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Article

Sustainable Wastewater Management—A Definition and Criteria for Assessment

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Abstract

Addressing sustainable wastewater management is not new; sustainability and wastewater are discussed so frequently together that the concept may feel overused. It is therefore surprising that such a widely used term as sustainable wastewater management does not have a clear, widely accepted definition. We argue that this hinders progress towards sustainability and might even lead to unsustainable decisions. Here, we propose a definition of sustainable wastewater management, applicable to both existing and planned wastewater systems and grounded in established and well accepted definitions of sustainable development, such as the United Nations Sustainable Development Goals. We present a set of objectives that frame and define sustainable wastewater management. The objectives cover the areas recipient protection, nutrient recovery, biodiversity, substances of emerging concern, climate change, energy and resource use, water reuse, collaboration, social aspects including fairness, and economy. We discuss what these areas entail and potential conflicts and trade-offs that must be handled. To support decision makers, we suggest criteria intended for use in multicriteria sustainability assessments. The criteria are linked to the objectives defining sustainable wastewater management. Both the definition and the associated criteria set presented here can support the wastewater sector in progressing towards sustainability.

Keywords: wastewater treatment; sustainable development; circularity; resource recovery; environmental protection; sustainability definition; indicators

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1. Introduction

Finding pathways to sustainable wastewater management (WWM) engages the wastewater (WW) community. As the deadline for achieving the United Nations (UN) Sustainable Development Goals (SDGs) for 2030 approaches, SDG 6 clearly emphasizes the necessity to ensure the availability and sustainable management of water and sanitation for all [1]. Moreover, one of the aims of the European Union is to contribute to a sustainable development of the Earth [2]. At the same time, the water sector is expanding, with many large investments being made. Together, these developments indicate a significant and growing interest in sustainable decision-making for WWM. This growing emphasis on sustainability highlights the need for clarity regarding what sustainable WWM entails, a need that is not yet fully addressed in the existing literature.

In 2020, 3.6 billion people still lacked safely managed sanitation. To accomplish SDG6, there must be parallel efforts on increasing the access to sanitation and developing existing WWM infrastructures into sustainable systems. Although the scientific literature frequently claims to offer solutions for enhancing the sustainability of established WWM systems [3], it often lacks a comprehensive definition or discussion of the concept of sustainable WWM. New process technologies, such as algae-based systems, microbial fuel cells, and membrane technologies, are proposed as potential pathways toward future sustainable WWM. Yet discussions addressing the fundamental meaning of sustainability are frequently absent [4–6]. One could argue that such a commonly used term requires no further clarification, but there is no full consensus on the sustainability concept in the wastewater context [7]. This makes it very difficult to verify if a suggested solution improves the overall sustainability of the WWM system.

One commonly applied approach, such as that used by Yang et al. [4], implies that sustainability is improved by reducing obvious non-sustainability [7]. However, this approach becomes problematic when focus is limited to a specific unsustainable practice without a holistic perspective. For instance, a negative energy balance for a wastewater treatment plant (WWTP) is often regarded as unsustainable. Co-digestion with external organic waste [8] can increase biogas production and improve the energy balance, yet such a solution may also result in negative sustainability impacts, such as reduced nutrient recycling if the external organic waste is contaminated. In such cases, a trade-off arises between improving the energy balance and maintaining nutrient recycling, making it difficult to determine the most sustainable option. A multicriteria analysis (MCA) can be conducted [9,10], providing a systematic way to evaluate sustainability holistically, but it should still rely on a clear underlying sustainability concept.

A holistic sustainability assessment is not sufficient on its own but needs to be grounded in a clear and well-defined concept of sustainability. Explicitly defining what constitutes sustainable WWM is essential, as different conceptualizations can lead to markedly different outcomes. A distinct example is the contrast between strong and weak sustainability, which reflects opposing views on the substitutability of natural capital [11]. Strong sustainability holds that natural capital is non-substitutable, whereas weak sustainability allows for substitution with human-made capital. For instance, a WWTP expansion that involves clearing a forest with recreational value could be acceptable according to weak sustainability, provided that the forest is replaced with a park. In contrast, strong sustainability would reject this type of replacement of natural capital with a human-made alternative. If the concept of sustainability for WWM is not clearly defined, both types of outcomes may be interpreted as sustainable alternatives, despite relying on fundamentally different principles.

Moreover, to identify sustainability synergies, it is essential not only to use the term "sustainable" but also to clearly define and explain its intended meaning. We believe that one reason the holistic perspective is often lacking in discussions about improving the sustainability of WWM is the absence of a commonly accepted, shared definition. The difficulty in developing a unified definition can be attributed to differences in regional contexts, political interests, levels of system development, technological and economic constraints, and institutional capacities, which together lead to differing priorities and, in some cases, limit the ability to adopt a holistic perspective. Rather than emphasizing these differences, the focus should be on identifying common principles that can guide the future development of sustainable WWM across contexts. Applying such principles through MCA allows for variations in priorities to be explicitly addressed, making the unified definition practical and adaptable to local conditions.

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Such a definition provides a common focus that enables different actors to work on separate system components while collectively contributing to overarching sustainability goals. A well-defined concept of sustainable WWM can therefore facilitate cooperation, support the identification of unsustainable practices, and guide improvements toward a more sustainable future wastewater sector. In addition, it strengthens the credibility of assessments by specifying which areas must be considered and ensuring that no critical aspects are overlooked. Such clarity also supports decision-makers in addressing overall sustainability in a manageable way.

The aim of this paper is to propose a clear and comprehensive definition of sustainable WWM, based on widely recognized and accepted frameworks for sustainable development interpreted for the wastewater context. To achieve this, we begin with a review of sustainable development frameworks, including the SDGs [1], Our Common Future [12], the Planetary Boundaries Framework [13], the four socio-ecological principles [14], and the concept of strong versus weak sustainability [11]. We then examine their implications for sustainable WWM, highlighting key similarities and differences, and present, through a theme-based approach, eleven sustainability areas, each with a distinct set of objectives, that together define sustainable WWM. Finally, we propose a set of criteria that are explicitly linked to the objectives, making the definition of WWM usable in practice (e.g., in MCAs) and enabling decision-makers to assess how changes to the WWM system contribute to sustainable development.

2. Methods

To develop a definition of sustainable WWM, the study first identified well-established, general definitions of sustainable development. The sustainability frameworks included were selected based on their holistic perspective on sustainability, their recognition in the literature, and their combined ability to provide a broad and sufficient basis for the field. The content of each framework was reviewed and summarized, after which each framework was interpreted in the context of WWM. These interpretations were carried out by persons with knowledge of established WWM practices (the authors of this paper).

In the next step, the individual interpretations were synthesized to identify points of alignment and divergence across the frameworks. To analyze the sustainability frameworks, we applied an inductive coding process [15] in which codes emerged directly from reading each of the framework interpretations. Initial codes were generated from these interpretations and were iteratively refined through discussions between the authors and comparison of overlapping concepts. This process involved consolidating similar codes and clarifying their meanings, eventually resulting in eleven broader sustainability areas. Each area was then assigned a set of objectives that define its scope and clarify how it relates to sustainable WWM.

The resulting areas and objectives were then compared with findings from an expert group study on priorities for future sustainable WWTPs [15], that identified low resource and energy consumption and a low CO_2 footprint as prioritized, to ensure that these aspects were incorporated into the proposed definition. Contradictions across and within the framework interpretations are discussed in Section 3.3.

Finally, a comprehensive review of the literature proposing sustainability criteria and indicators for the wastewater sector [16,17] was conducted. Based on this, a set of criteria was systematically aligned with the defined sustainability areas and objectives. This set of criteria supports the practical application of the definition through MCA and, secondarily, helps to delineate the content of sustainable WWM by supporting the same sustainability areas from an independent reference basis.

Figure 1 presents an overview of the complete methodological approach to develop the defintion of sustainable WWM, structured into areas, objectives, and criteria.

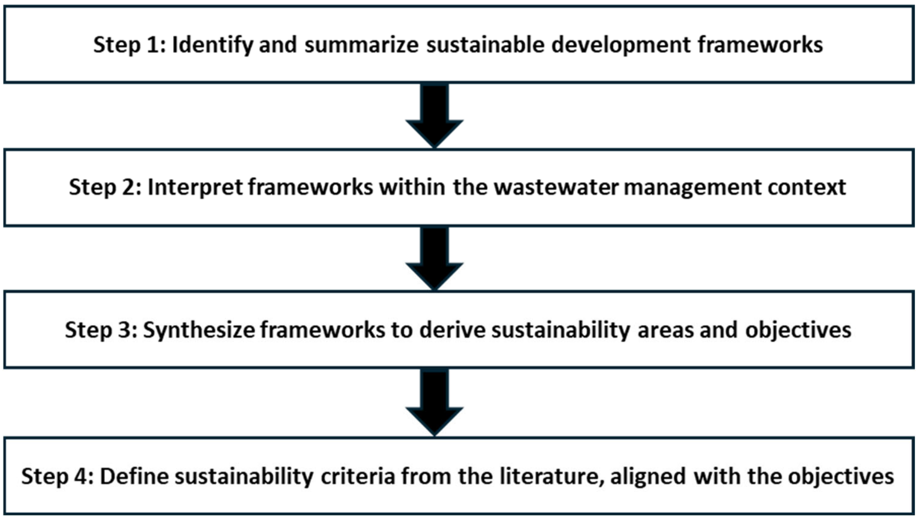

Figure 1. Overview of the stepwise methodological approach for developing a definition of sustainable wastewater management, structured into sustainability areas and objectives, and complemented by aligned criteria.

3. Results and Discussion

This section begins with summaries of key publications, frameworks, and other relevant sustainable development literature that form the basis for, or are particularly relevant to, the development of the definition of sustainable WWM. This is followed by the presentation of the identified sustainability areas and their specified objectives. Subsequently, the implications, consequences, and potential trade-offs associated with combining different sustainability definitions are discussed. The section concludes with a discussion of how to assess progress toward more sustainable WWM and the identification of sustainability criteria for practical application.

3.1. General Sustainable Development Frameworks

3.1.1. The Dimensions of Sustainability

Environment, society, and economy are well accepted as the three dimensions of sustainable development. The terms "the three pillars of sustainability", "the triple bottom line", or "people, planet and profit" all occur with generally the same meaning. The history of the three dimensions is a bit unclear, and Purvis et al. [18] state that the concept has gradually emerged. In 1987, Barbier [19] published a three system concept (biological, economic, and social) together with an intersecting circle illustration. The same year, an article by Brown et al. [20] and Our Common Future [12] were published, and these three are all considered early important contributions to the three dimensions concept.

While it is generally accepted that all three dimensions must be considered, opinions differ regarding how they relate to one another. Figure 2 illustrates three common variants: overlapping circles, three pillars for sustainability, and a nested model with economy and society embedded in the environmental dimension. The overlapping circles suggest that goals should be maximized across all three dimensions through an adaptive process of trade-offs [19]. The three pillars model suggests that all three are equally important for sustainable development [18]. The nested model reflects the perspective that economy is a subset of the other dimensions, and that human society depends on the environment, while the environment can continue without humans [21].

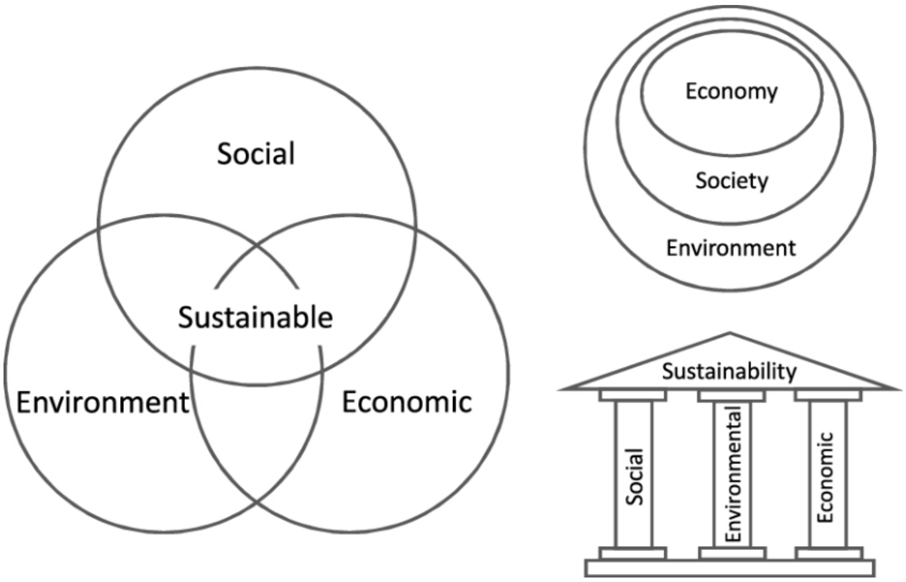

Figure 2. Different ways of illustrating the interconnection of the three sustainability dimensions environment, society, and economy [18], CC BY-ND 3.0.

3.1.2. The 'Our Common Future' Report

The 'Our Common Future' report, also referred to as the Brundtland report after Gro Harlem Brundtland, the leader of the commission, was published by the World Commission on Environment and Development in 1987. This commission, created by the UN, worked independently on analyzing and suggesting solutions to existing problems connected to the new concept "sustainable development". The report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This is, by many, considered as the general definition of sustainable development [12].

The commission clarified that economic development could no longer be handled separately from sustainable development. With this new point of view on many global challenges, the commission emphasized the need for existing and new international and national organizations at all levels. The commission stated that these would be crucial for changing peoples' awareness, attitudes, social values, and willingness to put the world onto sustainable development paths. Specific areas of focus in the report were food security, the loss of species and genetic resources, energy, industry, and human settlements.

The guidelines presented in Our Common Future [12] are well covered by the SDGs [1], which can be seen as a continuation and expansion of its ideas, while also including the program Agenda 21 [22] and the Millennium Development Goals [23].

3.1.3. The Sustainable Development Goals

The 2030 Agenda for Sustainable Development was adopted by all United Nations Member States in 2015 and contains 17 SDGs, visualized in Figure 3. The aim is to end poverty, protect the planet, and ensure prosperity for all, as part of a new sustainability agenda. The 17 SDGs consist of different targets that define what each goal seeks to accomplish with one or more corresponding indicator of how to measure the progress on each target [1].

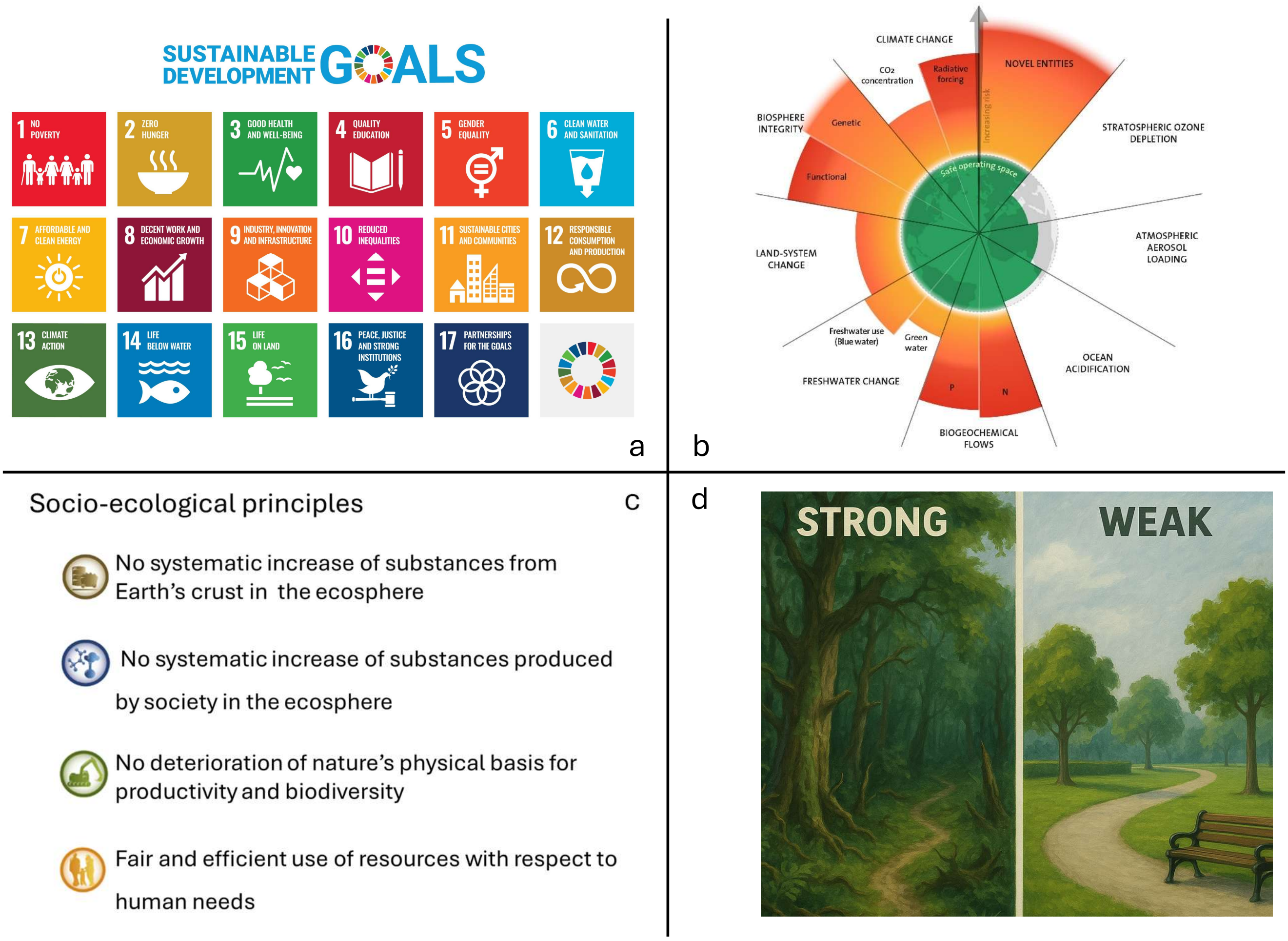

Figure 3. Four concepts correlated to sustainable development are incorporated in this study. (**a**) The 17 Sustainable Development Goals [1], CC BY-ND 3.0. (**b**) The evolution of the Planetary Boundaries Framework. Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on [13,24,25], CC BY-ND 3.0. (**c**) Sustainable development as a framework of four socio-ecological principles [14]. (**d**) Illustration of strong and weak sustainability regarding the natural capital of a forest vs. a park for recreation (the illustration for (**d**) was generated with the assistance of ChatGPT GPT-v4).

To exemplify the structure, the SDG6 Clean Water and Sanitation consists of eight targets and 11 indicators that cover: safe drinking water, access to sanitation, pollution and water-reuse, water scarcity, water resources management, water ecosystems, cooperation with developing countries in water business, and local water and sanitation management. The progress is continuously monitored but obtaining sufficient data for global statistics is a challenge. One key element for target 6.3 is reducing the proportion of untreated wastewater. In 2022, 76% of total wastewater flows were reported as receiving some form of treatment, based on data from 73 reporting countries. Nevertheless, this data accounts for only 42% of the global population [1].

3.1.4. Planetary Boundaries

In 2009, Rockstrom et al. [13] proposed the nine Planetary Boundaries, which they defined as "a safe operating space for humanity". They claimed that to avoid catastrophic environmental change, humanity must stay within the boundaries for nine essential earth-system processes: climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading. The processes affect each other and crossing one border can affect other processes, therefore all borders must always be considered together. The Planetary Boundaries might seem to be only within the environmental dimension, but another point of view is that economy and society are embedded parts of the biosphere or the environmental dimension (see Figure 3). Anyhow, the Planetary Boundaries concept is an important contribution in sustainability discussions and is therefore included here.

The Planetary Boundaries are mostly visualized as a spider chart, as in Figure 3 [24], where each wedge is one process and the circle in the middle is the safe operating space. In 2023, all nine processes were quantified for the first time, and it was concluded that six boundaries had been transgressed, which can be seen in Figure 3, as these wedges are colored beyond the safe operating space boundary and only three stays within. Since September 2024, the Potsdam Institute for Climate Impact Research produces a yearly update, called the Planetary Health Check [26].

3.1.5. Four Socio-Ecological Principles

When Holmberg, in 1995 [14], explained sustainable development as a framework of four socio-ecological principles (see Figure 3) that should be fulfilled, his work gained significant attention and international recognition, largely through the Natural Step Organization [27]. According to Grönlund [7], nearly all our environmental problems can be derived from these principles, which highlights the relevance of including the four socio-ecological principles for sustainable development. The four principles are formulated as follows [14,28]:

Substances from the lithosphere must not systematically increase in the ecosphere.

This type of accumulation will, beyond a threshold, cause damage. The extraction rate of metals and fossil fuels should be restricted, the recycling of material increased, and the use of scarce elements decreased.

Substances produced by society must not systematically increase in the ecosphere. The production of molecules and atomic nuclei previously known or unknown to nature will accumulate if the production is faster than they are being degraded or removed.

The physical basis for the productivity and diversity of nature must not be systematically deteriorated. Long-term functions of the ecosystems are crucial to society and the outtake of resources from the ecosphere must not exceed the regeneration, nor systematically reduce natural productivity or diversity by manipulating natural systems.

Resources must be used fairly and efficiently with respect to meeting human needs. The resources and services obtained from nature should be used efficiently where they are needed the most and fairly distributed among human societies and human beings.

3.1.6. Strong and Weak Sustainability

Strong and weak sustainability are two opposing perspectives regarding sustainable development. The key question dividing them is whether natural capital can be replaced by human-made capital (see Figure 3). According to weak sustainability, natural capital can be replaced by human-made capital if the total sum of capital is held constant. In strong sustainability, natural capital can never be replaced. Within strong sustainability, Neumayer [11] points out two differing variants: to maintain natural capital in value terms or to reserve the physical stock of natural capital. The first variant, to maintain natural capital in value terms, means that one form of natural capital can replace another if the sum is held constant. The second variant of strong sustainability, to preserve the physical stock of critical natural capital, does not allow for any substitutions but calls for keeping the function of the natural capital intact, which means that there can be an outtake if this does not exceed the regeneration. Neumayer [11] exemplifies this with erosion of top-soil, which cannot exceed the formation rate of such soil.

Luthman et al. [29] argues that there is a need for further division and advocates the use of four subdivisions: very weak, weak, strong, and very strong sustainability. With these subdivisions, weak sustainability deviates from very weak in acknowledging that there are environmental thresholds, although sees them as flexible. For strong sustainability human activities should not degrade the ecosystem beyond its functions, resilience and assimilative capacity, while very strong implies that the ecosystem is not negatively affected at all.

3.2. A Set of Objectives for Sustainable Wastewater Management

Based on the general sustainable development frameworks and key publications reviewed, together with the methodological approach described in the Methods section, we propose that sustainable WWM can be defined as a set of objectives grouped into 11 areas (Figure 4). In the following sections, these areas and their associated objectives are described and their relationships to the general sustainable development frameworks are discussed. An overview of how the general sustainable development frameworks relate to the 11 areas is provided in Table 1.

Figure 4. Sustainable wastewater management defined into 11 areas with specified objectives (the illustrations in this image were generated with the assistance of ChatGPT GPT-v4).

Table 1. Overview of the connections between the established sustainability definitions, interpreted for the wastewater context, and the 11 areas that define sustainable WWM.

	Our Common Future [12]	SDGs [1]	Planetary Boundaries [13]	Four Socio-Ecological Principles [14]	Strong and Weak Sustainability [11]
1. Sanitation and Hygiene	X	X			
2. Recipients	X	X	X		X

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Table 1. *Cont.*

	Our Common Future [12]	SDGs [1]	Planetary Boundaries [13]	Four Socio-Ecological Principles [14]	Strong and Weak Sustainability [11]
3. Recovery of nutrients			X	X	
4. Biodiversity	X	X	X	X	X
5. Substances of emerging concern		X	X	X	
6. Climate impact		X	X	X	
7. Energy and resource use	X	X	X	X	X
8. Water reuse		X	X		
9. Cooperations	X	X	X	X	
10. Social aspects	X	X		X	
11. Economy	X	X			

1. Sanitation and hygiene. This is directly related to SDG6 [1], which states that ensuring access to sanitation for all is a cornerstone for our society and a necessity for achieving other aspects of sustainable development. Wastewater management plays a crucial role in minimizing the risk of exposure to pathogens. A strong focus on hygiene is important both during the establishment of new WWM systems and when modifying existing WWM systems.

Objective 1.1: WWM should provide safe and adequate sanitation solutions that minimize the risk of water borne infection and health issues.

2. The ecosystem of the recipients. The whole sustainability discussion is strongly anthropocentric, but the effects on other living organisms, now and in the future, must be included in a sustainability definition. Our Common Future [12] states that future needs and consequences must always be considered and for WWM that could mean that the discharges should not have any long-term negative consequences on the recipients (i.e., the water bodies receiving the discharges from the wastewater treatment plants). Considering the Planetary Boundaries [13], WWM should avoid worsening "loss of biodiversity and extinctions" within the Planetary Boundary Biosphere Integrity. Likewise, the planetary boundary of biogeochemical flows of N and P entails that effluent flows of N and P from WWM systems must reach harmless levels. It should be noted that the Planetary Boundaries allow for geographical differences in discharge levels [30]. SDG6 and 14 are also related to the status of the recipients [1]. Target 6.6 is about protecting and restoring water-related ecosystems and target 6.3 is the proportion of wastewater safely treated. The latter target questions the acceptability of combined sewer overflows (CSOs) and sanitary overflows, which are common for many WWM systems today, but lead to discharge of untreated wastewater. In terms of strong and weak sustainability, the former does not allow degradation of a recipient whereas the latter could allow discharge of wastewater that degrades a recipient if its function can be replaced by human-made capital.

Objective 2.1: Avoid releasing untreated wastewater to the recipients.

Objective 2.2: Treat all wastewater to site specific safe levels of pollutants, for instance nitrogen, phosphorus, and organic matter, which do not negatively impact the ecosystems of the recipients, on short- or long-term.

Objective 2.3: Contribute to restoration of damaged water-related ecosystem.

Objective 2.4: Locate the discharge points for treated wastewater in a way that minimizes the impact on the recipients.

3. Recovery of nutrients. WWM is highly relevant for the Planetary Boundary concerning nitrogen (N) and phosphorus (P) flows to the biosphere and oceans [13]. Wastewater contains a lot of P, where the majority, with modern WWM, ends up in the sludge, and the recovery of N at WWTPs is generally very limited. The fourth socio-ecological principle—fair and efficient use of resources with respect to meeting human needs [14]—can be applied to P, which is an important finite resource with an important use as fertilizer for food production. A sustainable WWM system should, thus, increase the recovery of P, in order to save the scarce P resource for future generations. In Sweden in 2017, only 25% of the P in sludge was recycled to agriculture, despite an increase since 2017 it is still far from the potential 90% [31]. So clearly, there is room for improvement and, as pointed out by Pandey [32], nutrient recovery is important for sustainable WWM, but a systematic change will be needed. Studies on improved resources utilization at WWTPs and the development of Water Resource Recovery Facilities [33] are of great interest and importance for achieving sustainable WWM, although focus here is firstly on what needs to be accomplished.

Objective 3.1: Maximize recovery of finite resources, such as phosphorous, to save these resources for future generations.

Objective 3.2: Ensure high recovery of non-finite resources, e.g., nitrogen, organic compounds for soil improvement, and other nutrients to meet societal needs.

4. Protection of biodiversity and ecosystems. Expansion of WWM systems negatively affects the planetary boundary of land system changes [13]. Regarding the Planetary Boundary of Biosphere Integrity, which includes loss of biodiversity and extinctions, ecosystems at the location of WWM systems in the recipients and potentially where sewage sludge is applied could be negatively impacted. The potential effect from application of sewage sludge is not clear, but biodiversity could be negatively affected, according to Manzetti et al. [34]. Regarding accumulation of heavy metals, such as copper, zinc, and mercury, studies show moderate accumulation in the soil [35]. Some metals, such as aluminium and iron that are used in precipitation chemicals, are abundant in nature and the risk that emissions of these substances would cause a systematic increase in nature is therefore low [36].

The third socio-ecological principle state that physical manipulation or disturbance of ecosystems can impact the long-term productivity and biodiversity [14]. The loss of species and genetic resources was also one focus area in Our Common Future [12]. Of course, the location of a WWM system is an irreversible physical manipulation of nature. SDG15, which concerns ecosystems on land, and SDG6's target 6.5 on water-related ecosystems [1] are in line with the Planetary Boundaries and the social-ecological principles, but although a WWM system is an adverse intervention in nature, it is also a necessity for ecosystems both in waters and on land. The location of WWM systems and their expansion should be carefully chosen, with optimal design that minimizes the negative impact. Another example of land manipulation that is an indirect consequence of WWM is the harvest of biomass as a source for renewable energy or chemical production. This production must be done in a way that preserves biodiversity and the long-term productivity.

Objective 4.1: Locate and design WWM systems and their expansions so that disturbance and negative impact on ecosystems is minimized.

Objective 4.2: Produce crops, for chemicals or renewable energy production, in a way that preserves the biodiversity and the long-term productivity of the land.

Objective 4.3: Ensure that sludge application does not negatively impact biodiversity or cause accumulation of harmful substances in the soil.

5. Substances of emerging concern. The chemical pollution in our society today is addressed by several of the sustainability definitions. There are the Planetary Boundary Novel Entities [13] and the SDG target 6.3 [1] that address reducing pollution and minimizing the release of hazardous chemicals. DANVA [37] interprets the SDG14, better life below water, and states that removal of pharmaceutical residues and plastics, including microplastics, is needed to accomplish this goal. Further, the second socio-ecological principle [14] concerns substances produced by society that must not systematically increase in the ecosphere. The WWM system is one pathway for these substances to reach the ecosphere, which provides an opportunity for separation. However, for a long-term sustainable solution of phasing out these chemicals, focus must be on the source in terms of a ban or source reduction.

Objective 5.1: Do not use hazardous substances.

Objective 5.2: Influence upstream stakeholders to minimize the use of hazardous substances.

Objective 5.3: Contribute to minimizing hazardous substances in nature through wastewater treatment.

6. Climate change. Connected to loss of biodiversity are the Planetary Boundaries on climate change and ocean acidification [13], with CO_2 emissions as one joint problem. A sustainable WWM system should reduce its climate impact to a low level, using renewable energy, with no fossil CO_2 emissions, and minimizing the emissions of N_2O and CH_4 from treatment processes and collection systems. This is in line with the first socio-ecological principle [14], which states that usage of fossil fuels for chemicals, electricity, and other purposes must end. As mentioned, recovering and efficiently utilizing carbon and other resources in the wastewater will be very important to decrease the climate impact of WWM. Mitigating climate impact is important to achieve several SDGs [1], and for SDG7 in particular it is important to reduce reliance on fossil origin for energy production. Some actions on mitigating climate change can positively influence the planetary boundary of freshwater consumption and the global hydrological cycle, both of which are significantly impacted by climate change. SDG13 addresses both limiting and adapting to climate change, both aspects must be considered in the planning of future WWM.

Objective 6.1: Use only renewable resources for chemicals, energy, or other purposes.

Objective 6.2: Minimize emissions of N_2O and CH_4 from WWM, including the sewage system, treatment processes, and discharge.

Objective 6.3: Contribute to the reduction of CO_2 emissions from fossil sources in society, for instance by replacing fossil gas with biogas from wastewater treatment.

Objective 6.4: Optimize utilization of the existing carbon in the wastewater.

Objective 6.5: Establish WWM systems with flexibility to climate change and that have climate adaptation plans, developed together with other stakeholders.

7. Energy and resource use. Climate impact and energy use are strongly linked since much of the energy usage and electricity supply globally has fossil origin, and the burning of fossil fuels accounts for a large share of the CO_2 emissions. Replacing the fossil energy with renewable energy is therefore a requirement, both for the first socio-ecological principle [14] and for not crossing the Planetary Boundary for climate change [13]. Already in 1987, Our Common Future [12] put focus on energy and, to fulfil SDG7, affordable and clean energy [1], WWM should use only renewable energy sources for electricity, heating, cooling, chemical production, etc.

Another way of contributing to SDG7 would be for WWM to utilize as much of the energy as possible in the wastewater, such as for carbon source, converted to biogas, and through heat recovery [38]. Increased energy efficiency is important for renewable energy to be sufficient for all the societal needs. WWM is, in general, energy demanding, especially reduction down to very low effluent pollutant levels. An energy-wise sustainable development could be interpreted as not to treat the wastewater more than necessary in order to protect the aquatic environment. Nor can it be considered energy-efficient to have combined sewer systems or a lot of infiltration and inflow, since they lead to pumping and treating rainwater.

From a sustainability perspective, energy is often regarded as a limited resource, and parallels can be drawn to the use of other resources, such as the extraction of metals, scarce elements, fossil raw material, etc. The use of these resources needs to be restricted and their recycling increased to be sustainable in line with the socio-ecological principles [14] and to realize SDG12, Responsible Consumption and Production [1]. To achieve SDG12, it is necessary to minimize waste generation, use resources more efficiently, and influence consumer behavior toward more sustainable practices. Treatment processes used in WWM should therefore be chosen and operated towards minimized waste and resource consumption, which could become extra important at scarcity, such as precipitation chemicals.

Objective 7.1: Optimize utilization of the energy in the wastewater (thermal, chemical).

Objective 7.2: Minimize energy use and establish energy efficient WWM systems.

Objective 7.3: Do not treat the wastewater to lower levels than the recipients require if it comes with an increased energy or resource demand.

Objective 7.4: Contribute to the production of renewable energy.

Objective 7.5: Restrict the use and extraction of resources and contribute to recycling.

8. Water reuse. For SDG12, responsible consumption and production [1], consumer behavior should be guided towards lower water consumption. Increased water reuse can also contribute to increased energy efficiency (SDG7) and SDG target 6.4, increased water-use efficiency. Water reuse can be achieved through for instance grey water recycling, or the treated wastewater can be used for various applications. Treatment technologies for water reuse can be specific for the end use of the recycled water, giving a cost-effective treatment system called a "Fit-for-Purpose" strategy [39]. However, for some types of water reuse there is also the social acceptance to work on.

Objective 8.1: Guide consumer behavior towards lower water consumption.

Objective 8.2: Contribute to increased water reuse, such as upstream and downstream WWM systems, and internally at potential WWTPs.

9. Cooperations on different levels. Local, national, and international cooperation will be an important foundation to succeed in developing future sustainable WWM. Our Common Future [12], the SDGs [1], the Planetary Boundaries [13], and the socio-ecological principles [14] all agree on cooperations being crucial. For instance, although access to safe drinking water and adequate, equitable sanitation and hygiene (SDG target 6.1 and 6.2) is in general fulfilled in developed countries, a sustainable WWM must not only look to its own system, but contribute, cooperate, and share knowledge locally and internationally, as emphasized by SDG17 and targets 6a and 6b. For sustainable cities, SDG11 and part of SDG9, the water sector needs to cooperate with other sectors within a city. To fulfil SDG13 on climate action, WWM need to be flexible and work out climate adaptation plans together with various stakeholders. SDG target 6.5, to implement integrated water resources management, also requires more cooperation. Cooperating with different educational and research institutions could contribute to SDG4, Quality Education—Ensuring inclusive and equitable education for all. There are many more examples of why interaction and cooperation are needed from local up to international level.

Objective 9.1: Cooperate and share knowledge on local, national, and international level within the water sector and with other sectors.

Objective 9.2: Cooperate with stakeholders and educational and research institutions to contribute to equitable education for all.

10. Fairness and other social aspects. Connected to cooperation is the social aspect of how resources are used and distributed in the world. The fourth socio-ecological principle [14] concerns fair and efficient use of resources with respect to meeting human needs. A WWM system is, within a society, a fair way of using resources for equitable WWM for everyone. However, resources should be fairly distributed globally as well and regarding WWM, that is not fulfilled. This is also included in SDG10, Reduced Inequalities—Addressing income and social inequalities within and among countries. Greater investments and resources are needed for WWM in developing countries, but to align with the SDGs [1], the quality and level of WWT also needs to be enhanced everywhere, which demands more resources. Balancing these dual demands is a challenge. The reliance for the future is likely on the development of processes that efficiently reduce pollutants by utilizing the resources present in the wastewater.

Contributing to global fairness, when it comes to resources and other, is an important social sustainability aspect. Likewise, as previously written, so is contributing to improving SDG1, 2, 3 and ensuring safe sanitation. There are other social sustainability aspects, not unique for the WW sector, but requiring efforts on, for example, improving gender equity (SDG5), promoting decent and fulfilling jobs (SDG8), and reducing inequalities (SDG10). Examples of necessary efforts include ensuring equal pay, diversity on all levels, preventing discrimination, and supporting labor rights. For SDG11, Sustainable Cities and Communities, the WW sector needs to participate in building fair, inclusive, and resilient societies.

Objective 10.1: Contribute to resources for WWM being fairly distributed in the world.

Objective 10.2: Design and operate WWM towards minimized waste and resource consumption.

Objective 10.3: Contribute to a labor market with gender equity, diversity on all levels, no discrimination or inequalities, and that supports labor rights.

Objective 10.4: Participate in building fair, inclusive, and resilient societies.

11. Economy. We have primarily addressed the environmental and social dimension, with economy as the third of the three basic dimensions of sustainability remaining. The integration of economy and sustainable development was one of the fundamentals in Our Common Future [12], and several SDGs are within the economic dimension, where SDG8 regards economic growth, and SDG9, 10, and 12 also have economic character (Figure 3). Furthermore, economy usually establishes itself in most decisions and sustainability discussions. Grönlund [7] discusses sustainable wastewater treatment and brings up a citation by Balkema et al. [40] "economic sustainability is usually implied as paying for itself", with costs not exceeding benefits. Grönlund states [7] that if the monetary flow is seen as a subsystem supporting the long-term sustainability of a society, then some subsectors of the society can have higher costs. Food, drinking water, and wastewater could be argued to be such subsectors with inappropriate wastewater treatment threatening the long-term environmental supporting systems to society. Further Grönlund [7] lifts the hierarchical level regarding sustainable WWM, with focus often being on the details of a WWTP instead of looking at an entire region when it comes to economic sustainability.

Objective 11.1: Make responsible long-term investments that contribute to economic stability.

Objective 11.2: Contribute to a well-functioning infrastructure with a high level of resilience and civil preparedness that supports society and economic development.

Objective 11.3: Promote WWM systems that are adaptable and flexible to future changes in loading, demands, and external circumstances.

3.3. Consequences and Trade-Offs from Combining Sustainability Definitions

The areas and objectives specified in Section 3.2 holistically cover what sustainable WWM needs to fulfil. The SDGs alone impose many not easily compatible demands on future WWM and combining them with the other sustainability definitions makes it even more challenging. Some demands seem contradictory, and trade-offs needs to be carefully considered.

For instance, an anticipated demand for many WWTPs is removal of pharmaceutical residues, which DANVA [37] associates with SDG14 and aligns with the recent EU directive [41]. Although technologies for removal exist, they are energy or carbon intensive and combining implementation of these technologies with increased energy efficiency (SDG7) presents a significant challenge. Likewise, for SDG7 and SDG15, to restore ecosystems on land WWM can require removal of more pollutants than today. With existing technologies, this generally entails higher energy and resource consumption. Ultimately, the question becomes one of prioritization: should we focus on enhanced pollutant removal or on ensuring clean energy for all? This raises the broader issue of how to balance one SDG against another.

Perhaps future sustainable WWM could focus on improving their core business, removal of pollutants, and simultaneously invest in research on more energy or resource efficient WWM processes. WWM could also meet an increased energy demand by investments in more internal renewable energy production, with wastewater heat recovery representing one option to reduce net energy consumption [38].

The energy sector might also develop in a way that allows for an increased consumption of renewable energy. A different strategy would be to set today's energy and resource consumption as the limit and only allow for improvements possible within that limit. Yet another approach could be to decrease the volume of wastewater to treat by increasing water reuse, decreasing water consumption, and reducing infiltration and inflow. Treating less water uses less energy.

However, when considering the Planetary Boundaries, another approach might be needed. A study by Ryberg et al. [42] evaluated if a Danish WWM company could be considered sustainable based on the share of safe operating space within the Planetary Boundaries that wastewater treatment occupies. For more than half of the Planetary Boundaries, the assigned shares were exceeded, and they recommend prioritizing actions to reduce impacts related to climate change and nutrient emissions in water. This is consistent with Lima et al. [43], who studied two different WWM systems, and both systems exceeded eight of the assigned shares of Planetary Boundaries, including climate change and biogeochemical flows of nutrients.

When it comes to applying strong or weak sustainability to WWM, the implications differ significantly. According to weak sustainability, WWM system expansion is acceptable if the sum of capital is preserved, but is it possible to anticipate all the values that a natural capital may provide, both now and in the future? Peoples' knowledge and preferences regarding the values associated with forests, waters, fields, or mountains can change over time. As a result, substituting natural capital with human-made capital cannot ensure the preservation of all its values.

For instance, to pollute a swimming area and replace it with concrete swimming pools, or to let a fishing stock go extinct and instead start fish farms, may result in the loss of other values of the natural capital. Nevertheless, current centralized WWM systems do not align with the principles of strong sustainability and even with system changes to decentralized or source separating systems or even wetlands, natural capital would still be impacted. WWM systems will affect land, recipients, ecosystems, etc., both negatively and positively. We must strive to minimize the negative impacts and maximize the positive benefits. Further distinguishing the strong/weak concept, as Luthman et al. [29] suggest (very weak, weak, strong, very strong), would facilitate its practical application. In practice, positions falling between weak and strong sustainability, with Luthman et al.'s categorization [29], are likely to be the most relevant. The precise placement, however, should be determined case-by-case, reflecting local conditions and priorities.

How, then, should all the various demands, different aspects, and trade-offs associated with the holistic sustainability concept be addressed? A single, universal solution to all sustainability challenges and all contexts risks oversimplifying complex issues and is unlikely to maximize sustainability improvements. Different contexts face different barriers, such as regulatory constraints, levels of system development, variations between developed and developing countries, and differences in local priorities and needs. These barriers can constrain the range of feasible options and shape which sustainability objectives are prioritized in practice. As a result, a universally defined solution may fail to identify the most sustainable pathway in specific settings. While barriers and challenges will inevitably remain, a clear understanding of relevant sustainability objectives will support more informed decision-making. Each case should therefore be assessed individually to ensure the most sustainable path forward, taking into account site-specific conditions and contextual constraints, as emphasized by Kehrein et al. [33]. This highlights the need for a sustainability definition that is sufficiently structured to support assessment, yet flexible enough to accommodate contextual variation.

Findings from a review by Silva [44] suggest that a circular perspective may represent a promising pathway towards sustainability in many contexts, particularly when combined with the use of decision-support tools, an approach that is enabled by the definition and aligned criteria proposed in this study. The relevance of circularity for sustainable WWM is further supported by Kehrein et al. [33], who present a comprehensive framework that facilitates practical implementation from a resource recovery perspective. Circularity incorporates several principles included in the proposed definition, such as reduction, recycling and recovery. While the framework by Kehrein et al. [33] provides valuable guidance for the strategic planning of water resource factories, the present study places greater focus on the conceptual foundation of sustainable WWM and integrates the social dimension more strongly, through the areas ‘Sanitation and hygiene’, ‘Cooperations on different levels’, and ‘Fairness and other social aspects’. These aspects are included to ensure a holistic understanding of sustainability across all dimensions.

The proposed definition also aligns well with the work by Estévez et al. [45], which presents a road map and criteria for a potential environmental certification system. Shared elements include the protection of ecosystems and biodiversity, sustainable resource use, and considerations related to safety and labor conditions. The work and indicators proposed by Estévez et al. [45] remain highly valuable for practical assessment, but while their work is grounded in European legislative documents, the definition proposed in this study adopts a forward-looking sustainability perspective, defining requirements for future sustainable WWM rather than reflecting existing regulations. A further distinction lies in the social dimension: whereas Estévez et al. [45] focus more narrowly on socio-economic aspects, the proposed definition places stronger emphasis on cooperation, knowledge sharing across levels, and global fairness.

This convergence across studies underscores the potential of the proposed definition to support sustainability assessments and decision-making for wastewater management. However, applying the definition of sustainable WWM in practice requires an assessment method and clearly defined criteria to address trade-offs and support transparent decision-making.

3.4. Assessing Progress Towards Sustainable Wastewater Management

As trade-offs between sustainability objectives inevitably arise when WWM systems are developed or modified, a systematic methodology for identifying and evaluating these trade-offs is required. MCA is a tool that can be used to assess how different choices of WWM systems align with the sustainable development objectives. A general stepwise

MCA approach includes, among other steps, defining the assessment aim, selecting the criteria to be included, and allocating weights to those criteria [10].

When the aim is to compare sustainability performance, the selection of criteria must be sufficiently representative to provide a meaningful comparison. Using the objectives of the proposed sustainability definition as the basis for criteria selection enables alignment between objectives and criteria, thereby providing a foundation for a holistic sustainability assessment. Trade-offs are primarily addressed during the weighting step, allowing differences in regulatory conditions, system development levels, and local priorities to be explicitly reflected, thereby making the definition practical and adaptable to local contexts. An example of an application is a case study comparing the sustainability of different technologies for the removal of pharmaceutical residues from wastewater using MCA [10].

In the water research field, there are many publications suggesting criteria for assessing sustainability [16,46,47]. The criteria are typically categorized in the environmental, social, and economic sustainability dimensions. However, there is no consensus on whether these three dimensions are sufficient. Malmqvist et al. [16] suggested adding the dimensions 'health and hygiene' and 'functional and technical'. Marques et al. [46] advocate to include the dimensions 'governance' and 'infrastructure'. Opening for addition of more dimensions can lead to a lack of coherence.

The most important consideration should be that the relevant aspects are included in the sustainability discussion, and then the arrangement into dimensions can be seen as more of a structural issue. We therefore suggest adding the aspects brought up by Malmqvist et al. [16] and Marques [46], while organizing them under the three fundamental dimensions. For instance, 'Health and hygiene' is partly included in all dimensions but most strongly connected to the social dimension. Technical and functional can be seen as economic aspects because their primary consequences are economical. 'Infrastructure' that Marques et al. suggest [46] includes the aspects flexibility, adaptability, and reliability, which are commonly found in the economic dimension. The focus of the proposed definition is thus to ensure comprehensive coverage of relevant sustainability aspects without introducing additional sustainability dimensions or explicitly defining interconnections between them [48].

3.5. Sustainability Criteria

Building on the proposed definition of sustainable WWM, structured through the areas and objectives outlined above, the next step for practical application is an assessment method and the identification of concrete sustainability criteria. Sustainability criteria for WWM have been frequently presented in the literature [49,50]. Malmqvist et al. [16] state that the lists of criteria vary for differing applications, they should be selected for each context and the total number of criteria should be kept low to facilitate efficient work and involvement with stakeholders. Availability of information and stakeholder preferences are important considerations in criteria selection. However, data availability should not be interpreted as always requiring direct measurements, proxy indicators can sometimes provide sufficiently accurate and relevant information for a criterion to be included in an assessment.

To complement the proposed definition of sustainable WWM and make it practical applicable, sustainability criteria are presented in Table 2. The criteria are organized according to the same structure of areas as presented in Section 3.1, clearly indicating which objectives each aligns with. Criteria from different references that aim at the same aspect but are named differently have been combined into one to avoid doubles. When used, a criterium can be split up to be more specific and precise.

The criteria need to be specified in appropriate units when applied, suggestions exist in the referenced sources. Different approaches can be used when operationalizing the criteria. One approach is to select units that best suit the specific case and context, facilitating meaningful comparisons within the assessment Another approach is to normalize the criteria using standardized units, such as per population equivalent (pe) or unit volume of wastewater, which supports comparability across assessments and facilitates the use of reference values. Linking the proposed criteria to established operational indicators, for instance those aligned with the European Directive concerning urban wastewater treatment [41], would further enhance the applicability of this proposed definition.

A potential concern is that the proposed definition may not be adaptable to different contexts. However, the proposed definition and sustainability criteria aligns well with previous evaluations of sustainability in different contexts, for example a case study on different pharmaceutical removal technologies in Sweden [10], an assessment of urban wastewater management in Iran [51], a study of small-scale WWTPs in low and lower-middle income countries [52] and an evaluation of a community-based wastewater treatment system in Indonesia [53]. Together, these examples demonstrate that the proposed definition is adaptable across diverse contexts although specific case-specific criteria selection is encouraged.

Table 2. Sustainability criteria for wastewater management, organized into 11 areas, with each criterium linked to corresponding objectives (in parenthesis) and supported by prior publications.

Sustainability Area	Criteria (Related Objective)
1. Sanitation and Hygiene	Access to urban water services [46,54] (1.1) Health risks of infection or chemical risk [16,55] (1.1)
2. The ecosystem of the recipients	Proportion wastewater flows safely treated [1] (2.1) Recipient impact: Discharge of phosphorous, nitrogen, organic matter, suspended solids, pathogens, acidifying substances etc. [16,17,40,46,48,54–56] (2.2, 2.3) Effects on the aquatic ecosystem, exceeding environmental quality standards [16] (2.2, 2.3, 2.4)
3. Recovery of nutrients	Nutrient recovery: Recycling of N, P, K, S to agriculture or other applications [16,40,48,55] (3.1, 3.2)
4. Protection of biodiversity and ecosystems	Negative impact on groundwater [47,54] (4.1, 4.2) Air pollution: Polluting emissions to air excl. greenhouse gases [47,55] (4.1, 4.2) Contamination of sediment [47] (4.1) Land area used [40,55] (4.1, 4.2) Negative impact on soil ecosystems affecting biodiversity, land fertility or habitats, exceeding environmental quality standards [16,47] (4.1, 4.2) Toxic compounds, heavy metals and substances of emerging concern to soil and agricultural land habitats, exceeding environmental quality standards [16,47,48,54,55] (4.3)
5. Substances of emerging concern	Use of products with hazardous components [48] (5.1) Chemical use [40,55] (5.1) Release of heavy metals, toxic compounds and substances of emerging concern to water [40,54] (5.2, 5.3)
6. Climate change	Climate impact through greenhouse gas emissions [16,48,54,55] (6.1, 6.2, 6.3, 7.4) Optimal resource utilization or reuse [40,55] (6.4)
7. Energy and resource use	Energy use: Total energy use and energy recovered [16,40,46,48,54–56] (7.1, 7.2, 7.3, 7.4) Resource use: finite, critical non-renewable resources [16,40,47,48,54,55] (7.5, 10.2) Waste production, split in recyclable and non-recyclable waste [40,47] (7.5, 10.2)
8. Water reuse	Total drinking water consumption [55] (8.1, 8.2) Wastewater production [40] (8.1, 8.2) Water reuse: Proportion of wastewater reused [40] (8.2)
9. Cooperations on different levels	Knowledge and organizational requirements [40,54,56] (9.1) Local participation, responsibility, development and knowledge gain [16,40,46,47,55,56] (9.1, 9.2) Collaboration and communication between actors [16] (9.1, 9.2) External consequences: institutional, legal, political support [16,40] (9.1, 9.2)
10. Fairness and other social aspects	Public perception: awareness, acceptance, understanding (10.3, 10.4) Social inclusion and contribution to equity [16,47,54,55] (10.3) Work Environment [46,54] (10.3) Safety and security risks [48] (10.3) Effects on surroundings: Noise, smell, other disturbances or contribution of aesthetical or recreational value [40,47,48,56] (10.1, 10.4)

Table 2. *Cont.*

Sustainability Area	Criteria (Related Objective)
11. Economy	Annual cost for investment, operation, staff, transport, emission tariffs etc. [16,17,46,48,56] (11.1) Financial risk [16,55] (11.1) User cost [56] (11.1) Technical function: Reliability, work demand, maintenance needs, technical demand, performance level [16,17,40,46,48,54,55] (11.2, 11.3) Vulnerability and robustness [40,54,55] (11.2, 11.3) Flexibility and adaptability [54,55] (6.5, 11.3)

4. Conclusions

A comprehensive sustainability definition for WWM was developed in this study, by exploring and interpreting key publications and sustainable development frameworks in a wastewater context. The resulting definition holistically covers what sustainable WWM needs to fulfil and is structured in the eleven areas: sanitation and hygiene, the ecosystem of the recipients, recovery of nutrients, protection of biodiversity and ecosystems, substances of emerging concern, climate change, energy and resource use, waste reuse, collaborations on different levels, fairness and other social aspects, and economy. Each area is further specified by objectives that clearly describe its content and address what should be considered for sustainable WWM. This holistic perspective helps ensure that no critical aspects of sustainability are overlooked. It also proposes a uniform basis that enables synergies between working groups without compromising other sustainability aspects.

The definition of sustainable WMM induce multiple demands on WWM, for which there is no universal solution, instead, each case must be assessed individually to identify the most sustainable option. To support this process, this study also present reference-based sustainability criteria aligned with the objectives. This makes the definition suitable for use in multicriteria assessment methods. The use of clearly defined criteria enables decision-makers to systematically evaluate trade-offs and to assess how changes in WWM systems influence sustainable development, thereby supporting transparent and well-founded decision-making.

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