Application of wastewater treatment in sustainable design of green built environments: A review

Hamidreza Rashidi\textsuperscript{a}, Ali GhaffarianHoseini\textsuperscript{b,\dagger}, Amirhosein GhaffarianHoseini\textsuperscript{c}, Nik Meriam Nik Sulaiman\textsuperscript{a}, John Tookey\textsuperscript{b}, Nur Awanis Hashim\textsuperscript{a}

\textsuperscript{a} Department of Chemical Engineering, Faculty of Engineering, University of Malaya (UM), Malaysia
\textsuperscript{b} Department of Built Environment Engineering, School of Engineering, Faculty of Design and Creative Technologies, AUT University, Auckland, New Zealand
\textsuperscript{c} Department of Geography, Faculty of Arts and Social Sciences, University of Malaya (UM), Malaysia

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\textbf{A B S T R A C T}

Discharge of untreated wastewater is one of the most general performances threatening the local environment. Moreover, urban and rural regions are increasingly confronting challenges towards managing access to clean water supplies. Contemporarily, the growing interest in development of green buildings is observed while reflecting the necessity for creating environmentally responsive built environments. The main purpose of sustainability in green buildings is to mitigate the negative impacts of buildings and the respective lifecycle on the natural environment. It is essential to represent the substantial impact of green building evaluations as an inherent part of future building policies for creation of healthy living environments. Nevertheless, contemporary complex wastewater treatments process requires significant energy resources resulting in elevated emission levels. Likewise, diverse wastewater treatment practices may require considerable energy consumption deteriorating sustainability provisions. Consequently, this article proposes utilization of hybrid membrane wastewater treatment techniques to approach sustainable design of green built environments.

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\dagger Corresponding author.
\textit{E-mail address: ali.ghaffarianhoseini@aut.ac.nz (A. GhaffarianHoseini).}

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1. Introduction

Sustainability is principally defined as the appropriate integration of environmental fineness, economic affluence and social even-handedness [1,2]. Indeed, the notion of sustainability emphasizes the inseparable incorporation of economy, environment and welfare [3]. Various studies argue that it is a particularly important task to define and interpret the essence of sustainability before any green design implementations. Thus, extensive reviews concerning the implications of sustainability (with a view to its quality indicators) have been developed. In this regard, a recent study [4] provides an explicit elaboration of the main indicators of sustainability by analyzing its current implications in buildings:

“A sustainable building is characterized by the following fundamentals:

– Demand for safe building, flexibility, market and economic value
– Neutralization of environmental impacts by including its context and its regeneration
– Human well-being, occupants’ satisfaction and stakeholders’ rights
– Social equity, aesthetic improvements and preservation of cultural values” [4].

Looking into the significance of sustainability, development of low-carbon cities is proposed as an inherent component of future policies towards sustainable developments [5–10]. At present, low-carbon architecture is increasing in popularity in relation to the concurrent incorporation of social, natural, environmental and architectural trends [11,12]. Consequently a low-carbon economy has been developed to prepare for the implementation of clean energy. A significant amount of CO₂ emissions are recognized to be based on architecture, engineering and construction (AEC) implementations. Therefore a low-carbon economy is expected to result in sustainable architectural progress, ensuring the preparation of human welfare [13]. Likewise, significant energy saving can be achieved by applying energy-efficient building design and construction maintenance [14].

It is crucial to promote public awareness of the significance of energy efficiency as well as reuse and recycling as means to achieve sustainability. Moreover, a wide range of pioneering sustainable technologies have been developed such as solar energy collection—conversion, smart façades, solar heat and power systems, Internet-enabled energy services and smart buildings [14].

Various technologies have been developed to reduce the CO₂ emissions of new and existing buildings [15]. Cities are well known to be the foremost contributors of greenhouse gas (GHG)

![Fig. 1. Integrated impacts and interactions of air pollutants and climate parameters on built infrastructure, Adapted from [19].](image-url)
emissions [16]. Accordingly, the human race is exposed to the particular menace of energy scarcity and climate change. The majority of climate changes and global warming during the last 50 years have been identified to be correlated to GHG emissions, i.e. CO2 based on human activities [13,17].

Climate change has thus become one of the most vital controversies of the current generation, attributable to its undesirable influence on the planet [18]. Permanent anthropogenic emissions of GHGs into the atmosphere are expected to modify meteorological sciences. Consequently, precipitation and sea-level alterations, changes in geological soil conditions and ground water levels, increased occurrence of intense climatic events, and global warming occurs [19].

The worldwide mean surface temperature has increased by 0.6 °C since 1900 based on the increment of GHG emissions [20]. If existing emission tendencies are maintained, an additional 1.8–4.0 °C rise by 2100 will be unavoidable [20]. In addition, air pollutants, such as SO2, O3 and NOx, can be listed as corrosive gases, depreciating building materials based on chemical routes. Moreover, CO2 emissions influence environmental conditions and climate changes negatively. Building material durability, building integrity and transport infrastructures are also substantially affected [19]. Fig. 1 represents the impact of the air pollutants under consideration on the built infrastructure.

Urban areas are multifaceted structures that must consider social, economic and environmental essentials. More than 50% of the world’s population currently live in cities. Urban areas are expected to be populated by approximately five billion people by 2030 [18]. Therefore the urbanization growth-rate highlights the importance of climate change due to anthropogenic GHG emissions based on rigorous energy consumptions (Table 1) and surplus wastewater amplifications [18,21–27]. The urban-heat-island (UHI) effect has been conceptualized based on the comparison of temperature variation between certain urban areas and neighboring rural districts. It has formed the concept of regional climate change [28]. The UHI effect arises as a result of anthropogenic environmental alteration in consequence of substituting local vegetation with engineered materials that boost thermal storage capacity and radiative properties [29].

Currently, architectural advisors offer consultation services to developers prior to project materialization in order to sustain the natural and built environments [30]. In this regard, water conservation, waste minimization and reuse implementations within the built environment industry are recommended [30]. Correspondingly, it is postulated that efficient utilization of water during the lifecycle of buildings, could contribute to development of sustainable buildings [4]. Considering the notion of sustainability in future cities, this study concentrates on the essence of wastewater treatment applications in the sustainable design of green buildings.

2. Intergenerational equity

Scholars, economists and philosophers have been constantly concerned with the notion of intergenerational equity while approaching sustainability [31–34]. Intergenerational equity has been interpreted based on multidisciplinary factors. Environmental researchers consider global warming, climate changes and sustainable development pertaining to notions of intergenerational equity. Environmental intergenerational equity is the fact that current generation may not leave an adequate inheritance of natural resources for future generations [31]. In other words, intergenerational equity highlights the need for thoughtfulness in relation to intergenerational justice. Recent environmental degradation has urged researchers to promote environmental intergenerational equity [35–37].

Although there exists no absolute index of intergenerational equity, it is considered to be the gradual impact upon the environment over a particular period between two generations. Alternatively, environmental quality is sustained while generations change, hence corroborating appropriate intergenerational equity. Currently, global warming and climate change are considered to be the most critical intergenerational equity issues. The present generation is urged to stop environmental deterioration. In particular, water resource management and wastewater treatment play a significant role in terms of ensuring sustainable development for future generations [38].

3. The essence of green built-environments

3.1. Background

In recent years, a growing interest in the development of green buildings has been observed, reflecting the necessity for creating environmentally responsive and adaptable built environments. With a view to the issue of energy, it is emphasized that the buildings and their lifecycle phases consume approximately 40% of global energy [39]. Likewise, various studies highlight the negative consequences of climate change and global warming. As a result, governmental organizations and policy-makers are encouraged to develop legislative policies for developing healthy and energy-efficient buildings for future green eco-cities.

3.2. Significance of sustainability

The term ‘sustainability’ refers to a broad concept, encompassing various interrelated parameters regarding the environment, people and energy resources. The significance of sustainability for built environments is well-known as a multidisciplinary approach to the deliberation of environmental, economic and socio-cultural concerns. It is to mitigate the negative environmental impacts and to harmonize the living environments with socio-economic patterns. “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [40].

A building is ‘sustainable’ once the entire interconnected parameters of sustainability (environmental, economic and socio-cultural attributes) are fully taken into consideration [39]. Expanding upon these interpretations, new circumstances for incorporating environmental, socio-cultural and economic sustainability in creating responsive buildings have been implemented in recent years [41]. Recent studies are still concerned with standardized interpretations of sustainability based on a definite meaning of sustainability in built environments [4,42]. According to [43,44], strategic design, optimized design, dematerialization of design, longevity of design and design lifecycle are essential components of achieving sustainable built environments.

3.3. Role of low-energy buildings in sustainable development

Approximately 40% of worldwide energy is used in construction process of buildings, as well as their maintenance, operation, renewal and other interrelated lifecycle phases [45–47]. As such, sustainable development of future cities is crucial in creating a joint agenda for national government policies within the construction and building sectors. In view of this, sustainable approaches and eco-technologies have been innovated to reduce the rate of energy consumption in relation to resolving the negative impact of environmental hazards [42,48]. Attempts have
been made towards achieving this important goal [48], leading to development of low-energy and zero-energy buildings. These buildings are integrated with advanced technologies, energy-efficient systems and renewable energy resources to enhance buildings’ energy performance [49].

It is emphasized that the entire building energy consumption lifecycle consists of embodied and operational energies [45]. The energy used during a building's operation for such purposes as cooling, heating, lighting, etc., is called 'operational energy’. Energy used during the development and construction lifecycle phases excluding the building operation phase is called ‘embodied energy’ [50]. Literature confirms the rate of operational energy consumption is generally higher than the embodied energy consumption in buildings. Nevertheless, with a focus on the proliferation of low-energy buildings, it is also essential to recognize the significant role of embodied energy [45,50]. This study provides a state-of-the-art review of green roofs [51–53] as a sustainable design solution for the development of greener built environments.

4. The green building concept

4.1. The concept of green building

Li et al. [54] expresses that: “green building should be energy saving, land saving, water saving and material saving, environment-benign and pollution reducing.”

The main purpose of sustainability in green buildings is to mitigate the negative impact of the buildings and their lifecycle on the natural environment [55]. According to [56–58], green buildings are developed to mitigate environmental hazards, preserve natural resources, decrease waste consumption, enhance the indoor environment and improve the energy efficiency of buildings. Detailed objectives of sustainability encompass five main attributes. They include resource efficiency, energy efficiency, air quality enhancement, environmental congruity and integrated system approaches [59]. It is noted that analysis of sustainable buildings is correlated with the preservation of “energy, water and land resources” [60].

Utilization of renewable energy resources and recycled materials contributes significantly to the ultimate goals of green buildings [60]. To enhance the ultimate performance of green buildings, it is essential to focus on the role of occupants in relation to the operation and energy performance of buildings [61,62]. It is important to represent the impact of green building evaluations as an inherent part of future building policies for creation of healthy living environments. According to [63], green building evaluation includes versatile interrelated sustainable indicators. The concept of ‘water conservation’ has become a significant constituent of this green building. Average rainwater resources in different countries are compared and represented in order to indicate the importance of wastewater treatment in buildings.

Recent studies highlight the role of ‘water efficiency’ as one of the main sustainable indicators [64,145]. Similarly, it is deduced that environmentally responsive buildings must incorporate technologies related to water management, water efficiency and re-use of waste [60]. Nevertheless, it is argued that the contribution of green buildings must be beyond the level of environmental responsiveness and energy efficiency. It is suggested to consider the effectiveness of green buildings in providing comfort, satisfaction and well-being for occupants as well [61].

4.2. Assessment of green buildings

There are versatile assessment tools for evaluating, certifying and rating the effectiveness of green buildings. These tools consider their design, construction, operation and maintenance regards to sustainable and green design developments [65]. Reviewing the most globally acknowledged tools for assessing the environmental performance of green buildings, the study summarizes the findings in Table 2 [65]. LEED (Leadership in Energy and Environmental Design) in USA, is one of the most recognized international tools. It is apparent that based on credit classifications, green buildings could receive different certifications. They include Certified (40–49 points), Silver (50–59 points), Gold (60–79 points) and Platinum (80 and above points), respectively, “Sustainable cities”, “Water Efficiency”, “Energy and Atmosphere”, “Materials and Resources” and “Indoor Environmental Quality” are indicated as essential sustainability factors [66]. Looking into the assessment criteria of the Green Mark Scheme, Singapore, there are five main clusters including “Energy Efficiency”, “Water Efficiency”, “Environmental Protection”, “Indoor Environmental Quality” and “Other Green Features and Innovations” [67]. Reviewing the main areas of Comprehensive Assessment System for Built Environment Efficiency (CASBEE) Japan, the assessment principles embrace four modules, namely “Energy efficiency”, “Resource efficiency”, “Local environment” and “Indoor environment” [68]. On the other hand, the Green Building Index (GBI), Malaysia, encompasses six main criteria for the evaluation of green buildings, including “Energy Efficiency”, “Indoor Environmental Quality”, “Sustainable Site Planning and Management”, “Material and Resources”, “Water Efficiency” and “Innovation” [69]. Thus, water efficiency is characterized as a substantial area of concern. Hence, this study draws attention to the significant impact of applying wastewater treatment in green buildings.

5. Sustainability and wastewater treatment

The incongruity between water sources and human demands has frequently been reported with a view to population growth.
This situation requires a fundamental response in relation to sustainable implementations [70]. In this sense, discharge of untreated wastewater and landfills of sewage sludge are the most general acts threatening the local environment [26]. Urban and rural regions (especially in developing countries) are increasingly confronting the challenge of managing accessibility to clean water supplies [27]. Appropriate wastewater treatment significantly influences social-environmental sustainability [25]. Wastewater treatment is generally categorized based on centralized and decentralized approaches [23]. Centralized methods concern a unique treatment resolution of wastewaters. Decentralized techniques allow recovery and reuse of treated wastewater based on multiple treatment methodologies [23]. Utilization of decentralized wastewater treatment techniques has recently gained popularity, particularly for regions suffering water shortages, decreasing the population with limited access to a potable water [23,24,71].

Various wastewater collection systems (sewage networks) and treatment methodologies have been implemented to secure human and environmental healthiness [21]. It is broadly acknowledged that enhancements in worldwide welfare mainly rely upon superior hygiene practices, the accessibility of health amenities, and appropriate wastewater collection and treatment [21]. In arid areas, proper wastewater treatment is particularly advised, due to limited water resources [22]. Indeed, the use of water treatment and its associated applications is also recommended while confronting greenhouse gas emissions [72].

Versatile conventional wastewater treatment resolutions (centralized treatments and water-flush toilets) have not been comprehensively integrated. Besides, a blend of various wastewater flows complicates the recovery process [3]. Moreover, the presence of pathogens and toxic compounds, such as organic micropollutants and heavy metals within wastewater streams, make the treatment process more complex. The process requires significant amount of energy and financial resources resulting in elevated emission levels [3,21]. This article proposes utilization of hybrid membrane wastewater treatment techniques in order to approach the sustainable design of green-built environments.

The study theorizes that, despite the predominant focus of recent studies on the energy efficiency of green-built environments, less attention has been paid to the water efficiency of these buildings. Hence, the application of wastewater technologies as an integrated trend of the building services of green-built environments merit a broader consideration and more in-depth investigation. Theoretical investigations draw attention to the potential of integrating hybrid membrane wastewater treatments and green built environments. This integration is expected to regenerate building wastewater for non-potable purposes. It enhances the performance of green built environments to influence sustainable development principles.

6. Municipal wastewater management

6.1. Municipal wastewater management

One of the main concerns of all countries is environmental pollution control. It is categorized in terms of air, sound, water and wastewater pollution. Although industries and natural disasters can cause air pollution, wastewater usually comes from cities, industrial and agricultural effluents [73].

Wastewater is defined as the discharged water from any municipal or industrial source [74,75]. Furthermore, pollution control and treatment is one of the major health issues for societies. Such pollution is the cause of various mental and physical diseases. Furthermore, human life and social development are especially influenced as regards water consumption and corresponding wastewater production. Due to the concentration of social life quality on water-demand, wastewater treatment for water recycling is introduced as an alternative water resource for domestic and industrial purposes [76,77].

Untreated wastewater generally contains chemicals, such as heavy metals, cyanide, toxic organics, nitrogen, phosphorous, phenols, suspended solids, color and turbidity, from residential and industrial sources. These elements cause numerous environmental and economic problems while also endangering living habitats [78]. Based on the latest global water and wastewater regulations, improvement and modification of established conventional water and wastewater treatment techniques is necessary to achieve higher efficiency levels, especially in urban and municipal areas [79].

6.2. Municipal wastewater characterization

Development of an effective treatment method for untreated municipal wastewater before discharge into urban areas and the natural environment is essential. In order to design a proper wastewater treatment plant and to enable the selection of the most efficient treatment methodology, the need for familiarity with wastewater characterizations is urged. Accordingly, properties and characteristics of general municipal wastewater are represented in Table 3.

The environmental impact of discharging untreated wastewater directly into the environment depends on the effluent properties. Primarily, wastewater originates from municipal, industrial and

<table>
<thead>
<tr>
<th>Contaminants</th>
<th>Unit</th>
<th>Weak</th>
<th>Medium</th>
<th>Strong</th>
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<tbody>
<tr>
<td>Total solid (TS)</td>
<td>mg/L</td>
<td>350</td>
<td>720</td>
<td>1200</td>
</tr>
<tr>
<td>Total dissolved solid (TDS)</td>
<td>mg/L</td>
<td>250</td>
<td>500</td>
<td>850</td>
</tr>
<tr>
<td>Suspended solid</td>
<td>mg/L</td>
<td>100</td>
<td>220</td>
<td>350</td>
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<tr>
<td>Settle able solid</td>
<td>mg/L</td>
<td>5</td>
<td>10</td>
<td>20</td>
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<tr>
<td>BOD</td>
<td>mg/L</td>
<td>110</td>
<td>220</td>
<td>400</td>
</tr>
<tr>
<td>TOC</td>
<td>mg/L</td>
<td>80</td>
<td>160</td>
<td>290</td>
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<tr>
<td>COD</td>
<td>mg/L</td>
<td>250</td>
<td>500</td>
<td>1000</td>
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<tr>
<td>Nitrogen (N)</td>
<td>mg/L</td>
<td>20</td>
<td>40</td>
<td>85</td>
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<tr>
<td>Phosphorus (P)</td>
<td>mg/L</td>
<td>4</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Chlorides</td>
<td>mg/L</td>
<td>30</td>
<td>50</td>
<td>100</td>
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<tr>
<td>Sulfates</td>
<td>mg/L</td>
<td>20</td>
<td>30</td>
<td>50</td>
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<tr>
<td>pH</td>
<td>mg/L</td>
<td>5–7</td>
<td>7–9</td>
<td>9–12</td>
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<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>50</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Grease</td>
<td>mg/L</td>
<td>50</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>No/100 ml</td>
<td>$10^2$–$10^3$</td>
<td>$10^3$–$10^6$</td>
<td>$10^6$–$10^9$</td>
</tr>
<tr>
<td>Volatile organic components</td>
<td>µg/L</td>
<td>&lt;100</td>
<td>100–400</td>
<td>&gt;400</td>
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<thead>
<tr>
<th>Physical</th>
<th>Screening</th>
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<td>Membrane filtration</td>
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<td>Granola medium filtration</td>
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<td>Chemical and biological</td>
<td>Adsorption</td>
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<td>Disinfection</td>
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<td>Fenton reagent</td>
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<td>Ozonation</td>
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<td>Activated carbon</td>
<td></td>
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<td>Ion-exchange</td>
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Table 4 Alternative types of wastewater treatment for municipal wastewater [78–82].
agricultural water consumption, in addition to surface and subsurface sources. Wastewater generation rates are directly or indirectly related to a variety of factors and issues such as, the habitat, community size, life principles, water supplies, water and wastewater equipment, society industrialization rate and the cost of energy and services [78].

Several alternative treatment methodologies, such as chemical, physical and biological approaches, are used to remove pollutants from municipal wastewater. In order to obtain maximum efficiency, single-step wastewater treatment processes are merged with different treatment systems, such as chemical, biological and physical wastewater treatment techniques. Table 4 demonstrates the conventional wastewater treatment methods generally used in municipal wastewater treatment.

6.3. Membrane treatment method of wastewater

Physical wastewater treatment methods are considered to be the most popular techniques for municipal wastewater treatment. They are user-friendly compared to other wastewater treatment approaches. In particular, membrane treatment methods are highlighted as the most common physical wastewater treatment approaches [75,83–86].

Utilization of membranes as physical separators is one of the basic treatment methods used for the separation of chemical and physical components of wastewater according to their pore sizes. Therefore, contaminants with a high permeability can go through the membrane while those with less permeability will be rejected by the membrane. The degree of filtration directly depends upon the membrane pore size. The least efficient membrane is associated with microfiltration (MF), which cannot filter certain contaminants. However, the most efficient membrane is reverse osmosis (RO), which can remove singly charged (i.e., monovalent) ions, such as chloride (Cl) and sodium (Na) [87]. Due to the size of the pores in RO, the selectivity size goes to less than 1 nm only observable by powerful equipment such as microscopic methods.

Membranes are categorized into four major groups based on their pore size, including RO, NF, UF and MF. MF and UF have the lowest efficiency among all the membranes as regards removing the organic components of wastewater. NF and RO are considered to be the most effective. As a result, NF and RO are widely applied in industrial and municipal water and wastewater treatment plants [75].

In addition, RO and NF are the most applicable membrane techniques in municipal- and home-based wastewater treatment. Statistics show an increasing rate of applying these methods based on their special removal characterizations of components, such as nitrate, heavy metals and hardness [88].

Application of membrane treatments, either individually or in a hybrid approach while combined with other separation methods, offers various benefits such as

1. utilization of non-chemical applications during the separation process,
2. application of fewer solid contaminants,
3. user- and economic-friendliness,
4. the need for simpler and less filtration equipment,
5. production of high-quality permeate media for reuse [89].

7. Hybrid membrane use in wastewater treatment

7.1. Municipal hybrid membrane treatment plant flowchart

Hybrid membrane treatment technologies play a significant role in contemporary domestic and municipal wastewater treatment plants. This is due to their integration of chemical and physical filtration methods and the application of solid–liquid separation throughout the process. Among all the hybrid membrane treatment techniques, recently MBRs are more commonly used. A general MBR treatment plant uses a conventional suspended biomass to degrade chemical and physical components by biochemical and biological treatment processes. These processes must be implemented by membrane treatment, such as UF, MF and NF, by the removal of environmental factors by physical separation and filtration. Fig. 2 demonstrates different hybrid membrane treatment techniques in the application mechanism of municipal wastewater treatment plants.

Fig. 2 represents the general hybrid membrane wastewater treatment process in all municipal wastewater treatment plants. However, specific treatment methods that can be applied and used in various wastewater plants are different. This is due to differences in treatment plant region, chemical and physical properties of domestic wastewater and also characterization of population who live in the urban area.

7.2. Membrane bioreactor

Recent studies have confirmed the operational cost-effectiveness of membrane application processes in water and wastewater treatment, as well as highlighting its significant efficiency. In recent decades, membrane bioreactors have been widely applied (both in single and hybrid approaches) throughout water and wastewater treatments as an aerobic physical–biological hybrid membrane treatment technique [90].

Hybrid membrane bioreactor (HMBR) and conventional membrane bioreactor (CMBR) techniques are applied more frequently compared to other membrane bioreactor methods. These two methods provide better results for common MBR-related issues such as fouling and backwashing. It is based on operation condition modification, such as the application of suspended carriers as supporting media for biofilm development in aeration tanks [91,92].

HMBR and CMBR in municipal water and wastewater treatment over one year have been researched [92]. This established that some environmental parameters are improved. COD decline efficiency value rate improved to 94.2% as well as improving the nutrients’ and organic components’ removal efficiency [92]. Weiss and Reemtsma [93] reported on the application of MBR in relation to polar pollutants’ removal from water and wastewater. Measurements were performed using the municipal treatment scale for a 16-month operation period. The results of this study indicate that more than 50% of polar pollutants can be removed by MBR applications during a single filtration cycle. Similarly, [94] studied...
the nonwoven fabric bag (NFFB)-based MBR as a HMBR for domestic municipal and rural wastewater treatment. They reported that (after 20 min filtration cycle 10 mg/L) suspended solid achieved by this method and the sludge generation process effectively decreased while the sludge-removal efficiency represented a distinct decline. This study also highlights the cost-effectiveness and user-friendliness of applying NFFB-based MBR in municipal and rural areas [94].

MBR systems are implemented based on aerobic parameters. However, anaerobic membrane bioreactors (ANMBRs) have recently been applied. These include their use as an effective wastewater treatment methodology in domestic wastewater treatment plants. Excellent effluent quality, low sludge production and net energy production are considered to be the key advantages of utilizing ANMBRs [95].

The ANMBRs treatment method is not usually individually implemented for municipal wastewater treatment. It is due to general municipal wastewater chemical and physical characteristics plus the respective regional technological and environmental factors. However, the recent integration of applying hybrid membrane treatment techniques and ANMBRs as a sustainable wastewater treatment methodology for municipal areas has become broadly popular [95,96]. Contemporary studies have demonstrated the efficiency of hybrid membrane ANMBRs in removing municipal wastewater environmental factors, such as COD and TSS, by up to 90%. However, it is not as effective when confronting components such as total nitrogen (TN) and total phosphorus (TP) due to its anaerobic essence [97]. Nevertheless, pore size and flux as particular membrane operational properties can have a negative effect on COD- and BOD-removal efficiency when utilizing ANMBRs techniques [98–100].

Smith et al. [101] reported the high efficiency of the SANMBRs treatment method in psychrophilic conditions during municipal wastewater treatment. Although this method demonstrates a similar efficiency level compared to conventional MBR methods, it can be performed with lower energy consumption and higher environmental friendliness-levels. Submerged membrane bioreactors (SMBRs) incorporate a combination of conventional activated sludge and membrane filtration. This technique is also affected by the membrane’s operational characterization and parameters [102]. Sabia et al. [103] have reported on the effect of solid-retention time on SMBR efficiency during domestic wastewater treatment. Their results indicated the relationship between microbial metabolism (proliferated during the treatment process), sludge generation and membrane fouling. The results also confirmed the role of the solid-retention time (SRT) in relation to treatment efficiency factors, such as membrane fouling and flux, by producing a filtration cake on the membrane surface [103].

Ma et al [104] highlighted the application of SMBR with the addition of chlorine reclaiming municipal wastewater. According to the results, this method was efficient in reducing the total suspended solid (TSS) and biodegradable organic issues value. However, it was not efficient in relation to other environmental issues, such as dissolved organic matters and UV254. This was due to the production of Trihalomethanes (THMs) during the chlorination stage [104].

Khan and Ilyas [105] reported on the application of the nitrogen loading rate (NLR) on SMBR municipal wastewater treatment plants' efficiency. The approach was implemented on domestic wastewater within different NLR ranges. Correspondingly, they discovered that, by applying the optimum range for NLR (0.15 kg/m3/d) to SMBR WWTP, the COD removal efficiency, total nitrogen (TN) and total phosphorus (TP) were measured as above 95%, 74% and 35%, respectively [105]. Consequently, application of membrane filtration methods (such as RO, NF and MF) is recommended to achieve high wastewater treatment efficiency. Membrane wastewater treatment methods decrease health-risk parameters as well.

Dolar et al. [106] described the application of hybrid membrane treatment techniques, including RO and MBR, in relation to the pharmaceutical aspects of municipal effluents and wastewater treatment plants (WWTPs). They found the total removal efficiency to be within the range of 95–99% for both the MBR and RO methods rejecting more than 20 pharmaceutical functions from domestic wastewater [106].

Kim et al. [107] studied the application of a staged anaerobic fluidized membrane bioreactor (SAF-MBR) in domestic wastewater treatment. The SAF-MBR technique was introduced for wastewater treatment due to its efficiency in energy costs reduction compared to conventional MBR procedures. This method includes the application of an anaerobic fluidized-bed reactor (AFBR) followed by an anaerobic fluidized-bed membrane bioreactor (AFMBR) [107]. Consequently, they designed and ran the treatment system for general domestic wastewater under controlled-process conditions (a limited running time of 192 days, the pressure and temperature set at 25 °C and 0.1 bar, respectively). The outcomes of their research demonstrated the high removal efficiency of their method as regards COD, BOD and TSS parameter values. Correspondingly, the level of electrical energy requirements for the respective processes’ implementation during the test was beyond expectations [108].

Chon et al. [109] investigated the application of a hybrid membrane treatment system with an MBR plant and an NF membrane process in a municipal wastewater treatment plant. Their application procedure consisted of the utilization of a hybrid treatment process at the laboratory-scale. They initially applied MBR as the first stage, and implemented NF with two different flat
Table 6
Hybrid membrane for wastewater treatment purposes.

<table>
<thead>
<tr>
<th>Summary of reviewed research</th>
<th>Country</th>
<th>Type of membrane</th>
<th>Type of analysis</th>
<th>Results</th>
<th>Challenges</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MBR</td>
<td>Germany</td>
<td>Chlorinated polyethylene NF + conventional activated sludge</td>
<td>LC-ESI-MS/MS DOC by TOC analyzer</td>
<td>Polar pollutant removal efficiency</td>
<td>TN/TP removal</td>
<td>[86]</td>
</tr>
<tr>
<td>2 HMBR/CMBR</td>
<td>China</td>
<td>Aerobic reactor + hollow fiber membrane (MF)</td>
<td>COD/BOD/TSS/TP (NH₄-N), (MLSS), (MLVSS) and (SCOD), COD, NH₄⁺, turbidity</td>
<td>COD decline, organic pollutant removal efficiency</td>
<td>–</td>
<td>[88]</td>
</tr>
<tr>
<td>4 NFFB + MBR</td>
<td>Korea</td>
<td>Nonwoven polyester fabric + conventional activated sludge</td>
<td>COD, NH₄⁺, turbidity</td>
<td>TSS removal, sludge removal efficiency</td>
<td>–</td>
<td>[90]</td>
</tr>
<tr>
<td>5 ANMBR</td>
<td>China/Singapore</td>
<td>PVDF flat sheet membrane/PE flat sheet membrane</td>
<td>COD, NH₄⁺, turbidity</td>
<td>Excellent effluent quality, low sludge production, net energy production</td>
<td>Membrane operational properties, pore size and flux/high organic strength, low particulate content</td>
<td>[117]</td>
</tr>
<tr>
<td>6 Hybrid membrane ANMBR</td>
<td>UK</td>
<td>PE flat sheet membrane + CSTR</td>
<td>COD, NH₄⁺, turbidity</td>
<td>COD/TSS removal efficiency</td>
<td>Membrane operational properties pore size and flux</td>
<td>[118]</td>
</tr>
<tr>
<td>7 SANMBR/HANMBR</td>
<td>UK</td>
<td>Polyethylene flat sheet membrane</td>
<td>(TS), (VS), (MLTSS), (MLVSS) and (SCOD), COD, SCOD, TP, TSS, VSS</td>
<td>Flux, fouling and membrane rejection efficiency/lower energy consumption/high SCOD, COD removal</td>
<td>Not capable in limited temperatures 20 °C</td>
<td>[119]</td>
</tr>
<tr>
<td>8 SMBR</td>
<td>Italy</td>
<td>Conventional activated sludge + hollow fiber microfiltration membrane</td>
<td>COD, BOD, TSS, NH₄⁺ (MLSS), (MLVSS), (SOUR), (SCOD), (COD), (MLSS), (MLVSS), (SOUR)</td>
<td>TSS reducing efficiency/biodegradable organic issues value</td>
<td>Microbial metabolism, sludge generating and membrane fouling/solid retention time (SRT)</td>
<td>[99]</td>
</tr>
<tr>
<td>9 SMBR with chloride addition</td>
<td>China</td>
<td>PVDF hollow fiber</td>
<td>COD, BOD, TSS, NH₄⁺ (MLSS), (MLVSS), (SOUR), (SCOD), (COD), (MLSS), (MLVSS), (SOUR)</td>
<td>COD, TN removal efficiency</td>
<td>Not efficient for dissolved organic matter and UV₉₀₅ removal</td>
<td>[112]</td>
</tr>
<tr>
<td>10 Nitrogen loading rate (NLR) + SMBR</td>
<td>Pakistan</td>
<td>Acrylic hollow fibers</td>
<td>(NO₃⁻ – N), (NO₂⁻ – N), (PO₄³⁻ – P), (TN), (TC), (COD), (MLSS), (MLVSS), (SOUR)</td>
<td>COD, TN removal efficiency</td>
<td>Poor phosphorus removal in treating a high strength synthetic wastewater.</td>
<td>[101]</td>
</tr>
<tr>
<td>11 RO + MBR</td>
<td>Spain</td>
<td>Flat sheet membranes + cross linked negative charge, aromatic polyamide RO membrane</td>
<td>Bacterial, microbial, pharmaceutical tests</td>
<td>More than 20 pharmaceutical functions removal, RO rejection efficiency</td>
<td>–</td>
<td>[102]</td>
</tr>
<tr>
<td>12 Fluidized membrane bioreactor (SAF-MBR)</td>
<td>Korea</td>
<td>Fluidized-bed reactor (AFBR) + anaerobic fluidized-bed membrane bioreactor (AFMBR) + PVDF hollow fiber</td>
<td>COD, SCOD, BOD, TSS, VSS</td>
<td>Less energy consumption and less fouling compare to conventional MBRs/COD, BOD, TSS removal efficiency, high-efficiency cost-effective</td>
<td>–</td>
<td>[104]</td>
</tr>
<tr>
<td>13 NF + MBR</td>
<td>Korea</td>
<td>NF flat sheets + PVDF MF membrane hollow fiber + activated sludge</td>
<td>DOC, TN, TOC</td>
<td>Flux decline, high rejection rate, organic material removal efficiency</td>
<td>Membrane hydrophilic and hydrophobic properties, flux decline based on NF properties</td>
<td>[73]</td>
</tr>
<tr>
<td>16 ANMBR treatment method in psychrophic condition</td>
<td>USA</td>
<td>Flat-sheet microfiltration polyethersulfone membranes</td>
<td>BOD, COD, TSS, VSS</td>
<td>COD, BOD removal efficiency, flux managing</td>
<td>–</td>
<td>[97]</td>
</tr>
</tbody>
</table>

Table 7
Fouling and its impact on MBRs in wastewater treatment.

<table>
<thead>
<tr>
<th>Fouling reasons</th>
<th>Concentration polarization, external fouling, and internal fouling</th>
<th>Biofouling, organic fouling, and inorganic fouling</th>
<th>Reversible, irreversible, residual, and irrecoverable fouling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>Concentration polarization</td>
<td>Biofouling (biosolids)</td>
<td>Reversible fouling</td>
</tr>
<tr>
<td></td>
<td>[120–122]</td>
<td>[131,132]</td>
<td>[136]</td>
</tr>
<tr>
<td></td>
<td>External fouling [127,128]</td>
<td>Organic fouling [133,134]</td>
<td>Irreversible fouling [137]</td>
</tr>
<tr>
<td></td>
<td>Internal fouling [129,130]</td>
<td>Inorganic fouling [135]</td>
<td>Residual fouling [138]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Irreversible fouling [139]</td>
</tr>
</tbody>
</table>
sheets as the second stage. They discovered that the fouling and flux decline in hybrid membrane methods are influenced directly by the membrane surface characterization. To achieve better efficiency in wastewater treatment, the hydrophilic and hydrophobic properties of the membrane surface should be modified [109].

A dynamic membrane reactor (DMR) is one of the most recently-developed treatment techniques and is expected to become popular in municipal wastewater treatment plants. During this process, certain substances such as activated sludge [110], diatomite [111], kaolin clay and powder-activated carbon (PAC) [112,113] are applied to generate the main activated carbon substance and the nylon membrane. A stainless mesh is used as a supporting layer in DMR [114]. This method is considered to be more efficient in comparison to the other hybrid membrane wastewater processes used in municipal wastewater treatment plants, such as MBRs. This is based on its sustainable design parameters, such as low energy consumption and cost effectiveness.

Chu et al. [115] elaborated upon the high efficiency of a bio-enhanced powder-activated carbon dynamic membrane (BPDM) during the removal of organic and inorganic contaminants from municipal wastewaters in continuous operational processes [115]. Ma et al. [116] studied the recent application of dynamic membrane systems in municipal wastewater treatment process. They investigated how, during the 300-day operational progression period, the organic matter recovery-rate was measured at over 81.6%. In addition, they discovered that the DMS treatment process is an acceptable alternative for conventional treatment methods in municipal and domestic wastewater treatment. This technique can be an efficient process for application during sustainable urban and habitant developments based on its environmental-friendly characteristics [116].

Consequently, due to the increasing demand for fresh water in all human societies, wastewater treatment as an international environmental agenda, has taken been widely into consideration. Based on the mentioned studies and on-going research, hybrid membrane wastewater treatment presented great efficiencies in terms of both economic and environmental aspects. As a result, it is expected that these techniques will be commonly used in domestic and industrial wastewater treatment plants. Table 5 presents the advantages and disadvantages of applying contemporary techniques in wastewater treatment.

The reviewed studies revealed that MBR-based technologies are considered to be the most efficient treatment techniques for municipal and domestic water and wastewater treatment.

7.3. Status and challenges of membrane implementations in sustainable design

Application of membrane hybrid wastewater is not limited to municipal wastewater areas, however, it can be widely used in various segments of business and industry. To summarize, Table 6 represents and compares current attempts in applying hybrid membranes for wastewater treatment purposes.

Application of hybrid membrane wastewater treatment techniques is gaining popularity based on its positive characteristics such as user eco-friendliness and cost-effectiveness. This application is still new compared to the other common chemical wastewater treatment techniques used in municipal wastewater treatment plants. Moreover, it has not been widely publicized among users yet.

Fouling is the most common operational issues in all membrane application procedures. As a result, the main sources of fouling and their impact on the applied MBRs in domestic and rural water and wastewater treatment are mentioned in Table 7.

To reduce the impact of fouling on the membrane treatment application process, shortening the membrane pores’ blockage duration is necessary. Correspondingly, the main treatment method to overcome this issue is membrane cleaning. The cleaning method in MBR applications is generally categorized according to two main typologies:

1) In-situ (online or in-place) cleaning and ex-situ (offline or out-of-place) cleaning: based on keeping the membrane module within the membrane tank throughout the cleaning process.
2) Physical, chemical and biological/biochemical cleaning, based on:
   - physical: adding particles/carriers, vibration, rotation and ultrasonic cleaning;
   - chemical: acids, bases and oxidants are typical cleaning reagents plus metal chelating chemicals, surfactants and formulated detergents;
   - biological/biochemical: enzymatic, energy-uncoupling and quorum applications, respectively [128,140–144].

Consequently, the importance of applying suitable cleaning methods for hybrid membrane treatment systems during domestic wastewater treatment is undeniable. These techniques enhance the sustainability parameters of various hybrid membrane-based water treatment applications. However, the original membrane lifecycle is shortened due to the chemical and physical tensions on the main membrane structure. Thus, usage of this method within the shortest possible time is essential.

8. Summary and conclusions

Referring to the current status of natural resource depletion, sustainable design of green built-environments is crucial to the future planning of cities and urban areas. Development of low-carbon and eco-cities has become an inherent element of energy policies as regards the sustainable development of future urban areas. To achieve this goal, particular attention must be paid to current environmental challenges while also considering the impact of resource management and ecological design. Looking into the analysis of current green building-assessment tools, the effectiveness of buildings in terms of ‘water efficiency’ is highlighted as a major component. Explicating the role of green buildings in the enhancement of sustainability with a view to the aims of this study, the important role of wastewater treatment applications is reported and elaborated upon. In this regard, the rapidly increasing habitant population in societies as well as the consequent limitation of water resources is highlighted. Importance of government regulations for the reuse of domestic wastewater is can be seen as highly significant.

Efficient use of natural environment and energy resources, preservation of natural resources and enhancement of economic well-being are essential for sustainable developments. Particular attention should be paid to the invention, redevelopment, analysis and enhancement of environmentally sustainable design approaches in relation to green development of future cities. In view of the sustainable design of future cities, the role of wastewater treatment has become significant.

Application of wastewater treatment contributes to the enhanced performance of low-energy, ultra-low-energy (and eventually zero-energy) buildings. This application is essential as regards establishing green built-environments. The study covers a review of the current conventional wastewater treatment methods and applications in municipal sustainable design (both their advantages and disadvantages).
This research highlights the use of hybrid membrane treatment methods during wastewater treatment to positively influence sustainable built-environments. A number of the more common applicable commercial and industrial hybrid membrane treatment methods are discussed, in particular membrane bio-reactors (MBRs). Moreover, the specific applications and effects of hybrid membrane treatment methods in relation to various aspects of municipal wastewater; physical, chemical and environmental factors are detailed and described. The notion of sustainable future cities is promoted. Wastewater treatment is expected to remain a key factor in prospective sustainable developments.

This review study has focused on the application of current hybrid membrane treatment methods in relation to sustainable design and green municipal wastewater treatment technique. Hybrid membrane treatment techniques are proposed to be applied in green design for urban and municipal implementations, due their cost-effectiveness, user-friendliness and eco-friendliness.

MBR methods and their main sub-categories, such as HMBrS and CMBrS, have recently been applied more frequently. This is due to their high efficiency in terms of environmental factors, such as COD, polar pollutants, a lower fouling rate, and easy backwashing. Due to the excellent effluent quality, low sludge production and net energy production, An MBRs techniques have also been applied in wastewater treatment areas. Furthermore, a combination of NNFB and MBRs also demonstrates high levels of efficiency in a cycle run for TSS and sludge removal. On the other hand, this technique is noteworthy for urban populations. Ultimately, this review highlights the significance of utilizing hybrid wastewater treatment systems in achieving sustainable built-environments.

Acknowledgment

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