MARIANO MARCOS STATE UNIVERSITY

Novel Urban Ecosystem for Enhanced Ecosystem Services in Cities: The Case of AIT's Freshwater Mangroves

The Mariano Marcos State University, Philippines has collaborated (SDG 17) with the Asian Institute of Technology, Thailand in gathering or measuring data for the Sustainable Development Goals. This research provides new concepts on how to potentially enhance the green spaces with benefits through embracing novel ecosystem as an option to restore and rejuvenate wetland areas in cities. At present, the concept is used at the Asian Institute of Technology to help improve water quality, reduce the proliferation of harmful blue-green algae in the campus wetlands and enhanced the vegetation for climate change mitigation and adaptation (SDG 13). Specifically, the researchers from both countries worked on novel urban ecosystem (SDG11) to enhance ecosystem services in cities (SDG 9). Below is the abstract of their paper.

The use of the non-traditional ecology concept such as fresh water mangroves is still debatable among experts and non-experts alike. This can be a hindrance in accepting the NUEs as part of the urban landscape. This R&D on ecological engineering using freshwater mangroves addresses a problem of urban wastewater along with water pollution and its health concerns, climate change mitigation, as well as typically low aesthetic appearance of cities. The ecotechnology creates an opportunity for the wastewater flowing into lake from adjacent restaurants located on campus into solution for many urban challenges including the use of nutrient-rich water as a fertilizer for mangrove trees in a Novel Urban Ecosystem (NUE). As a result, the enhanced growth of the mangrove trees yields to a greater biomass that is proportionate to carbon sequestration. The growth of the freshwater mangroves is almost similar to the coastal mangroves, an indication that these mangroves can perform similarly as carbon sink even when placed in a different habitat. In addition, this research has proven that mangrove roots increase dissolved oxygen in water. Despite that novel urban ecosystem makes use of an introduced species such as mangroves into freshwater wetlands, its acceptability in AIT community is relatively high. The majority of the respondents agree that the mangroves on campus provide habitat for wildlife and opportunities for contact with nature. Additionally, a greater number of the respondents agree that the NUE is not causing any problems both to people and to other organisms on campus. A strong indication that the fresh water mangroves as NUE is successful are increased areas for green spaces and habitat

for biodiversity, which is providing an additional opportunity for outdoor recreation and therefore adding to the well-being for the community. Additionally, SDG mapping of the potential outcomes of a freshwater mangrove in cities indicates that out of the 17 Goals, 10 were directly and indirectly linked with the freshwater mangrove project in AIT with 18 indicators satisfied.

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Chapter · September 2024

DOI: 10.1007/978-981-97-6639-0_16

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Abstract The use of the non-traditional ecology concept such as freshwater mangroves is still debatable among experts and non-experts alike. This can be a hindrance in accepting the NUEs as part of the urban landscape. This R&D on ecological engineering using freshwater mangroves addresses a problem of urban wastewater along with water pollution and its health concerns, climate change mitigation, as well as typically low aesthetic appearance of cities. The ecotechnology creates an opportunity for the wastewater flowing into lake from adjacent restaurants located on campus into solution for many urban challenges including the use of nutrient-rich water as a fertilizer for mangrove trees in a Novel Urban Ecosystem (NUE). As a result, the enhanced growth of the mangrove trees yields to a greater biomass that is proportionate to carbon sequestration. The growth of the freshwater mangroves is almost similar to the coastal mangroves, an indication that these mangroves can perform similarly as carbon sink even when placed in a different habitat. In addition, this research has proven that mangrove roots increase dissolved oxygen in water. Despite that novel urban ecosystem makes use of an introduced species such as mangroves into freshwater wetlands, its acceptability in AIT community is relatively high. The majority of the respondents agree that the mangroves on campus provide habitat for wildlife and opportunities for contact with nature. Additionally, a greater number of the respondents agree that the NUE is not causing any problems both to people and to other organisms on campus. A strong indication that the freshwater mangroves as NUE is successful are increased areas for green spaces and habitat for biodiversity, which is providing an additional opportunity for outdoor recreation and therefore adding to the well-being for the community. Additionally, SDG mapping of the potential outcomes of a freshwater mangrove in cities indicates that out of the 17 Goals, 10 were directly and indirectly linked with the freshwater mangrove project in AIT with 18 indicators satisfied.

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A. Sharifi (ed.), *Environmental Sustainability and Resilience*,
World Sustainability Series, https://doi.org/10.1007/978-981-97-6639-0_16

Keywords Freshwater mangroves · Novel urban ecosystem · Ecosystem services · Ecotechnology

1 Opportunities in Novel Ecosystems for Environmental Restoration

The concept of novel ecosystem presents a new perspective in understanding the fundamentals and emerging concepts in ecology. In previous analysis on the application of novel ecosystem, it is put into emphasis that it does not replace restoration but rather provides a wider range of options by being an alternative approach for ecosystems where conventional restoration fails (Higgs 2017). An understanding of novel ecosystem in terms of their growing contribution to the Earth system offers new opportunities for further insights into threshold dynamics, ecosystem structure, and longevity (Morse et al. 2014). Whatever purpose a novel ecosystem may serve, its highlights are rooted in the process of human transformation that motivates the restoration of damaged, degraded, and destroyed ecosystems allowing the provision of or enhanced delivery of eco-services (Morse et al. 2014; Hobbs et al. 2009).

Sustainability is becoming increasingly popular in the context of landscape ecology for its potential in addressing complex relations and fragile balance between humans and natural environments (Lovell and Taylor 2013). Nature-based solutions (NbS) are interventions that simultaneously promote social, economic, and environmental sustainability by bringing a multifunctional solution for urban sustainability (Dorst et al. 2019). Various studies examined the role of urban green areas in providing a wide spectrum of ecosystem services especially regulating services (Chang et al. 2017) and cultural services (Mao et al. 2020).

The emerging knowledge on novel ecosystem is still debated especially to conservationist because it is in conflict with the concept of traditional conservation practice. Conversely, novel ecosystems can also provide opportunities to broaden the framework of ecological restoration and contribute to biodiversity conservation (Perring and Ellis 2013) and other eco-services function. The concept of novel ecosystem has been used over a decade but its definition was just recently evolving. Novel ecosystem concept was first used by Chapin and Starfield in 1997, and it was first defined as ecosystems' biotic and/or abiotic characteristics altered by humans (Morse et al. 2014). Hobbs et al. (2009) described novel ecosystems as a consequence of changing species distributions and environmental alteration through climate change and land use and thus resulting to a different composition and/or function from present and historical systems.

Humans have modified ecosystems for their own benefit. As a consequence of increased ecosystem degradation, human has also learnt to create anthropogenic ecosystems and recognizes their ability to provide various ecological services such as artificial wetlands (e.g. ponds, lakes, waterways). Ecologists distinguish the combination of a human-influenced ecosystems and ecosystems with degraded structure and functionality as a novel ecosystem (Morse et al. 2014). Few examples of novel ecosystems that include introduced species have shown to facilitate the regrowth of native species and to enhance ecosystem services from impacted or designed states (Lugo and Helmer 2004).

There are unique opportunities to further our understanding of many fundamental and emerging concepts in ecology. It is highly suggested by Morse et al. (2014) that novel ecosystems should be studied for their growing contribution to the earth system and their inherent effects on underlying ecological characteristics such as resilience, competition, extinction, and speciation. This concept is widely accepted in urban areas as it is increasingly assumed as largely widespread and occurring urban ecological novelty throughout urban green spaces over non-urban areas, which is considered more problematic to conservation and restoration (Teixeira et al. 2021). Urban ecosystems and urban landscapes are novel—in the sense of being new and different from what was known before (Ahern, 2016). The NUE can emerge in a variety of ways. For example, some may come from the invasion of alien species, while others may come from pieces of native vegetation that has been deteriorated or from the intentional management of ecosystems that have been developed.

Enhancement and reinforcement of urban wetlands are among the restoration focus in urban areas because their role is highly recognized in making cities and towns more livable. Having the resilience to varying environmental conditions, mangroves have the potential to be a pioneer species in creating ecosystems in an anthropogenically impacted urban wetlands with the novelty to become a medium in revitalizing ecosystem health and for the enhancement of ecosystem services delivery. Mangroves in their natural habitat provide numerous ecological services as—coastal barrier, carbon sink, habitat and refuge of marine biodiversity, and a natural filter of pollutants from terrestrial to the marine environment. In fact, it is widely recognized that mangroves are efficient and an economical method of treating wastewater from aquaculture, sewage, and other sources with the massive urbanization (Ouyang and Guo 2015). The effectiveness of mangroves to improve water quality is attributed to the extensive root systems that create an aerobic zone in the rhizosphere for oxidation (Wu et al. 2008) and that a diverse group of microorganisms harbor the soil and roots that play an essential role in nutrient transformation and removal. Mangroves are woody in structure; thus, overgrowth should not be a major problem as it creates a canopy for microclimate regulation in urban space. Mangroves decompose much more slowly, acting effectively as nutrient sinks in urban wetlands. Unlike macrophytes, mangroves are perennial plants that do not require regular harvesting or replanting (Yang et al. 2008). Additionally, mangrove ecosystem is well-recognized as the greatest carbon sink among all types of forests, even surpassing tropical rain forest (Alongi, 2014). In light of these benefits, mangroves can provide substantial opportunities and advantages over conventional wetland plants.

Mangrove trees having unique features that are more superior compared to macrophytes for wastewater treatment have been studied and put into application even in the absence of tidal flushing and salinity. Recently, an emerging technology on the use of freshwater mangroves for water quality improvement is integrated with urban landscaping particularly in the urban wetlands while previous researches on mangroves and their services mainly focused on the assessment of coastal mangroves' efficiency for water quality improvement as a natural wastewater treatment system and its other contribution such as carbon sequestration, biodiversity, economic and ecological productivity, and resilience. Since freshwater mangrove ecosystem is rare, there is no well-documented study focusing on the efficiency of freshwater mangroves to deliver different ecosystem services, thus, this is what this study aims to address. The overall objective of this study is to investigate the potential of an eco-technology based on freshwater mangroves to deliver ecosystem services by following the principles of ecological engineering and NUE. Specifically, it (1) measures the dynamic performance of the eco-technology in delivering various ecosystem services, (2) assess the contribution of integrating freshwater mangrove-based NUE in cities to the achievement of the SDGs, and (3) determine the awareness and acceptability of the NUE concept within AIT campus.

2 Novel Ecosystem in the Urban Context

Urban development can result in degradation and may be difficult to recover without assistance, which results in the reversal of ecosystem benefits. In line with the call of United Nations to improve urban ecosystems in order to better exploit their potential, urban ecosystem restoration initiatives are evolving. There is a strong emphasis on the adoption of Nature-based Solutions (NbS) in providing solutions to most of the environmental and societal challenges (Fig. 1).

Interventions can take place through the traditional approach of restoring ecosystems with the use of endemic species of flora and fauna in the area. However, the intended result may not easily achieve due to the severity of the environmental alteration that may affect the regeneration rate of the endemic species. Shifting the traditional restoration concept to new approaches such as novel ecosystems does not

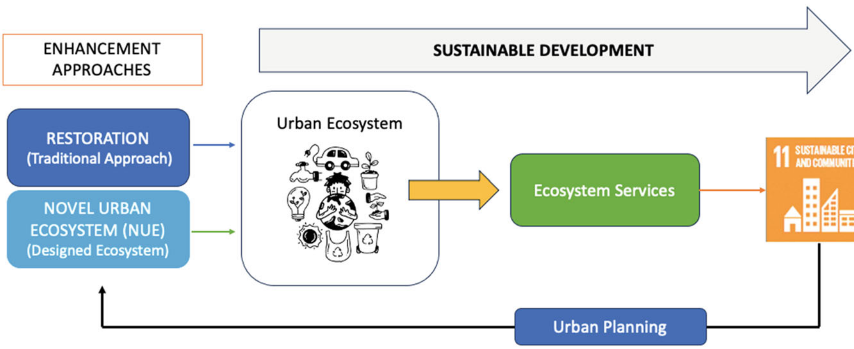

Fig. 1 Conceptual framework of the study

intend to offer an absolute replacement but offers an option that will bring similar purpose of rejuvenating ecosystems to optimize the ecosystem services.

3 Ecosystem Services: How Novel Ecosystem Revives Functionality of Urban Ecosystem

A designed ecosystem is a combination of plants, microorganisms, materials, and design features to maximize the required qualities and even beyond. Higgs (2017) defined designed ecosystem as an ecosystem comprising a variety of ecological approaches including reclamation (returning a degraded ecosystem to its productive capacity), green infrastructure, and agroecological systems. This concept was the foundation in the creation of a freshwater mangrove ecosystem in several parts of AIT campus with the objective of enhancing ecosystem health to deliver better ecosystem services to AIT community. With the introduction of a NUE in AIT campus as a model, the succession trajectory is projected with the following outcomes.

3.1 Restored Environmental Quality

Mangroves are efficient in absorbing nutrients in soil and water. The enhanced removal of nutrients in soil and water is typically reflected in the biomass accumulation of mangroves as it is giving a fertilizing effect to the trees. Removal of nutrients in wastewater varies depending on the mangrove's species used. However, a general note in all literature indicates that the removal rates of organic matter and nutrients are positively correlated with plant growth (Mahmood et al. 2013). The absorbed nutrients particularly N and P accumulate as part of plant biomass. In the study of Ye et al. (2001), N concentration in the body parts of the mangrove species under non-saline condition increased after receiving livestock wastewater as compared to saline condition. In addition, absorbed N from wastewater mainly accumulated in the above-ground parts and less significant in the roots while P absorption is more on root and stem (Ye et al. 2001). Mangroves being a tolerant and resilient plant to various environmental make it as an ideal plant material for phytoremediation.

With the mangroves' unique adaptations to stressed environments, a massive nutrient requirement because of fast growth, high primary productivity, metabolism, and yield makes it ideal for ecosystem rehabilitation of a eutrophicated wetland. Plant uptake is the common major mechanism for nutrient removal in all the paradigms as mangroves are generally nitrogen and phosphorus limited. Characterized by high productivity, mangrove trees have a natural ability to absorb nutrients in excess, without any apparent of structural damages. Since nitrogen and phosphorus have been implicated as the nutrients most likely to limit growth in mangroves, their

Table 1 Average height increase of mangrove saplings introduced at AIT wetland (West Lake)

	Treatment site	Control site
Maximum (cm)	42	19
Minimum (cm)	25	10
Average (cm)	33.5	14.5

abundance in the water as contributed by waste nutrients can be sequestered and used to fuel the growth and development of the freshwater mangroves (Table 1).

The growth of the introduced mangrove trees was monitored on a quarterly basis. The maximum tree growth recorded was 42 cm, which was among the trees in the treatment site, and lowest growth was 10 cm and located in the control site. On an average, the height increase of the mangrove trees from the initial planting period (March 2018) was 33.5 cm and 14.5 cm at the treatment and control site, respectively. The higher growth of mangrove trees at the treatment site can be attributed to a higher concentration of nutrient concentration essential for plant growth. According to Reef et al. (2010), nitrogen and phosphorus had been implicated as the nutrients most likely to limit the growth in mangroves. Because of their productivity, mangrove plants have a large demand for nutrients and many mangrove habitats struggle with a nutrient deficiency problem yet are still flourishing. For the efficiency of mangrove for pollutant removal, studies have proven that mangrove wetlands are highly efficient in adsorbing and absorbing wastewater-borne pollutants, including nitrogen and phosphorus. This mechanism of freshwater mangroves is associated with the robust biomass accumulation of mangroves due to the fertilizing effect of the nutrients in the water absorbed by mangroves increases ability, thereby, increasing the ability to accumulate carbon over time. Mangrove ecosystem is well-recognized as the greatest carbon sink among all types of forests, even surpassing tropical rain forest (Alongi, 2014).

In addition, the root system of the mangroves enhances the oxygen supply in its anoxic soil and adjacent water. A comparison of the monitored dissolved oxygen in the library pond water indicates that a greater amount of dissolved oxygen was recorded adjacent to the pneumatophores. An increase of 0.12–0.52 mg/L in DO concentration was observed as shown in Fig. 2.

According to Kitaya, 2002, the aerial roots of the mangroves that spread from the ground such as the pneumatophores are where oxygen can passively diffuse and make oxygen easily diffused to water. A photosynthetic reaction takes place at the surface of the pneumatophores and play an important role in the gas exchange between the pneumatophore and the roots' environment (subsoil or water). The radial oxygen loss from the roots creates an aerobic zone in the area immediately adjacent to the roots which helps to enhance microbial activity in the decomposition of organic matter in the water or soil. This effect of mangroves' roots has several times proven in constructed mangrove treatment wetlands where the dissolved oxygen of the water continuously increases over time when restrained despite of the presence of wastewater (high OM loading). The more oxygen supply there is, the greater the microbial activity of AOAs and AOBs for the nitrification process.

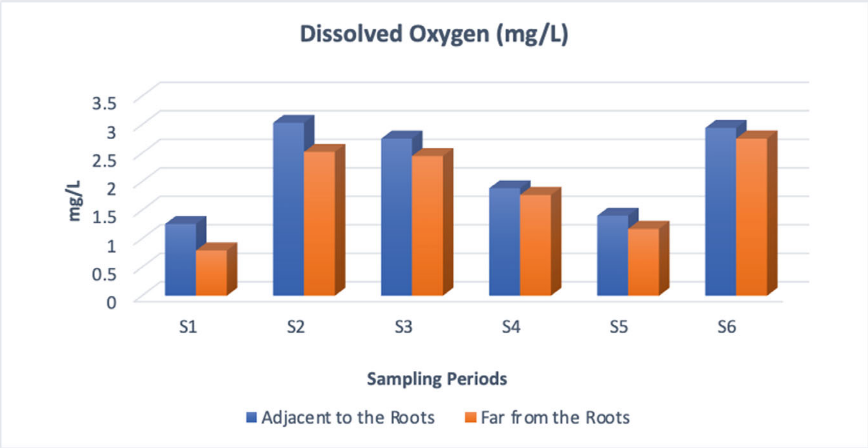

Fig. 2 Influence of root system to the dissolved oxygen (mg/L) concentration in water

3.2 *Enhanced Biodiversity*

Novel ecosystems have higher diversity than historical ecosystem. This is frequently the case with urban ecosystems, which are often hybrid ecosystems comprising native and non-native vegetation. While over the past several hundred years, most landscapes have been altered by anthropogenic activities, and in many cases outright habitat destruction, the terminology describing the resulting ecosystems is inconsistent and inadequate for effective cross-sectoral management.

For this study, the new canopy of freshwater mangroves in AIT wetlands has significantly attracted bird species over time and provided a favorable nesting ground for birds. Meanwhile, the massive root system of the mangrove is a favorable habitat for fish and other wetland organisms. It provides a habitat and shelter to juvenile organisms. This is a popular role of mangrove forests in coastal areas, particularly serving as a breeding ground and sanctuary of juvenile species in the marine environment (Nature Conservancy 2021).

As a novel ecosystem, the freshwater mangroves are purposely used for water quality improvement by enhancing the diversity and abundance of beneficial microorganisms in wetlands. The relationship between the abundance of macrophytes, DO concentration to the population of rotifers and the Potential Nitrification Rate (PNR) of nitrifiers shows that as the mangrove roots' volume and spread increased over time, there is an enhancement of DO in the water. DO measurements indicate that water adjacent to the mangrove root systems had the DO concentration in the range of 0.12–0.52 mg/L, which was slightly higher than in the sites distant from the mangrove trees. When oxygen is available in an almost anoxic bottom substrate, it augments the bioconversion of organic material by the microbial community. Figure 3 shows the implication of increased DO in water.

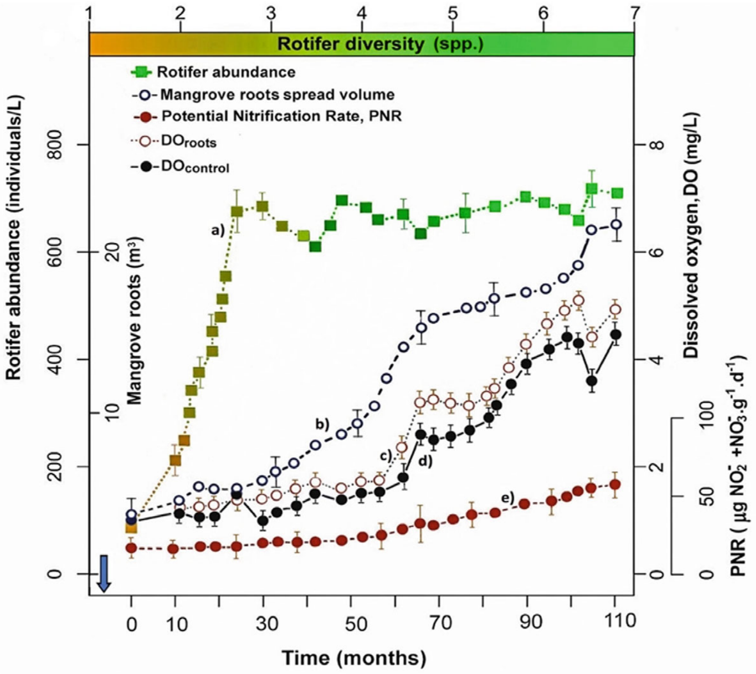

Fig. 3 Impact of eco-engineered mangrove-based diversification of a previously unvegetated wetland ecosystem

This AOB and AOA community harboring sediment and submerged plant parts and roots of macrophytes are very important in the N cycle pathway of a wetland as it converts organic N to ammonium nitrogen that can be absorbed by plants through their root systems, immobilized by ion exchange in the sediments, solubilized and returned to the water column, volatilized as gaseous ammonia, anaerobically converted back to OM by microbes, absorbed by phytoplankton/floating aquatic macrophytes in water column, or aerobically nitrified by aerobic conditions (EPA 2019).

The enhanced microbial activity is attributed to the increased dissolved oxygen in the surrounding microenvironment of mangrove plants. The development and increased density of mangrove roots in the AIT wetlands are attributed to the increase in abundance of the rotifers and microorganisms responsible for the conversion of nitrogen. DO is one of the factors affecting nitrification as the organisms involved in the process are aerobic microorganisms (Yao 2018). The extensive root system of mangroves creates a significant aerobic zone in the rhizosphere for oxidation and together with its soil, harbor diverse groups of microorganisms responsible for nutrient transformation (Chen et al. 2012). The root exudates also provide carbon for denitrification in aerobic microhabitats (Alongi, 2005). Thus, mangroves in constructed wetlands enhance the efficiency of both nitrification and denitrification process. The study (Wang et al. 2015) also demonstrated that mangrove and other plant vegetation significantly shaped the communities of AOA and AOB that created a significant impact on the ammonia-oxidizing process in the mangrove sediment. The aerial roots of the mangroves that spread from the ground such as the pneumatophores are where oxygen can passively diffuse and make oxygen be easily diffused to water (Kitaya et al. 2002). The radial oxygen loss from the roots creates an aerobic zone in the area immediately adjacent to the roots which helps to enhance microbial activity in the decomposition of organic matter in the water or soil. This effect of mangroves' roots has several times proven in constructed mangrove treatment wetlands where the dissolved oxygen of the water continuously increases over time when restrained despite of the presence of wastewater (high OM loading).

3.3 Pollution Buffer

The condition of the wetlands in AIT campus was very poor in quality after the great flood in 2011. As a solution to this, several eco-engineering applications using different aquatic plants were initiated in the ponds and canals on campus to help improve water quality and protect the health of AIT community. The same concept was applied in the establishment of freshwater mangroves in selected wetland areas. As an example, after the establishment of freshwater mangroves at West Lake, water quality monitoring conducted shows a significant decrease in water pollution concentration. Initially, the pollutant ion concentrations at West Lake were 1.47 (NH_3-N), 2.45 (TKN), 0.08 (TP), and 3.13 mg/L (TOC). A 44.6% reduction in NH_3-N concentrations was recorded at the end of the monitoring period. The final percentage reduction in TKN, TP, and TOC concentrations was 61.6%, 41.2%, and 63.7%, respectively. It is likely that the mangrove ecosystem introduced into West Lake, coupled with water circulation and aeration, was successful in improving the eutrophic conditions of the lake water.

Monitoring chlorophyll levels is a direct way of tracking algal growth. Surface waters that have high chlorophyll conditions are typically high in nutrients, generally phosphorus and nitrogen. Initial assessment of the *chlorophyll-a* at the Library Lagoon had six species of microphyte at a concentration of 334 μg/L and is fluctuating according to season such as monsoon season that brings dilution. The long-term impact of the mangrove is the diversification of the species of microphytes while reducing their concentration in the water. For almost 10 years, a change in the diversity was observed while simultaneously decreasing the concentration to 112 μg/L. Notable development in the pilot area of freshwater mangrove on campus was the complete disappearance of *Spiriluna* especially at the time when mangrove trees were increased. The same observation was noted at West Lake where *Spiriluna* was present during the water quality baseline assessment and disappeared when the eco-engineering components were introduced such as the mangrove introduction, soil mounds creation, and the enhancement of water circulation and aeration through a

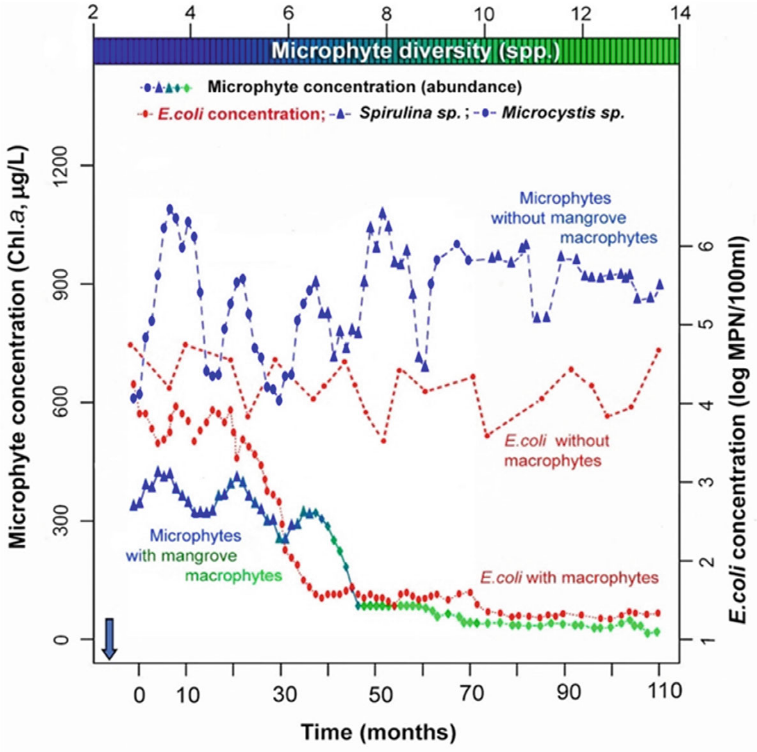

Fig. 4 Correlation of a novel urban ecosystem of freshwater mangrove-based to (a) abundance (as Chl. *a* concentration) and taxonomic diversity of microphytes

water pump. Figure 4 shows the temporal change of microphytes at the library pond area of AIT campus.

One of the notable developments in the NUE pilot area of freshwater mangrove on campus was the complete disappearance of *Spiriluna* especially at the time when mangrove trees were increased. The same observation was noted at West Lake where *Spiriluna* was present during the water quality baseline assessment and disappeared when the eco-engineering components were introduced such as the mangrove introduction, soil mounds creation, and the enhancement of water circulation and aeration through a water pump. The high concentration of *Escherichia coli* was a health concern on campus since 2013. However, the introduction of macrophytes along with mangrove trees in the canal and pond water was seen to provide a positive impact by reducing the concentration of *E. coli* in the water.

Generally, both AOA and AOB require oxygen for their metabolic activity. A comparison of the monitored dissolved oxygen in library lagoon and canals and West Lake revealed that a greater amount of dissolved oxygen was measured in water adjacent to the mangrove pneumatophores. The mechanism of mangrove roots is to increase dissolved oxygen in the surrounding area of the root system supported the improvement of AOA and AOB community in the rhizosphere of mangroves that played a pivotal role in the biotransformation of nitrogen pollutants in West Lake water. A study (Wang et al. 2015) also demonstrated that mangrove and other plant vegetation significantly shaped the communities of AOA and AOB that created a significant impact on the ammonia-oxidizing process in the mangrove sediment. The aerial roots of the mangroves that spread from the ground such as the pneumatophores are where oxygen can passively diffuse and make oxygen be easily diffused to water (Kitaya et al. 2002). The radial oxygen loss from the roots creates an aerobic zone in the area immediately adjacent to the roots, which helps to enhance microbial activity in the decomposition of organic matter in the water or soil. This effect of mangroves' roots has several times proven in constructed mangrove treatment wetlands where the dissolved oxygen of the water continuously increases over time when restrained despite of the presence of wastewater (high OM loading). Thus, the more oxygen supply there is, the greater is the microbial activity of AOAs and AOBs for the nitrification process.

In natural mangrove habitat, they play an important role in the regulation of the nutrient balance in the coastal environment by absorbing the excess nutrients and sequester other pollutants from entering water while enabling the export of organic matter that support productivity (Boonsong et al. 2003). The potential of mangroves as better plant material for treatment wetlands is attributed to its resilience to hostile environment such as nutrient and toxic water pollutants (heavy metals, hydrocarbons found in petroleum) that other plants cannot tolerate. Some literatures have proven the ability of mangroves to remove organic pollutants in wastewater. *Kandelia candel* when introduced to treatment tanks (subsurface horizontal flow) is effective in removing organic matter, nitrogen, and phosphorus from primary settled municipal wastewater (Wu et al. 2008); *Kandelia ovata, Aegiceras corniculatum,* and *Bruguiera gymorrhiza* together with non-mangrove plants in a pilot scale of a sub-surface flow wetland system for treating municipal sewage from domestic and industrial sources were noted effective in removing organic matter, nutrients, and heavy metals with no detrimental effect on the plants (Wu et al. 2008). Mangroves being a tolerant and resilient plant to various environmental make it as an ideal plant material for phytoremediation. Mangrove species used in a constructed wetland (*K. candel*, *A. corniculatum,* and *Sonneratia caseolaris)* are able to reduce OM content by 70%, 50% TN, 60% NH_3-N, 60% TP and 90% coliforms from the influent indicating a high efficiency of this waste treatment (Wu et al. 2008). This proves that despite of the constant inflow of wastewater at the West Lake, a low organic loading rate was recorded because of enhanced capacity of the lake for nitrogen biotransformation leading to its removal from the lake from the eco-engineering components implemented at West Lake. Mangroves create a suitable environment for the removal and transformation of pollutants in wastewater (Wu et al. 2008) due to its extensive root system that create a significant aerobic zone in the rhizosphere for oxidation and harbor diverse groups of microorganisms that play essential roles in nutrient transformation.

3.4 Climate Change Mitigation and Adaptation

Freshwater Mangroves for Climate Change Mitigation

Carbon sequestration rate for this study was determined using extensive data on mangrove wood production with varying age stand of mangrove forests. It is notable that carbon sequestration differs as every mangrove species has its own wood characteristics such as density. A projection was made for the freshwater mangrove established in one of the wetlands (West Lake) in AIT following the pattern and trend from literature on wood production, the aboveground sequestration rate is within the range of the global values. The projected total C sequestration at year 5 of two dominant mangrove species planted in AIT is 504 gm^{-2} y^{-1} C and around 330 gm^{-2} y^{-1} C for *Rhizophora* spp. and *Sonneratia* spp., respectively (Table 2).

The ability of mangroves to capture CO_2 is correlated to its primary productivity. Mangroves are among the plants with the highest primary productivity that accumulates and stores significant amounts of C in its biomass that may have a significant influence to global carbon budget (Kathiresan and Bingham 2001). The relatively high primary production and low decomposition process in mangrove soils are considered to bring about unusual carbon dynamics (Komiyama et al. 2008). The soil of the mangrove acts as a huge reservoir of carbon that can store three times its biomass (Kauffman and Donato 2012) and that it can even surpass the ability of terrestrial trees to store carbon. Moreover, what is interesting in the literatures on carbon sequestration potential of mangroves is that it is inversely correlated to water salinity (Perera et al. 2013; Mizanur Rahman et al. 2015) mainly because at higher salinity, mangroves spend more energy to maintain water balance and ion concentration rather than for primary production and growth (Perera et al. 2013).

3.5 Education and Awareness

Mangroves are one of the ecosystems used for education and awareness because of its well-known ecosystem services. Coastal mangroves are famous destination of students, corporations, and non-government organizations for field trips and reforestation activities because it has been used as a symbol for biodiversity, conservation, climate change initiative, and others.

Similarly, the freshwater mangroves in AIT are used for education and building awareness on the ecosystem services of mangrove ecosystems. Moving mangroves inland, closer to the cities make it more accessible and possible for people to understand and appreciate the value of mangroves. The trees planted in AIT were provided with information (scientific and common name) to integrate the education component by familiarizing AIT community with the different mangrove species. The freshwater mangrove prototype on campus is now a regular site for educational and awareness visit for AIT community and other institutions outside.

Table 2 Estimated carbon sequestration rates of freshwater mangroves in comparison with coastal mangroves

Species	Tree age (years)	Above ground sequestration rate g C m^{-2} y^{-1}, calculated[1]	Below ground (root) sequestration rate g C m^{-2} y^{-1}, calculated[1]	Total sequestration rate g C m^{-2} y^{-1}, calculated[1]
Rhizophora mucronata and *R. apiculata*	*Saline water* (Xiong et al. 2019)			
	1	18 ± 5	4 ± 2	22 ± 7
	3	345 ± 66	89 ± 50	434 ± 116
	5	357 ± 95	164 ± 49	521 ± 144
	10	498 ± 160	234 ± 106	732 ± 166
	25	527 ± 183	248 ± 101	775 ± 284
	40	696 ± 179	327 ± 156	1023 ± 335
	85	637 ± 241	300 ± 138	937 ± 379
	This study (freshwater)			
	1	14 ± 3	6 ± 2	20 ± 5
	3	245 ± 109	113 ± 49	358 ± 158
	5	409 ± 142	95 ± 34	504 ± 176
Sonneratia spp.	*Saline water* (Xiong et al. 2019)			
	1	25 ± 10	8 ± 4	33 ± 14
	3	287 ± 136	132 ± 53	419 ± 89
	5	631 ± 315	291 ± 141	922 ± 456
	10	554 ± 166	255 ± 145	809 ± 311
	20	246 ± 78	116 ± 61	362 ± 139
S. caseolaris	*This study (freshwater)*			
	3	281 ± 138	78 ± 29	359 ± 167
	12	691 ± 244	393 ± 156	1084 ± 400
S. ovata	6	235 ± 64	95 ± 35	330 + 99
Lumnitzera racemosa	*Literature data (saline water)* (Xiong et al. 2019)			
	3	22 ± 7	10 ± 5	32 ± 12
	37	135 ± 43	62 ± 29	197 ± 72
	This study (freshwater)			
	2	30 ± 17	10 ± 6	40 ± 23
	8	598 ± 270	439 ± 199	1037 ± 469

[1] are used to denote the area and number of year

Fig. 5 Mature freshwater mangroves at AIT campus

3.6 Landscape Value

Urban wetlands play a significant role in reviving cities and increasing human well-being through the provision on cityscapes for physical and recreational activities, outdoor relaxation spaces, and improving social life from more frequent human interactions and more access to "green spaces". It has been emphasized that incorporating "biophilic design" principles should be integrated with urban planning to achieve sustainable cities. The use of freshwater mangrove is an innovation that addresses the challenge of using emergent and free-floating plants (macrophytes) that usually have short life span and thus need frequent harvesting making it expensive in labor and maintenance. Therefore, there is an advantage of substituting soft-tissue plants with woody vegetation (trees) such as mangroves (Fig. 5).

AIT's wetlands (ponds and canals) were integrated with freshwater mangroves and created a fancy landscape of floating-like trees in the middle of wetlands. Their extensive and magnificent prop roots created substrates for other plants and trees to grow, creating a diversity despite of a limited space to grow and expand. In addition, the roots of the mangroves submerged in the water are habitat to many fish species.

3.7 Increased Property Value

The ability of mangroves as a pollution buffer helps to bring a better environmental quality in cities and green spaces contributes to enhancing environmental amenity of a place. Several studies have been conducted to evaluate the relationship of property values such as residential property value environmental quality (air quality, area of trees, and greenery spaces) (Iman et al. 2014). Additionally, since physical environment is an essential determinant of health, green spaces are amongst the most significant measures of quality and wellness of the urban environment and substantially attribute to living standards.

4 SDG Mapping: Freshwater Mangroves in Urban Landscape and Its Contribution to the SDGs

NUE has a potential role to play in the delivery of the SDGs. Given the scope of this project, this role is however more consequential with some SDGs, reflecting the multi-functional environmental benefits that this innovation could present. Among the projected outcomes of the freshwater mangroves in cities, the improved environmental quality and climate change mitigation/adaptation use have the greatest connections to the SDGs. Meanwhile, combined attribution of all the outcomes will result in the greatest contribution to the SDG 11. The remaining SDGs are influenced directly or indirectly but with lesser degree of connection from the outcomes. Out of the 17 SDGs, 10 goals were found to have a connection with the seven outcomes of the urban freshwater mangroves. The most relevant targets for the key SDGs are presented in Table 3 where impacts toward SDG targets in the specific context of a NUE project to increase ecosystem resiliency and services.

Establishing NUE is expected to contribute to 10 out of the 17 goals. The assessment was based on the integrated process and outcomes of ES, which are a product of successful NUE integration in the form of freshwater mangroves in urban areas for the SDGs. Out of the 169 indicators of the SDGs, 18 indicators are expected to be addressed with the integration of freshwater mangroves as NUE in the urban environment.

5 Knowledge and Perception of NUE and Freshwater Mangroves at AIT

In support to the promotion of FWM use in urban wetlands to deliver different ES for sustainability in cities, the beneficiaries' perception on the concept and application of FWM as a NUE was determined. As a new ecosystem performing different ES, a validation was asked to members of AIT community on their knowledge and awareness of NUE and freshwater mangroves and their ES.

The first part of the survey asked the awareness of the respondents of three key concepts associated with this study. The knowledge and familiarity with "novel ecosystems", "ecosystem", and "ecosystem services" were asked of the respondents. The concept of "novel ecosystems" was completely new to 30% of the respondents and only 7% were familiar with the said concept. On the other hand, the concept of

Table 3 Linking novel urban ecosystem (freshwater mangroves)'s potential outcomes with the SDGs

Target (number)	Target (name)	Indicator	Target goals in the NUE context
SDG 3: good health and well-being			
3.9	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and **air, water, and soil pollution and contamination**	3.9.1 3.9.2	Increase air pollution buffer and water pollution reduction due to the natural elements used Reduce exposure of people to poor water and air quality
SDG 6: clean water and sanitation			
6.3	By 2030, **improve water quality** by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.2 6.3.1	Improve water quality from natural solution Water pollution reduction Increase water recycling and safe reuse
SDG 4: quality education			
4.7	By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development	4.7.4	Accessibility to important ecosystems for learning and awareness most especially to urban population Promotion of biodiversity, ecosystem conservation and protection
SDG 7: affordable and clean energy			
7.3	By 2030, double the global rate of improvement in energy efficiency	7.3.1	Enhancement of microclimate in cities that will help reduce extensive energy use of cooling systems
SDG 8: decent work and economic growth			
8.4	Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to couple economic growth from environmental degradation, in accordance with the 10-year framework programmes on sustainable consumption and production, with developed countries taking the lead	8.4.1	Encourage in decoupling environmental degradation in business operations
SDG 9 industry, innovation and infrastructure			

(continued)

Table 3 (continued)

Target (number)	Target (name)	Indicator	Target goals in the NUE context
9.4	By 2030, upgrade infrastructure and retrofit industries to make them **sustainable**, with increased resource-use efficiency and greater adoption of **clean and environmentally sound technologies** and industrial processes	9.4.1	CO_2 sequestration through natural element approach
9.5	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging **innovation** and substantially increasing the number of research and development workers	9.5.1	Research and pilot-scale projects for the implementation of NUEs as NB solution
SDG 11: sustainable cities and communities			
11.3	By 2030, enhance inclusive and **sustainable urbanization** and capacity for participatory, integrated and sustainable human settlement planning and management	11.3.2	Stakeholder involvement in NbS/NUE
11.6	By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to **air quality** and municipal and other waste management	11.6.1 11.6.2	Increase sink of air pollution sequestration Sustainable improvement of surface water quality
11.7	By 2030, provide universal access to safe, inclusive, and accessible, **green and public spaces**, in particular for women and children, older persons, and persons with disabilities	11.7.1	Increase the provision of green spaces in limited urban areas Enhanced and accessible green landscape in cities
SDG 13: climate action			
13.1	Strengthen **resilience and adaptive capacity** to climate-related disasters	13.1.3	Regulation of microclimate in cities against urban heat effect
13.2	Integrate **climate change measures** into policy and planning	13.2.1 13.2.2	Offer multi-benefit approaches and NUE results contribute to development Support climate change mitigation policies in cities
SDG 15: life on land			

(continued)

Table 3 (continued)

Target (number)	Target (name)	Indicator	Target goals in the NUE context
15.1	By 2020, ensure the conservation, **restoration** and sustainable use of terrestrial and **inland freshwater ecosystems** and their services, in particular forests, **wetlands**, mountains and drylands, in line with obligations under international agreements	15.1.1 15.1.2	Rehabilitation and restoration of degraded natural wetlands for urban development
15.5	Take urgent and significant action to **reduce the degradation of natural habitats**, halt the **loss of biodiversity** and, by 2020, protect and prevent the extinction of threatened species	15.5.1	Provision of habitat corridors for biodiversity Enhance biodiversity in cities
SDG 17: partnership for the goals			
17.G	Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology, and financial resources, to support the achievement of SDGs in all countries, in particular developing countries		Industry-academe partnerships in promoting sustainable practices

"ecosystem" was agreed by 59% of the respondents as a very familiar concept and 26% of the respondents are familiar with "ecosystem services". A greater percentage (20 and 21%) of the respondents indicated of their familiarity with the concept and 9% indicated that they have never heard the concept before.

In addition, the perception of the importance of selected ES was asked, for which the result is presented in Table 4 showing that a higher percentage of the respondents agree that the given ES are highly important. Among the listed ES, clean water/ improved water quality obtained the highest agreement as highly valued (75%), followed by pollution buffer (55%), contributes to well-being (55%), and habitat for wildlife.

On the other hand, the respondents were also asked on their familiarity about mangroves in AIT campus. 70% of the respondents are familiar that there are mangroves growing on the different wetlands on campus while the remaining 30% are not aware of the mangroves on campus. Similarly, the respondents were also asked to confirm on whether the listed ES are applicable for freshwater mangroves as an NUE. Result of the survey showed that a greater number of the respondents believe that on a scale of 0–6, all the listed ES are provided at a 4–6 level (extremely to moderately provided). Meanwhile, around 18–20% of the respondents indicated that they are uncertain on whether the listed ES are provided by the freshwater mangrove on campus.

Table 4 Perception (%) of AIT community on different ecosystem services ($n = 69$)

Ecosystem services	0	1	2	3	4	5	6
Clean water/improved water quality (%)	1		7	7	1	9	75
Microclimate regulation (%)	1	3	3	12	19	36	26
Mitigate climate change (%)	2	1	7	9	9	26	46
Habitat for wildlife (%)	3	3	4	9	10	17	54
Pollution buffer (%)	1		11	9	4	20	55
Public open space for outdoor recreation (%)	3	7	6	9	14	20	41
Opportunities for contact with nature (%)	1	3	6	12	6	29	43
Improve the value of an area (%)	3	3	15	7	6	27	39
Contributes to the well-being (%)	1	1	6	7	10	17	55
Fosters a sense of community (%)	1	1	12	12	13	19	42

In addition, some potential problems arising from an NUE were also listed and verified by the respondents using the scale of 0–6 where 0 means "not a problem at all" while 6 means "severe problem". The responses are presented in Table 5.

The majority (28–52%) of the respondents indicated that the listed conditions are not caused nor associated with the presence of freshwater mangroves on campus. Only 3–4% of the respondents agreed that the listed conditions are severe problems linked with the presence of freshwater mangroves.

Given the services and disservices of the freshwater mangroves in AIT, the existing mangroves were maintained, and with plan to expand in areas where mangroves can be introduced as part of making the campus a botanical garden as one of the strategies toward a net zero campus. The respondents were also asked about their perception on the indicators of the successful NUE on campus. Table 6 shows the result of the survey using a scale of 0–6 (where 0 if strongly disagree and 6 if strongly agree).

Among the six given indicators of a successful establishment of a NUE such as the freshwater mangroves, a greater percentage of the respondents strongly agree that more green spaces are created (55%), followed by provision of habitat for wildlife (46%), and additional venue for learning and awareness (36%). Other indicators such as increased visitors at AIT, increased property values on campus, and increased public access to green spaces obtained a moderate agreement on these indicators.

Table 5 Disservices by freshwater mangroves on campus

	0	1	2	3	4	5	6
Nuisance wildlife (%)	36	17	9	9	19	7	3
Source of irritating smell (%)	28	14	10	12	22	12	3
Blocks beautiful views (%)	52	13	7	10	10	3	4
OFAM have to spend so much time and money for maintenance (%)	30	20	7	13	16	9	4
Makes water landscape ugly (%)	52	9	10	7	14	4	3

Table 6 Perceived indicators of a NUE success

Indicators	6	5	4	3	2	1	0
More visitors coming (%)	16	28	22	15	12	3	8
Increasing property values (%)	10	30	26	10	7	9	7
Increasing public access to natural areas (%)	10	32	23	10	3	1	4
More green spaces on campus (%)	55	25	13	4			3
More habitat for wildlife (%)	46	28	15	4	3	1	3
Additional venue for learning and awareness (%)	36	30	22	6	3	1	3

6 Conclusion

The extraction of potential outcomes from an innovation creates an awareness and inspiration to find more solution to address emerging local and global problems. The case of freshwater mangrove, which involves the integration of an exotic (novel) species in an ecosystem for rehabilitation, leads to the identification of seven positive outcomes and is linked to the achievement of 10 development goals. Despite the fact that the solution's essential elements are not described in any technical or scientific literature, references, patents, implementations, or publicly available evidence suggests that a solution of this kind has previously been used, the outcomes generated as a result of the projected ecosystem services were all agreed by stakeholders in AIT. This means that radical approaches to solving social and environmental issues are already well-accepted by the society. Additionally, the NbS has already been long recognized as sustainable solutions to different environmental challenges, however, the use of non-traditional ecology concept such as freshwater mangroves is still in debate and doubted by expert and non-expert people. This is a potential hindrance in accepting the NUEs as part of the urban landscape.

Additionally, this research demonstrated that novel "freshwater mangrove ecosystem" introduced at the West Lake is one of the very few urban novel ecosystems described scientific literature. Vast majority of novel ecosystems described globally over the last two decades are natural, out-of-city ecosystems, while need and potential for urban ecosystems are very significant. This novel ecosystem of considerable diversity was shown to develop naturally and successfully over the period of 3.5 years since a start-up from baseline state in March 2018. This novel ecosystem has proven to provide several ecological benefits such as nutrient absorption as evidenced in the growth of mangrove trees and macrophytes located at the treatment site. It was also proven the carbon sequestration rate in relation to enhanced biomass accumulation rate at the treatment site and water quality improvement as evidenced by the gradual improvement of TKN, TP, Chlorophyll *a*, and turbidity of West Lake water from the baseline situation to current condition. This developed novel ecosystem enhances biodiversity in urban environment that helps to improve ecosystem flexibility, resilience, and survivability.

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