Materials Act 2023	Phosphorous identified as a critical element in the list. Assigns quota quantities to domestic production of critical raw materials throughout the EU in each process. Stakeholder engagement, supply chain self-sufficiencies, circularity and sustainability principles incorporated, workforce reskilling, climate change, indigenous protections, GHG footprint, technology support, transparency, impact assessments, policy framing, budgetary support, risk management, measurement systems, partnerships management, and political structure of governing bodies.	[154]
Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture Amended by: (EU) 2019/1010 EU Parliament 5th of June 2019.	Governs contaminants of heavy metals and soil applications by use of sewage sludge, prohibitions of sludge contact in soil with fruits and vegetables or otherwise specified, sludge and soil analysis methods.	[155]
Net Zero Industry Act 2023	Investment areas, simplifying administrative burdens for manufacturing, drive public support and participation through schemes across procurement, sandbox testing, skills training for net-zero, carbon capture project facilitation and partnerships development.	[156]
Proposal for a Directive on Soil Monitoring and Resilience (Soil Monitoring Law)	Proposal document as part of Soil Strategy 2030 to preserve soil fertility for food production, decrease presence of microplastics in sewage sludge on soil, and development of clean circular bioeconomies.	
(Working Document) Measuring progress towards circular economy in the European Union – Key indicators for a revised monitoring framework	Proposes a circular economy monitoring framework on material recycling rates, waste generation, material footprint, green procurement, investment in jobs and CE sectors, GHG emissions, imports and exports of CE materials, innovation, raw material self-sufficiency, CE resilience and sustainability.	[157]
(Working Document) THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on a revised monitoring framework for the circular economy	Resource productivity, GHG emissions, material dependencies and footprints. Indicators were covered for this: waste generation, recycling rates, investment into green innovation, CE resilience and sustainability, trade in secondary raw materials and recycled material contributions and material consumption.	[158]
Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste Amended by: (EU) 1357/2014; (EU) 2015/1127; (EU) 2017/997; (EU) 2018/851.	Amends the waste directive to factor in CE goals. Factors in Raw Materials Initiative, introduce quota percentages for recycling rates by weight for waste management facilities, and holding accountable the European Environment Agency for reviewing member state's CE performance every two years.	[159,160]

chemically intensive, while climate neutrality goals require these technologies to simultaneously capture carbon and produce energy [192]. Microalgae is one solution to treat wastewater for irrigation that meet standards in Regulations (EU) 2020/741 [181] and 91/271 [39], however, it remains an emerging method [193]. In countries like Switzerland, P-recovery is mandatory [194], meanwhile, in California,

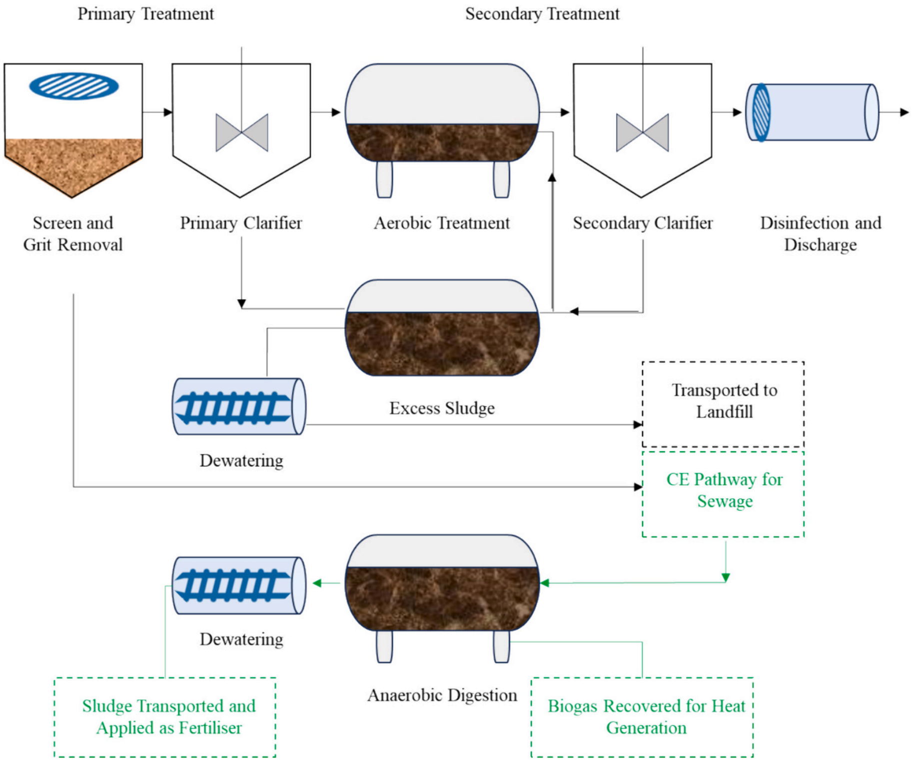

Fig. 6. Conventional and CE Pathways for WWTPs. In a conventional WWTP the sludge is disposed of in landfills and the water treated and discharged into the environment. Integrating CE, the sludge is recovered for both nutrients and biogases.

disposal of organic waste in landfills is prohibited [146,195]. However, regulatory strengths in the EU for treated wastewater irrigation via fertigation varies from country to country [196] and is made more difficult by the ever-changing standards and regulations [197], therefore, regional fragmentation and transitional nature in regulatory strengths, concepts and practices makes CE implementation difficult. Preisner et al. [198] found that not all 15 member EU states achieved acceptable nutrient loading removal rates, and this was exacerbated by the difficulties in nation-specific regulations on wastewater treatment, failure to consider eutrophication, bioavailability and nutritional criticalities.

Various methodologies have been proposed to evaluate the environmental impacts that CE has [199]. Water scarcity is the central theme in the nutrient CE paradigm which factors in drought and flood disasters as part of food supply resilience [81,196]. Lifecycle assessments such as ReCiPe have been used to assess the depletion of resources and GHG emissions from the CE process [200]. Frameworks to transition WWTP towards P-circularity by involving the meso, micro and macro stakeholders with WWTPs to overcome systemic and technical lock-ins, are needed to consider all of the stakeholder's interests. Nutrient profiles could be mapped to identify misallocated and displaced nutrients from areas where they are needed [201], indicating that there is potential for improved management and distribution of nutrients into areas with higher crop productivity. However, the study [201] does not consider the logistical costs of reallocating nutrients into more population-dense or crop-productive areas or the use of chemical fertilisers – an issue raised in another study [202]. The SWAT model can also be applied to simulate the natural flow of nutrients from rainfalls, and how it may impact sowing practices and timing among farmers [203]. Therefore, LCA and model assessments of nutrient and pollution flows will need to be factored into frameworks to assess impacted CE stakeholders.

Irrigation from wastewater effluents was proposed as a water-reuse method of circumventing issues relating to nutrient pollution and water wastage by dosing low quantities of N and P for crop fertigation, although, there are risks towards polluting groundwater systems through salinisation, alkalinisation and soil degradation [58,187,196,204], and benefits such as GHG emissions reduction via fertiliser substitution [111,205]. Fertigation themes have centred around cutting down water consumption given that farming practices consume approximately 70 % of the global freshwater supply [58,206]. Accordingly, there is a need to move from removal to recovery among WWTPs to minimise its treatment energy consumption and realise its full potential for cutting down fertiliser costs [58,111,207]. Additionally, some LCA studies do not consider the use of recovered products and social dimensions of the studies [207].

The application of recovered biosolids and treated effluents for fertigation have soil remediation properties that can reverse soil degradation and reduce landfilling [208,209]. ReCiPe LCA approaches that meet the ISO 14044 lifecycle standard [200], have been used to ensure landfill reapplications of sewage sludge are safe, and have even been combined with ML [210]. While other LCA studies have sought to include ponds and water bodies for remediation or restoration [211], or penalties from non-compliant effluent discharging, controls on contaminants, transportation costs and pipelines [212]. Regardless of which LCA is used, the impacts of nutrient reuse on the environment should be factored in.

3.3.4. CE WWTP technologies available

Nutrient recoveries recovery focuses will be on phosphorous and nitrogen, and different technologies will be chosen depending on the concentration efficacy of these nutrients. Technology CE selection would factor in social issues covering water security, energy security, food security, technology adoption, acceptance and human health [58]. These difficulties are compounded by the specific types of P recoverable [213], purity needed [214], primarily in the form of struvite [213,215]. Meanwhile, the EU Green Innovation Deal sees great potential in using AnMBR as an effective [216,217] and compliant [218] technology. Therefore, the most promising sources of P will come from wastewater, sludge and sewage sludge ash [62,219,220].

One of the significant barriers to P-recovery are chemical [221] and energy costs [222]. For example, it is estimated that the cost to recover P is around €6 to €10 per kg recovered [221]. The profit margins from P-recoveries are extremely small, and there exists weak economic, demand-driven reasons for P-recovery [223], moreover, it is difficult to determine the true operating costs given the emerging status of nutrient CE technologies [209,224], and the lag period that exists for benefits to be realised [199]. Given that there are more than 30 P-recovery technologies [219], and more than 24 decision support tools for its selection [225], it becomes difficult and cumbersome to identify the best solution for a given WWTP [219], or avoid biases through policy incentives [226]. Technological Readiness Levels, Lifecycle assessments (LCA) and Material Flow Analysis (MFA), emergy analysis, Input-Output analysis are effective starting points for CE framework formulations at the macro scale [28,227,228] that also need to be compliant [58,229]. For example, 3 out of the 24 CE WWTPs in the EU failed to meet regulations [171].

Technology applications will depend on the type of influents and products produced from recoveries. For example, nutrient recoveries for biosolid slow-release fertilisers can use crystallisation and electrodialysis, pure substances through ammonia stripping, gas permeable membranes, electrochemical [230] and bioelectrochemical systems [82], or face limitations such as the inability to separate heavy metals from valuable waste seen in microalgae and photosynthetic bacteria [105,179,231] which can prevent its selection. Cost is another barrier to the implementation of CE WWTP technologies, given the debate between centralised and decentralised CE WWTPs - both have their pros and cons. For example, the high treatment coverage and cost effectiveness from centralised WWTPs [232], and the high transportation costs, weaker regulations which can overcome legacy infrastructure barriers stemming from decentralised CE WWTPs [83,107,170,175,233]. Investments, policies, economics and social acceptance for CE WWTP technologies play a critical role to its success [146]. Despite the debate, Torre et al. [234] proposed striking the right balance depending on the unique CE challenges that country faces.

The recovery of nutrients requires further process efficiencies and commercialisation improvements before it can be applied to scale [105,219]. Mature technologies for nutrient and resource recoveries include electrodialysis (ED), AnMBR, upflow anaerobic sludge blanket digestion, expanded granular sludge beds, inverse fluidised bed reactors, AD hybrid reactors, dewatering, incineration, composting, P-precipitation, ash leaching, and animal bone biochar [105,173,213,217,219,230,235,236], in particular, it appears AD is more acceptable [111], and could consume food waste as a substrate [237]. In Hidalgo et al. [236] study, the most promising methods for recovering nutrients are thermally-driven and crystallisation, however, there are other established approaches through liming, constructed wetlands, ammonia stripping, drying, and biological treatment for K-recoveries. Despite AnMBR being promising, challenges to the technology include membrane fouling, pathogen and heavy metals presence, the need to balance energy and nutrient recoveries, and the piloting stages of the plant.

3.3.5. Stakeholder involvement

Several indicators were proposed covering international and national priorities for water, energy and food security, investors, plant operators, suppliers, community and consumers [238] and elaborated in Fig. 7. From the community level, younger demographics appear to be more receptive to innovations in the CE WWTP technologies [238]. Moreover, there will be different influential actors throughout the nutrient supply chain depending on the beneficiaries (farmers and businesses), but there is still a lack of inclusion for the former [9,146]. The study [146] identified regulatory, communication or linguistic, commercial, visual (certification/label acceptance), technological, structural and ideological barriers to nutrient CE adoption. Furthermore, academic and media work hand-in-hand to disseminate the success of nutrient CE research throughout the broader stakeholder network. Given that approximately 80–87 % of struvite in the EU is being sold at prices lower than the market value of €250–412 per ton, investors may refrain from P-recovery projects fearing unprofitability [171].

3.3.5.1. Consumers. The reuse of nutrients to grow forage crops or biomass feed for animal and aquacultural consumption has instead, gained much more popular acceptance [68,111,239], there are however, certain divisive attitudes regarding consumer confidence in the safety of growing crops with WWTP CE nutrients that deters the adoption of new technologies [111]. In Sweden, more consumers held favourable perceptions towards P-recovery through ash than dried urine due to the presence of pharmaceuticals [189]. The 127 surveyed grocery stores however, were unlikely to push for nutrient CE-derived products unless consumers demand it [189]. Urine reuse as fertiliser had an acceptance rate of around 85 % and only 50 % by farmers in the EU [240], but globally this number drops to an average of 59 % [241]. The more processed the recovered nutrient was, the higher the acceptance. The commercial success of nutrient CE depends on the acceptance of consumers of these products [242].

3.3.5.2. Farmers. Fertiliser costs have increased drastically since the COVID-19 pandemic and farmers will become enticed to pursue nutrient CE WWTP products if the price is competitive relative to synthetic substitutes [243]. Changes to conventional farming practices may be necessary depending on the fertiliser, crop and even aquaculture [244]. For example, the design of supply chains to support farmers to switch to organic fertilisers [245], decentralised waste management [246] and to better participate in CE through better education and engagement with innovative farming CE practices [247]. There must be financial incentives and effective educational programs for farmers to adopt nutrient CE products and disposal practices. Moreover, farming carries significant carbon footprints and CE is seen as an effective model for reducing this via effective end-of-life strategies and energy recovery [248]. The most promising products farmers can use from CE WWTPs are recycled water for irrigation and nutrients [242,249]. While energy recoveries are largely applied to offset operating costs for WWTPs and reduce carbon emissions [59].

3.3.5.3. Businesses. Among businesses, there is hesitancy among large organisations to invest in technologies without proven returns, and lack of smaller startups which have proven technologies. The EU is seeking to improve commercial prospects by evaluating the range of technologies that pilot plants have been implementing for phosphorous recovery [250]. Given the recent legislations around carbon disclosures, businesses would welcome CE as a low-carbon strategy to reuse cheaper alternative and sustainable materials and energy [251], there are infrastructural policy, regulatory and supply chain barriers. The value of CE must also be aligned across different stakeholders that the business is affecting and is being affected by to minimise conflicts [252]. Most notably, the cost to transport nutrients and valuable resources to those who need it [246]. Moreover, if there is demand by consumers for CE products, surely opportunities for businesses to tap into this market opportunity would flourish, however, this requires societal perceptions on waste to change.

3.3.5.4. Governance. Regulators, governments and legislators all have a key role to play in driving the implementation of CE to practice - being the bridge between knowledge and application. The EU and China for example, are heavily involved in CE activities and policy implementations, but challenges remain in retraining and regulatory specifications for recovering valuable nutrients [246]. These drivers of policies include water scarcity and high synthetic fertiliser prices [242]. A weak regulatory framework, low financial investments and unclear goals will create weak conditions for CE to close phosphorous cycles [253]. The stringency of frameworks and regulations set out by governments clear

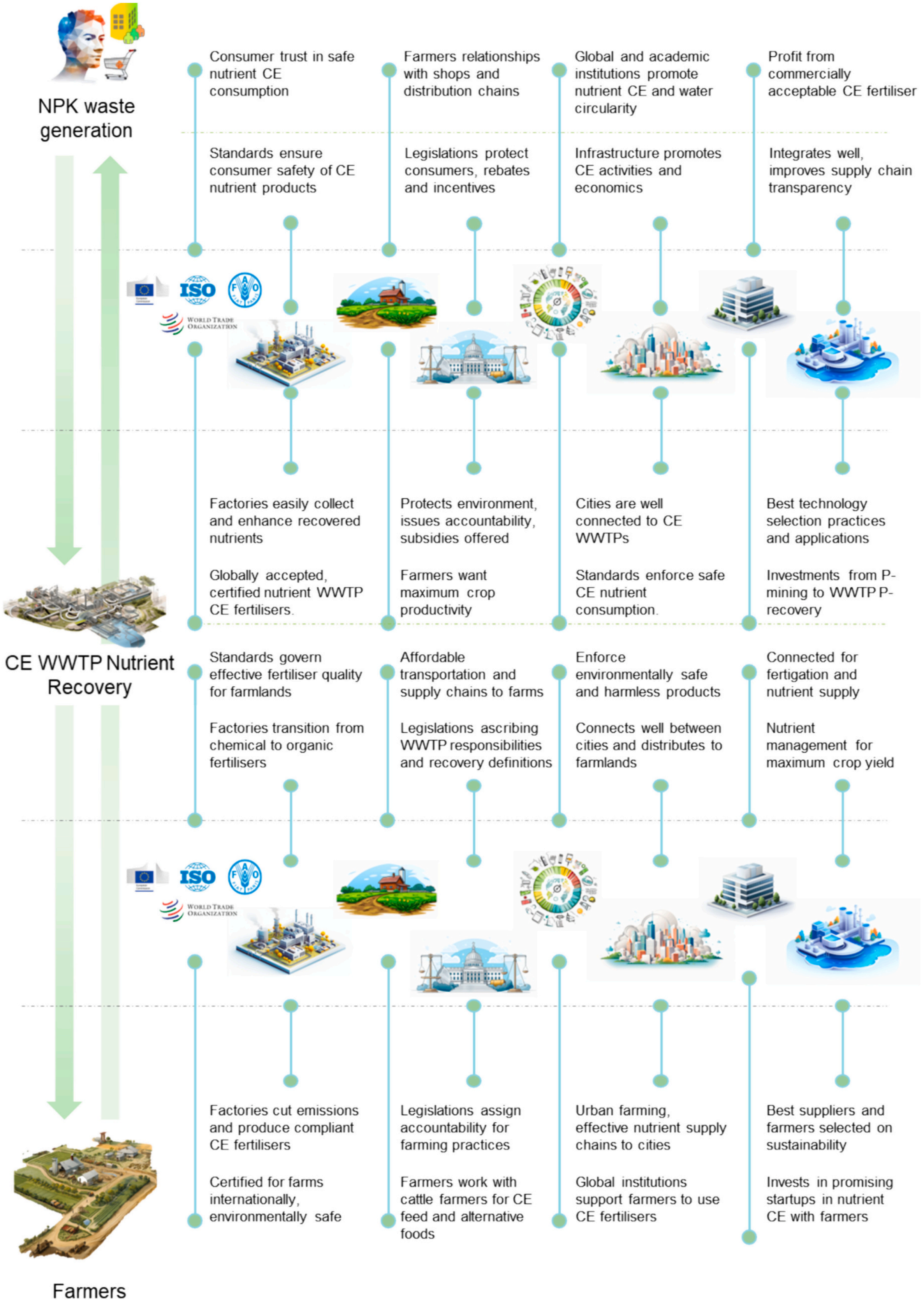

Fig. 7. Stakeholder nutrient CE map showing the stakeholders involved in nutrient CE WWTP.

on its goals enforced by strong institutions are critical for promoting nutrient circularity. These regulations should also be built into other sustainability dimensions such as carbon emissions and bioproducts management [254,255] to prevent regulatory silos.

3.3.5.5. Construction and infrastructure. Current WWTP infrastructure is heavily centralised and relies on collecting wastewater from connected households. There are several recommendations to how countries can move towards CE WWTP, one involves maximising the use of existing infrastructure through retrofitting WWTPs, have additional services and provide optimal deliveries [256]. Within residential settings, wastewater infrastructure is not designed to separate urine and faecal matter for efficient resource recoveries, and therefore, there is a lack of CE systems in place [257]. The other is through the use of decentralised CE WWTP treatment systems embedded across urban settings to allow public participation into wastewater CE projects without retrofitting existing buildings [258]. Regardless of the strategies undertaken, a cost-benefit analysis is assessed to determine which urban CE approach is most effective, but it is accepted that such approaches should have high participation and support rates across communities.

Despite proposed involvement of farmers, policy makers, and fertiliser producers, little involvement has been made with industrial sectors [111], given that zero-waste and reduced GHG emissions were a major reason for favouring CE WWTPs [259]. This makes sense however given the fear stemming from heavy metal waste generations and the difficulties arising from its removal or recoveries. The dairy wastewater industry for one, emits large quantities of CO_2, lost energy and nutrients [17,34,62,224,260], and in Ye et al.'s [62] study, 54.1 kg CO_2-eq/m^3 reduction was realisable with the use of AnMBR technologies, with valuable recovered nutrient market value of \$13.8/m^3.

3.3.6. Tracking value-adding products

Authors such as Cooney et al. [261] utilised a top-down strategy for identifying and sorting by-products from most to least valuable. For example, in descending importance: chemicals that can be used in pharmaceutical medicine, followed by food ingredients, animal feed, fertilisers and energy. The recirculation of value-added products should also track the environmental benefits from refusing virgin extraction of nutrients because avoiding the use of N can alleviate up to 95 % of the environmental impacts from fossil fuel and heavy metal depletions [200]. Previously, the measure for efficiency was based on reductions in virgin material use and pollutant removal according to EU Directive 91/271/EEC [232]. Some valuable products that can be recovered go beyond nutrients and include bioplastics and VFAs [173], while pharmaceuticals are a grave concern for groceries [189].

Crop productivity will vary due to differing geographical conditions, regulations and social attitudes [58]. Therefore, the importance of stakeholder relationships between interested parties will differ from region to region. Nutrient leakages into the environment can also be an indicator of the value lost in CE WWTPs [262] and as a measure of the effectiveness of the WWTP plant in meeting or exceeding regulations. The value derived from recovering nutrients from WWTPs should also factor energy consumption flows [263].

There is also a growing trend of using artificial intelligence and ML with nutrient CE WWTPs [264,265] to improve the reliability and quality of recovering nutrients from WWTPs through forecasting. Moreover, ML can help forecast the demand for nutrients [266], aid sustainable supplier selection [267], however, ML CE faces regulatory, standards and acceptance barriers [268]. The technology can also improve the tracking and transparency of nutrient movement throughout supply chains – giving greater visibility to impacted stakeholders and nutrient monitoring. This would address some concerns raised by surveyed participants relating to fertiliser contaminations, nutrient traceability and safety certifications [175]. Given that the bulk of operating costs from WWTPs come from personnel [269], ML can be used to reduce labour costs through automation. Given the open-source data that can be used to model the impacts nutrients have on the natural environment, nutrient pollution monitoring and tracing it back to the root cause is crucial [203] for CE environmental management.

3.3.7. Policies

EU water regulations cover the Water Framework Directive, Urban Wastewater Directive, and HELCOM [270]. Subsidies could be proposed to incentivise the production of CE nutrients from WWTPs [236,271], given that nutrient standards on fertilisers differ globally, even with the right support, the production of such fertilisers may not be acceptable on the commercial market or to human safety [146,171,229]. Higher GHG emissions and lower nutrient recovery efficiencies can make the technology more harmful than it is beneficial [262,263], meanwhile, reducing emissions and eutrophication was touted as a value proposition for communal acceptance [188,262]. In poorer countries especially, nutrient leakage and inefficient applications are severe given the lack of infrastructure or regulations in place. Furthermore, it becomes very difficult to tie nutrient recovery technologies together given the lack of funding, knowledge and infrastructure in place [105], legislative gaps to identify highly efficient sites for nutrient application [205], or prohibitively, protective legislations and regulations which make CE WWTP economically difficult [259]. It is purported that further policy intervention for nutrient CE technologies will be required to expedite its economic and technological feasibility [40], given some standards do not include LCA for CE WWTPs [207]. Such policies, with Germany's SUSKULT program as an example, factored in consumer prices, food security, energy consumption, nutritional quality, and impact on farmers when transitioning WWTPs to CE [9], however, given that some EU regulations do not typify the categorisation of nutrient waste as a commodity [213], this is regarded as a significant legislative barrier mirroring a societal assumption that waste is waste, not as a valuable commodity recovered for reuse on farmlands.

Countries within the EU lack clear WWTP nutrient recovery regulations, investment and research programs, and research into recovery of critical raw materials are still in its infancy stages [219,272]. This was further backed by surveys completed with a lack of clear policies, slow regulatory changes to accommodate new CE technologies, incompatibilities between agricultural practices and nutrient CE, and guidance on the available P-recovery technologies there are available [40,73]. For example, phosphorous is listed as a critical raw material across the EU since 2014 [273], despite this, most WWTP regulations focused on removal, rather than the recovery of P from effluents. Additionally, some fertiliser standards and regulations globally do not recognise recovered CE nutrients as appropriate for market sale [73,146,213], and there are varying limitations on the concentration of fertiliser content (maximum of 250 kgN ha^{-1} under Scottish Waste Management Licencing 2011 land reapplication [205] and Polish Regulation of the Minister of Agriculture and Rural Development mandating a minimum N-P-K fertiliser composition of 2 % each [274,275], Poland's cadmium concentrations at 50 mg/kg [274,275] compared to 40 mg/kg in P-fertilisers by the EU [276]). Currently, the replacement of conventional fertilisers through recovered P in the EU is about 0.5 %, and a maximum theoretical value of 13 % replacement of P imports could be reached [171], therefore, more needs to be done improve the self-sufficiency of P.

Moreover, the ownership of the nutrient CE process has come into question on what happens after sewage sludge exits the WWTP and enters the process recovery chain, who bears the cost of burden, the tendering process and profiteering [73,175,277]. An example of a legislation ascribing responsibilities for this is Poland's Waste Act which charges sludge producers with the responsibility for transporting sludge, testing and reporting to environmental protection agencies [83], with the difficulties surrounding the legal treatment of sewage sludge ash [220]. This responsibility becomes much more blurred when the sewage sludge is sold to multiple parties downstream, for example, companies processing the sludge for other purposes besides agricultural application. Therefore, some laws focus on waste management to prevent harm to society and environment, rather than on CE recoveries. In developing countries, the focus is ensuring hygienic and safe working conditions, transforming social perceptions and better waste management and accounting systems [202].

4. Proposing the framework

Scope 1, 2, 3, 4 and 5 impacts of the nutrient CE WWTP are considered for the proposal of the new framework. These fall under the categories of:

1. Scope 1: The recovered products and their economic, social and environmental impacts from the plant onto the wider surroundings considered at the meso, macro and micro levels. These include complimentary recovered products from the nutrient recovery process (e.g., biogases, syngas, biomasses, electricity, and thermal energy). Scope 1 is applied across Scopes 2–6.
2. Scope 2: Transitory effects from changing regulations, policies and legislations have on the treatment and definitions of CE waste to products.
3. Scope 3: Technological compatibility with the treatment of influents and their economic viability, efficiencies, acceptability, integration via retrofitting, and readiness.
4. Scope 4: Societal acceptance of nutrient CE technologies regarding hygiene, safety, and educational awareness.
5. Scope 5: Inclusion of stakeholders such as mining firms, farmers, consumers, academia, regulatory bodies, governments, plant operators, and standards institutions.
6. Scope 6: Infrastructural systems in place to facilitate effective nutrient CE between WWTPs and end consumer. For example, source separation and decentralised urinals.

Smol et al. [128] covers the recovery of energy, nutrients, water and removal of toxic chemicals within the context of the EU, however, the framework inadequately fails to consider the meso, macro and micro impacts that the recycling and recovery of nutrients WWPTs will have. The term “reclamation”, or removal, has been proposed as a substitute for one of the 10R principles to eliminate harmful toxins and chemicals from WWTP influents by the author [128], however, there is a gap in the framework which does not consider: CE metrics, factoring in market conditions and commercial opportunities; current research into pilot plants in existence; and the lifecycle of the WWTP plant itself; and is more confined with localised EU directives. Smol et al.'s [57,128] 6R principles were:

1. Reduction: Reduce use of water
2. Reclamation (removal): Pollutants removal
3. Reuse: Water reuse
4. Recycling: Water recycling
5. Recovery: Nutrient, materials and energy recovery
6. Rethink: Public awareness

Norton et al. [278] proposed the 4R principles for nutrient stewardship, these include: the right amount, right fertiliser, right time, the right way. In other words, nutrients should be used sparingly to achieve the desired crop yields, high efficiency in both removal nutrients and efficient nutrient delivery into produce. It is expected that the R principles will evolve with time depending on advancements in policy, technology and social attitudes. For example, crop yields have increased with P-efficiencies given improvements in crop genetic modifications, planting technologies and improved fertiliser management [76]. However, the R principles proposed by previous authors do not consider strongly the social, economic and environmental dimensions of nutrient CE.

Table 5
Dynamic framework for Nutrient CE WWTPs.

Scope 1		Economic	Environmental	Social
Scope 2	Meso	Regulations protect consumers during economic exchanges and maintain company profitability.	Promotes water circularity and environmental preservation (e.g., CE WWTP nutrient fertigation).	Regulated training and induction for CE WWTP workers.
	Micro	Regulations on profit/loss ownership and accounting. Transitional regulations are not financially disruptive.	Regulations on safe nutrient CE consumption. Transitional regulations promote individual environmentalism.	Consumer education and awareness.
	Macro	Regulations on imports and exports of nutrients. Does not lock-in inefficient technologies.	Regulations are enforced within a zone (region/globe).	Globally accepted and overcomes national barriers on nutrient CE regulations, education and
Scope 3	Meso	Technology integrates well with other WWTP networks and/or households, effective selection methods.	Technology poses no adverse environmental damage.	Technology is accepted by industry, beneficiaries, operators, and standards institutions.
	Micro	Commercially viable and profitable for operators, nutrients can be purchased by households.	High efficiencies in nutrient recovery and toxins or pharmaceuticals removal to consumers.	Technology sufficiently builds trust and reliability.
	Macro	Subsidised technologies by governments.	Technology is certified as environmentally friendly.	Technology is socially acceptable due to long established reliability.
Scope 4	Meso	Widely accepted practice that is proven to be profitable.	Supports environmental objectives across society.	Alignment with NGOs and NFP organisations.
	Micro	Consumer and WWTP affordability.	Supports communal demands for safe, healthy environments.	Households and companies champion being connected to CE WWTPs.
	Macro	Supports job creation opportunities.	Tackles goals from a governing body reflective of global values (e.g., UN SDGs).	Countries advance CE reputation throughout the global community.
Scope 5	Meso	LCA of CE WWTP on economic performance with stakeholders.	LCA between CE WWTPs and stakeholders with environmental factors.	Transparent supply chains to build trust and accountability between CE WWTPs and stakeholders.
	Micro	Financial incentives to nutrient recycling.	Individual responsibility for environmental performance.	Individual responsibility for safe nutrient disposal.
	Macro	CE-driven economic growth.	Governments, institutions, regulatory bodies, and regional standards	Global cultural and national acceptance of CE WWTPs for society.

(*continued on next page*)

Table 5 (*continued*)

Scope 1		Economic	Environmental	Social
			publishers for CE WWTPs.	
Scope 6	Meso	Infrastructure links communities, farmers and WWTP operators to investment opportunities.	Infrastructure meets net-zero emissions and supports CE nutrient consumption among stakeholders.	Community support of nutrient CE wastewater infrastructure.
	Micro	Consumers can purchase and monetise infrastructure for wastewater nutrient recoveries.	Consumers can access and use CE WWTP infrastructure.	Consumers and households can promote and endorse the benefits of using nutrient CE infrastructure.
	Macro	Major infrastructure investments that promote greater CE WWTP integration and commercialisation.	National and international infrastructure networks supporting WWTP CE nutrient supply chains.	Heavily used and accepted by society – has become omnipresent.

In Table 5, social, environmental and economic goals of nutrient CE WWTP should be factored in with the meso, micro and macro elements of society. The framework captures the dynamic nature of Scopes 2–6. For example, regulations are constantly changing and facing discrepancies between local, regional and international zones regarding fertiliser and reapplication nutrient contents; different countries will have varying levels of infrastructure compatibilities to support nutrient CE, technology maturity and compatibility will also vary; and inclusion of the stakeholders will also differ depending on their capabilities and vested interests reflective of the institutions, social, environmental and economic acceptance of nutrient CE.

5. Discussion

From the analysis, governments and in particular within the EU, are beginning to implement a range of measures that serve both protectionist and sustainable goals towards material conservation and circularity. A lot of research in academia has been translated into nutrient recovery pilot plants and these remain emerging, Fig. 8 ties in the research elements that create the CE WWTP ecosystem. Nation-driven programs such as Germany's SUKSULT or the EU's Critical Raw Materials Act, are policy-backed examples for attaining macro-scale material self-sufficiency and sustainability. However, little is done to tie in broader society support and awareness about phosphorous scarcity using wastewater sewage and urine P-recovery technologies. There is a noticeable shift towards expanding nutrient efficiency from recovery to include delivery into farmlands, the incorporation of ML digital systems to automate and streamline nutrient recovery efforts, and much more inclusive regulations and legislative definitions on categorising CE waste. Market interventions in the forms of government subsidies and investor awareness are needed to support the expansion and adoption of maturing, nutrient CE technologies with WWTPs. There is however, currently insufficient support for nutrient recovery projects for WWTPs on a global scale, given the uncertainty around profitability or swathe of emerging technologies and selection methods that have yet to garner trust and reliability. Different countries will have unique priorities and recovery technologies depending on the availability of funding, types of infrastructure compatible with nutrient CE WWTPs, and economic priorities.

The involvement of many different stakeholders will prove crucial - namely governance, farmers, regulators, legislators, businesses and consumers - to make CE possible for WWTPs. Consumer acceptance, strong regulatory support enforced by institutions, businesses willingly participating in this commerce, and farmers who are actively engaged and purchasing nutrient CE products are all necessary, with governments exploring a range of technologies available to make the CE process a reality. However, each country will be different given the varying urban densities there are, strength of institutions, water connection rates, the level of centralisation of water treatment systems, and perceptions on waste reuse. This is also affected by the level of water

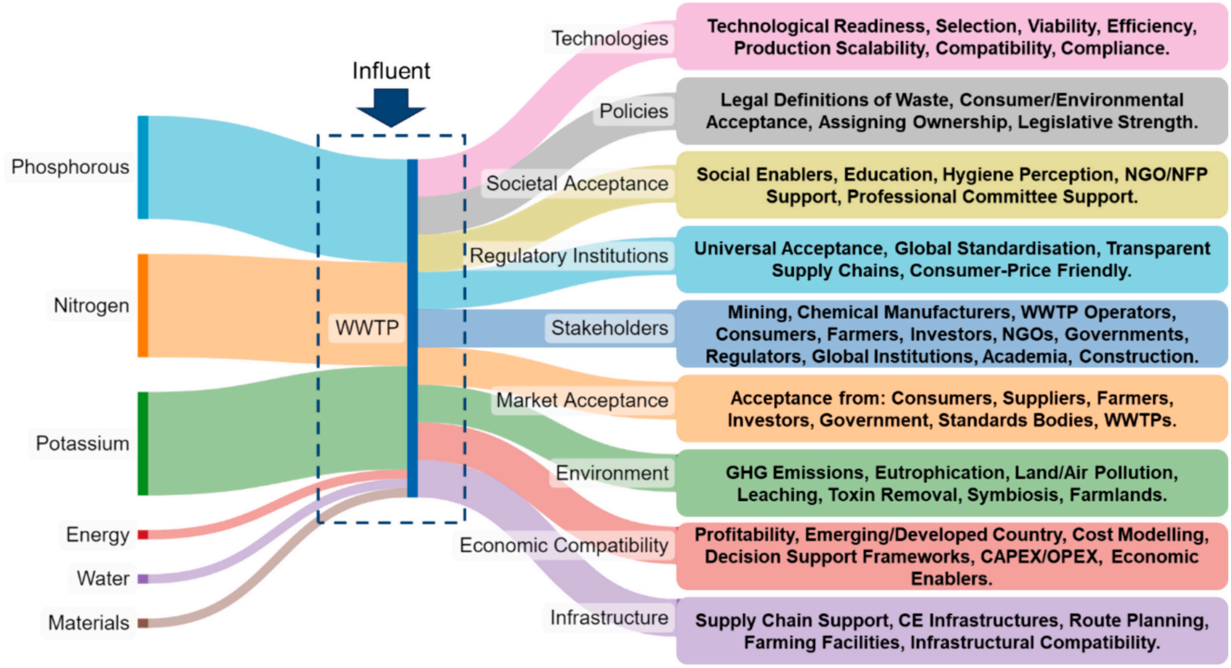

Fig. 8. The intermeshing of priorities, stakeholders, social, economic, environmental, infrastructural, commercialisation, regulatory and legislative factors that are required to realise CE WWTP.

scarcity and prices of synthetic fertilisers where farmers may be incentivised to switch to a more organic substitute or reclaimed water for irrigation. WWTP operators can either process the waste into reusable fertiliser, or outsource this process to a dedicated nutrient recycling provider. Therefore, the introduction of cheaper, organic nutrient CE WWTP fertilisers would become beneficial for consumers as food prices become lowered. The main critical ingredients for this to work rely heavily on favourable economics for all parties involved that is safely regulated by governments and institutions.

6. Conclusion

It has become clear that the move towards nutrient CE WWTPs requires factoring in environmental, societal, political, commercial, economic, consumer, regulatory, legal, infrastructural, technological, international compliance, academic, agricultural, and WWTP operators for nutrient CE to be a success. The translation of CE into a feasible system of practice for countries, regions and the world, remains difficult due to localised legislative barriers on the treatment of waste and resources. Meanwhile, nutrient recovery plants are being piloted for the purposes of identifying best NPK recovery approaches. However, many of these pilot plants are heavily subsidised by governments and research institutions, rather than being driven by commercial investment opportunities. Given the emerging status of some nutrient recovery technologies, caution is taken to ensure that policies do not lock-in inefficient technologies. Therefore, fear among investing in unproven technologies exists that serves as a resister to nutrient CE WWTP commercialisation. The framework identifies regulations, subsidies, commercial incentives, consumer acceptance, wastewater professional CE practice acceptance as enablers for CE WWTP adoption, meanwhile, stakeholder inclusion using a bottom-up approach is crucial. Given that most CE policies are concentrated throughout the EU to achieve net-zero circularity in material consumption, a large amount of nutrient CE research and piloting is done in this region, and practices are increasingly becoming enforced through legislations such as the Critical Raw Material Act of the EU. Therefore, regulatory directives contribute significantly to CE activities. Meanwhile, upscaling CE solutions will depend on the unique infrastructural and economic challenges and priorities that a country faces, and in essence, a one size fits all approach may not be appropriate for global CE WWTP. This framework is posited to factor in situations facing the meso, micro and macro environments to which nutrient CE is implemented. Conclusively, WWTPs are undergoing an unprecedented transformation to become nutrient and resource recovery centres, with this framework setting clear guidelines on its interdependencies for success.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Ho Kyong Shon serves as a co-Editor-in-Chief for the Desalination journal, while the editorial handling and review of this manuscript were overseen by a different Editor.

Data availability

No data was used for the research described in the article.

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