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The Application of Nature-Based Technologies for Addressing Urban Environmental Problems

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도시 환경 문제를 해결하기 위한 자연 기반해법의 적용

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Abstract

LID technologies are capable of mitigating the negative impacts of non-point source (NPS) pollution generated in different land uses. Apart from the increase in point and non-point pollutant generation, highly developed and paved areas generally affect microclimate conditions. This study evaluated both the efficiency of Low Impact Development (LID) facilities in treating NPS pollutant loads as well as the unit pollutant loads (UPL) generated in various urban features (such as parking lots and highways). This investigation also looked at how LID technology helped to alleviate Urban Heat Island (UHI) conditions. As compared to the typical unit pollutant loads in South Korea, the unit pollutant loads at Kongju National University were relatively low, because of no classes, limited vehicular transmission, and low anthropogenic activities during vacation. After receiving treatment from the LID facilities, the effluent pollutant loads were significantly decreased. The sedimentation in filtration mechanisms considerably reduced the pollutant fractions in the influent. Additionally, it was shown that LID facilities' mean surface temperatures are up to 7.2°C lower than the nearby paved environment, demonstrating the LID systems reducing the UHI impact on an urban area.

Key words : low impact development, nature-based solution, unit pollutants load, urban heat island

요 약

LID 기술은 다양한 토지이용에서 발생되는 비점오염원(NPS)을 저감하는 기술이다. 점오염과 비점오염원의 증가와는 별도로 불투수지역 내 도심지는 일반적으로 도시기후에 영향을 준다. 본 연구에서는 LID 기술이 도시열섬현상(UHI)을 저감에 대한 영향분석을 공주대학교를 대상으로 수행하였다. 공공부지인 학교는 보행자의 통행량, 차량운행이 특정시기에 증가되기에 일반적인 원단위 부하량보다 낮은것으로 나타났다. LID 시설은 강우유출수 내 오염물질을 여재부 내 흡착, 여과 등을 통해 오염물질이 저감되는 것으로 분석되었다. 또한 LID 시설 내 강우유출수 저감 및 저류를 통해 유역 내 불투수면적보다 최대 7.2 ℃ 낮은것으로 나타났다. 따라서 LID 시설은 비점오염물질 저감 및 도시열섬 현상을 완화시키는 것으로 분석되었다.

핵심용어 : 저영향개발기법, 자연기반해법, 단위부하율, 열섬현상

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1. Introduction

Population growth and rapid urbanization severely affected the state of water resources in recent decades. Urbanization-related problems, such as aggravation of environmental pollution, loss of green and natural spaces, and increasing temperatures, are widely observed globally (Byeon et al., 2016; Herath et al., 2018). Stormwater runoff is among the major causes of water pollution in urban areas. Surface runoff from urban areas transports sediments that contain, organics, nutrients, and heavy metals (Yano et al., 2019). Processes, including dry and wet atmospheric deposition, contribute considerable amounts of pollutant loads in the sediments that accumulate on impervious surfaces. Through the wash off process, the pollutant-rich particles from various urban land uses are transported to nearby receiving water bodies and may result to water quality degradation. To assess the overall pollution loadings from different land uses, such as residential, commercial, industrial, transportation, and open spaces like parks and golf courses, the unit loads are frequently used in urban areas (Lee et al., 2008). The unit pollutant load (UPL) method can used to quantify the amount pollutants per unit area of the catchment throughout a given period (Reyes et al., 2018; Li et al., 2015). Generally, UPL gives an overview of the deposition and wash off characteristics of pollutants within a catchment area.

Apart from the increase in point and non-point pollutant generation, highly developed and paved areas generally affect microclimate conditions. The urban heat island (UHI) effect, which is described as the phenomenon wherein the observed ambient temperature in urban areas are greater than those in the surrounding rural areas, is also considered one of the major effects of land use changes (Balany et al., 2020). Heat islands are created when natural features are replaced with surfaces that absorb and transfer heat to its surrounding environment (USEPA, 2022; Heaviside et al., 2017). The prevalence of UHI increases energy consumption due to the higher demand for cooling apparatuses. Moreover, UHI can also pose increased water demand, affect the air quality, and in extreme cases, lead to fatalities as a result of heat stress (Santamouris et al., 2015; Czarnecka et al., 2014).

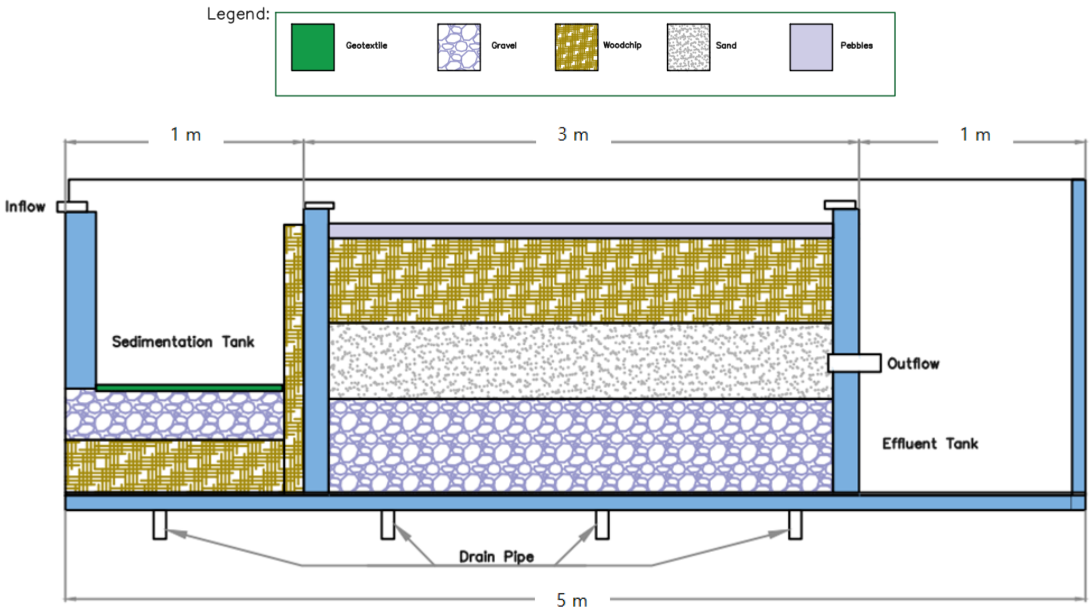
In areas that produce relatively high non-point pollutant loads, decentralized treatment systems are necessary to prevent the excessive deposition of pollutants in receiving water bodies (Hong et al., 2020). Low-impact development (LID) strategies have been implemented in different countries to address different environmental issues (Hilliges et al., 2017). LID technologies were previously used solely for stormwater runoff treatment, but further advancements in the design of these systems also expanded their functions and benefits. LID technologies are capable of mitigating the negative impacts of non-point source (NPS) pollution generated in different land uses. LID technologies are considered as cost- effective alternatives to traditional stormwater treatment systems since these facilities are capable of reducing runoff volumes and pollutant concentrations using nature-based mechanisms (Reyes et al., 2018). Facilities, including infiltration trenches, bioretention systems, permeable pavements, and constructed wetlands, among others rely on physical, chemical, and biological mechanisms to effectively manage and treat polluted stormwater runoff (Maniquiz-Redillas & Kim, 2016).

Both UHI and excessive NPS pollutant loads are the result of changing natural landscapes into paved areas and thus, incorporating nature-based technologies, in recent urban developments has become a common practice in several countries (Shafique et al., 2017). This study was conducted to evaluate the multiple benefits of low impact development technologies installed in an urban setting. The stormwater unit pollutant loads generated in various urban features (i.e. roads and parking lots) and the effectiveness of LID facilities in treating polluted urban stormwater runoff was investigated in this inquiry. The surface temperature variations in different urban features were also evaluated to establish the contribution of LID technologies in alleviating UHI conditions.

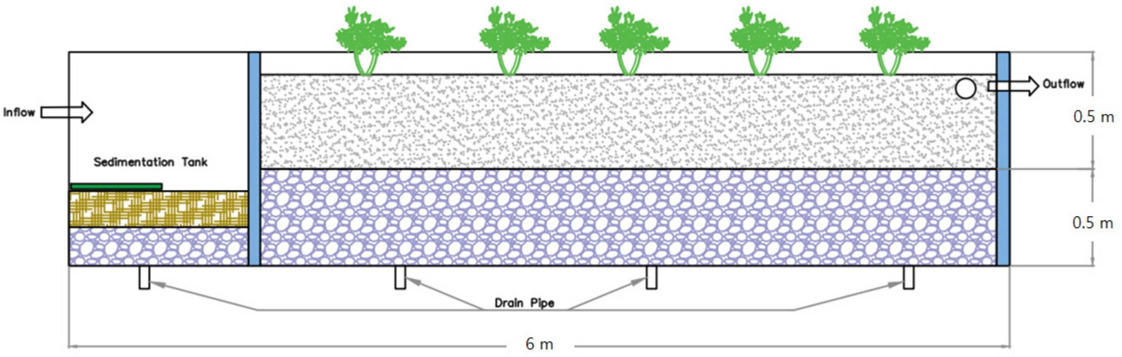
2. Materials and Methods

2.1 Characteristics of the study area and LID technologies

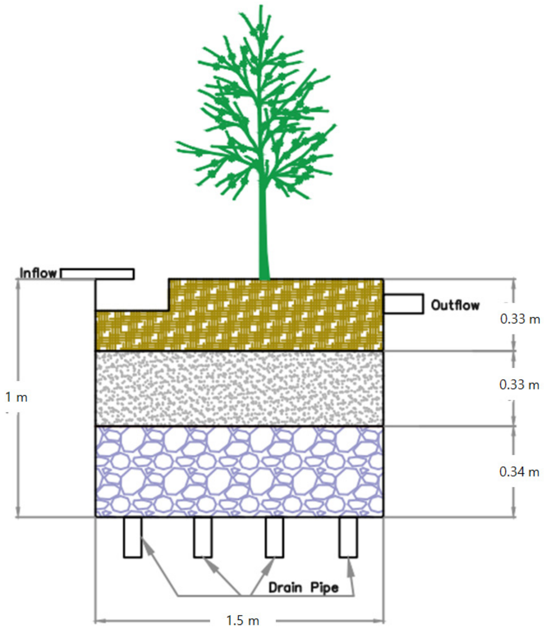
The schematic representation of the infiltration trench (IT), rain garden (RG), and tree-box filter (TBF) located at the Kongju National University (KNU), Chungnam Province, South Korea were illustrated in Figure 1. The LID facilities were designed to accommodate runoff from 100% impervious roads and parking lots. All three facilities can be divided into three zones, namely: 1) sedimentation or settling zone, filter bed, and effluent tank. The sedimentation tank was primarily designed to remove the particulates and sediments in stormwater. This zone is



(a) IT



(b) RG



(c) TBF

Fig. 1. Longitudinal section diagrams of (a) IT, (b) RG, and (c) TBF

Table 1. Characteristics of the LID technologies

Parameter	Unit	IT	RG	TBF
Year Constructed	-	2009	2014	2010
Media	-	Sand, gravel, woodchip	Sand, geotextile, gravel, woodchip	Sand, gravel, woodchip
Runoff source	-	Road	Parking lot	Parking lot
Dimension,(L:W:H)	m	5:1.2:1.3	6:1.2:1.2	1.5:1:1.3
Storage volume	m^3	3.54	2.88	0.71
Catchment area	m^2	371	481	379
No. of monitored events	-	67	37	33
Monitored period	-	May 2009 to July 2022	May 2014 to August 2022	May 2010 to July 2022

primarily composed of porous media (i.e. woodchip and gravel) to facilitate efficient infiltration and effective runoff reduction. The filter beds of the facilities are equipped with woodchips, sand, and gravel layers. These filter media are typically used in LID systems to enhance the filtration performance, moisture retention, and pollutant removal within the facilities (Reyes et al., 2018; Baltrėnaitė et. al, 2016). The IT does not contain plants since it was specifically designed for immediate water drainage. RG was planted with a bridal wreath (*Spiraea prunifolia var. simplicifora*), blue star creeper (*Pratia pedunculata*), rainbow pink (*Dianthus chinensis L.*), and marigold (*Tagetes erecta L.),* whereas dawn redwood (*Metasequoia glyptostro boides*) was planted in the TBF. The plants used in the LID facilities were selected due to their high nutrients and heavy metal uptake capabilities (Lee et al., 2021; Gurung et al., 2018; Hatt et al., 2008). The detailed characteristics of the LID facilities and the total number of monitored events and periods were summarized in Table 1.

2.2 Monitoring procedure, and water quality analysis

Stormwater samples were collected in the inflow and outflow ports of the facility as the rainfall event progresses. The first samples were collected as soon as the inflow or outflow started, whereas the succeeding stormwater samples were collected after 5, 10, 15, 30, and 60 minutes. After the first hour of sampling, additional water samples were collected at hourly intervals throughout the remaining duration of the rainfall event. Flow rates were also measured at the inflow and outflow ports every five minutes to account for the volume flowing in and out of the facility. Standard laboratory procedures prescribed by APHA; AWWA; WEF et al (1995) were conducted to determine total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) concentrations in stormwater. The concentrations of nutrients, such as total nitrogen (TN) and total phosphorus (TP), and heavy metals including chromium (Cr), iron (Fe), zinc (Zn), and lead (Pb), in the stormwater samples were also investigated in the study. The equation used for calculating the UPL was shown in Equation 1.

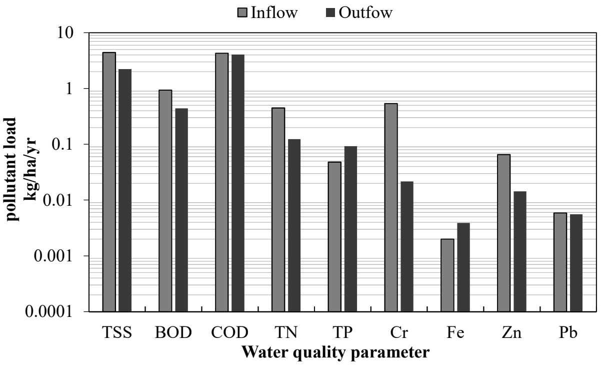
$$\text{UPL (kg/ha/yr)} = \frac{\Sigma C(t)\,Q(t)\,\Delta t}{A} \tag{1}$$

In order to evaluate the effects of LID technologies in UHI effect mitigation, the Testo-875- 1i thermal infrared camera was utilized. Thermal images were taken from October 2019 to August 2022 to record the temperature in the facility and its surrounding areas. The images were processed using the Testo IRSoft software and the database containing temperature values were analyzed statistically.

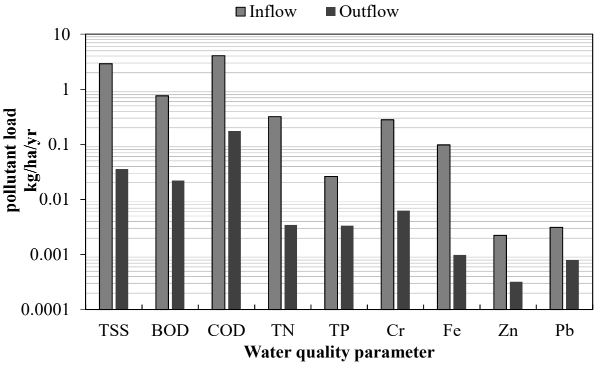
3. Results and Discussion

3.1 Stormwater UPL in urban catchments

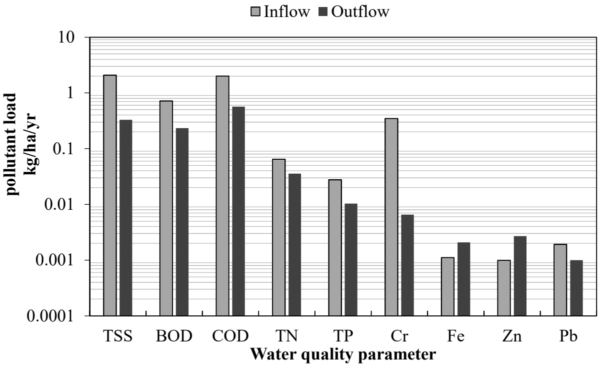
Pollutant deposits on impermeable surfaces may originate from anthropogenic and natural sources (Jung et al., 2008). The calculated UPL of different stormwater constituents were summarized in Figure 2. Among the water quality parameters, TSS has found to be the highest in the stormwater influent for IT and TBF, whereas COD was highest in the influent for RG. The increased deposition of particulates and organics in stormwater runoff can be attributed to the external sources of pollutants in the catchment area. TSS and COD loads can originate from a variety of sources, such as pavement (due to wear), vehicle exhaust emissions, vehicle components, pedestrian trash, plant and leaf litter, and atmospheric deposition of particles (USEPA, 1999; Taylor and Owens, 2009). In the case of nutrients, the main contributors are automobile exhaust and litter from plants (Jani et al., 2020; Yang et al., 2018). Among heavy metals, Cr loads



a) IT



b) RG



c) TBF

Fig. 2. The inflow and outflow of annual unit pollutant loads for LID facilities

were found to be the highest. The primary sources of Cr in urban catchments are leakage of vehicle fluid, brake wear, tire wear, and road wear (Petrucci et al., 2014; Budai et al., 2011). As compared to IT, the UPL of the influent stormwater samples collected from the RG and TBF were lower by up to 33% and 53%, respectively. RG and TBF treat runoff from parking lots, whereas IT receives road runoff. Vehicular activities in parking lots are relatively lower as compared to roads, thus resulting to lower pollutant deposition potential.

Majority of the effluent pollutant loads were considerably reduced after undergoing treatment from the LID facilities. Stormwater TSS loads were reduced by up to 98% in the IT and TBF. The sedimentation tank primarily contributed in the removal of particulates and particulate-bound pollutants, whereas the filter media greatly enhanced the removal of finer particles that cannot be removed through sedimentation. In the case of RG, the efficient removal of TN, amounting to 98%, was observed due to the presence of plants further enhanced the removal of pollutants through uptake and assimilation. In some cases, the effluent from LID facilities exhibited larger pollutant loads as compared to the influent pollutant loads. It was noted that effluent Fe and Zn loads in the TBF and effluent TP load in the IT were higher than the influent loads. Once saturated, the pollutants can leach from the facilities' media and result to higher effluent pollutant loads from the facilities (Hatt et al., 2009; Jiang et al., 2017).

The Korea Environment Institute (KEI) conducted a nationwide study regarding the typical stormwater pollutant loads from various land uses in South Korea (Choi and Shin, 2002). The report published by KEI indicated that the typical BOD, TP, TN, Zn, and Pb unit pollutant loads in the runoff from a 100% impermeable

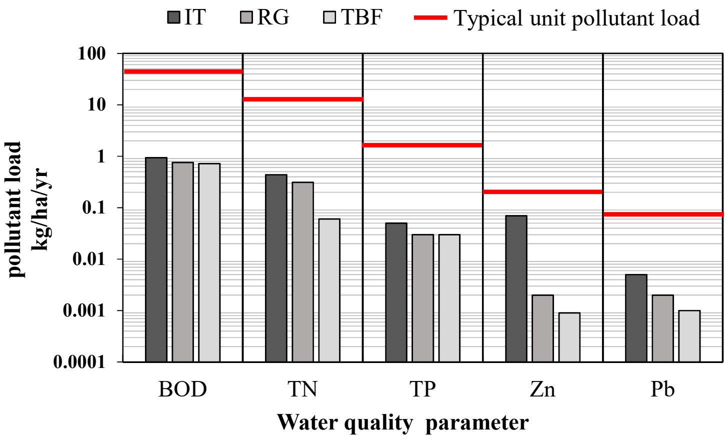


Fig. 3. Comparison of the analyzed stormwater runoff and the typical UPL values in South Korea

catchment were approximately 44 kg/ha/yr, 2 kg/ha/yr, 17 kg/ha/yr, 0.31 kg/ha/yr, and 0.16 kg/ha/yr. As shown in Fig. 3, the pollutant loads in the stormwater collected from Kongju National University's parking lots and roads were relatively lower than the typical unit pollutant loads in South Korea, implying that minimum intervention is required to treat the runoff from the study area. Variations in stormwater pollutant loads can be highly influenced by the degree of catchment imperviousness and the extent of anthropogenic activities. Despite the high imperviousness rate of the catchment, anthropogenic-related activities in the university's compound are limited especially during academic breaks, thus resulting in low pollutant deposition potential.

3.2 UHI mitigation function of LID technologies

The effect of LID facilities on the urban surface temperature was exhibited in Figure 4. The mean surface temperature in the IT, RG, and TBF were 13.83°C, 16.71°C, and 17.01°C, respectively. The mean surface temperature of natural landscapes ranged from -7.06°C to 38.03°C, whereas paved areas have noticeably higher mean surface temperatures ranging from -7°C to 49.46°C. It can also be noted that the mean surface temperature in LID facilities are up to 7.2°C lower than in the paved environment, indicating that these nature-based technologies have the potential to alleviate UHI conditions. Plant transpiration and evaporation both transfer water from the previous media in the facilities to the atmosphere, thereby resulting in lower temperatures in the LID facilities (Oral et al., 2021; Martineau et al., 2012). The mean surface temperatures in RG and TBF were 17% to 18% higher than the mean surface temperature in IT. Unlike RG and TBF which are located in open areas (i.e. parking lot), the IT was situated in a roadside area shaded by trees. Although there were plants within RG and TBF, these facilities were directly exposed to sunlight, which resulted in greater surface temperatures.

The UHI phenomenon occurs when built-up areas exhibit warmer surface temperatures as compared to their surrounding regions. The complex interaction between anthropogenic activities and the structures in an urban space are the primary cause of elevated ambient air temperatures in urban areas (Rizwan et al., 2008). Urban environments are usually cooled by the shades provided by tree canopies and green spaces where smaller plants, like grass and bushes, grow (Shafique et al., 2017). According to the report published by the Climate Adaption Platform (2020), incorporating LID technologies in urban landscapes primarily contributes to the expansion of permeable areas, improving the water circulation function, ground surface cooling. In the case of vegetated LID systems, plants may enhance evapotranspiration in order to reduce the heat intensity of the surroundings (Mun-Soo et al., 2021).

3.3 The Comparison of UHI mitigation strategies with other countries

During summer seasons when surface air temperature and solar radiation are higher, the impact of UHI can also be greater (Balany et al., 2020). UHI has the potential to increase air pollution, the demand for electricity, and heat-related diseases and fatalities. LID and other green infrastructures (GI) can reduce the UHI effect by providing shade and promoting evapotranspiration (Skelhorn et al., 2014). In the case of facilities without plants, the media filters can aid in maintain a cool ambient temperature cool by regulating the moisture within the pores and emitting

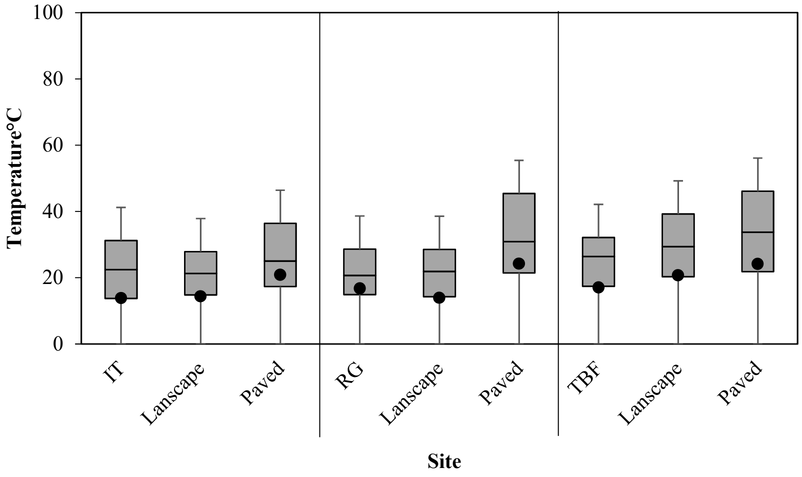


Fig. 4. Box plot of highest average temperature for LID technologies

Table 2. Urban Heat Island mitigation strategies in different countries

Country	Green infrastructure type	Major finding	Reference
Greece	Green space expansion	Air temperature up to 0.5°C and surface temperature up to 19°C can be reduced	Tsoka et al., 2018
Saudi Arabia	Green roofs	At roof level, the day-time average temperature can be reduced by 12.8°C with the application of green roof	Alexandri and Jones., 2008
Australia	Urban greening,	The green cover led to a reduction of 0.2°C in atmospheric temperature	Jamei et al., 2017
Finland	Wetlands	Air and surface temperature reduced up to 2°C to 1.5°C	Alikhani et al., 2021
South Korea	Porous blocks/ Greening blocks	Porous blocks can have 3.9°C to 22.6°C lower surface temperatures as compared to asphalt	Mun -Soo et al ., 2021
Sri Lanka	Green wall	A temperature decrease of up to 1.86°C with different urban greening strategies	Herath et al., 2018
USA	Green roofs	The application of green roof resulted to 19°C lower surface temperature during the summer season	DeNardo et al., 2005
Poland	Rain garden	The surface temperature in a rain garden was 7°C to 20°C lower than its surrounding area	Kasprzyk et al., 2022
South Korea	LID facilities	The mean surface temperature in LID facilities are up to 7.2°C lower than the surrounding paved area	This study

water vapor. Some of the case studies concerning the application of LID technologies as urban heat island mitigation strategies in different countries were summarized in Table 2. Tsoka et al (2018) reported that the application of urban greening and green space expansion strategies in Greece can potentially decrease air and surface temperatures by up to 0.6°C and 15°C, respectively. The Envi-met simulation results indicated that replacing parking lots with small vegetated parks can contribute to urban cooling by providing additional shades to paved surfaces and lowering the heat storage in mineral surfaces. A study in Saudi Arabia and the USA also found that the implementation of green roofs can help reduce air and surface temperatures by up to 12.8°C and 19°C, respectively (Alexandri and Jones, 2008; DeNardo et al., 2005). Green roofs act as envelopes that neutralize the heat from sunlight. Moreover, it was also noted that areas with hotter and drier climate can benefit more from vegetated surfaces. Jamei et al (2017) and Herath et al (2018) explored the UHI mitigation benefits of urban greening strategies. It was noted that a general increase in green space can considerably contribute to urban cooling and UHI mitigation. Moreover, technologies such as green roofs and green walls were found to have greater applicability in areas with spatial constraints or limitations (Jamei et al., 2017; Herath et al., 2018). The potential of urban wetlands in mitigating the negative impacts of UHI were discussed in the work of Alikhani et al (2021). The hydrological connections between wetlands, the surrounding built environment, and the presence of vegetation in wetlands were found to have a cooling effect ranging from 1.5°C to 2°C.

Paved areas generally contribute to UHI by absorbing solar energy and releasing it to the surrounding environment in the form of heat (Ibrahim et al., 2018). Mun-Soo et al (2021) indicated that LID-based materials like porous pavements or blocks can reduce surface temperature by up to 22.6°C. Permeable pavements have large water storage capacities that can aid in temperature cooling through moisture content regulation (Wang et al., 2018). Rain gardens are extensively used as stormwater management facilities due to its high pollutant removal performance and aesthetic value. Kasprzyk et al (2022) assessed the UHI mitigation potential of rain gardens to increase its value as a smart tool for urban climate adaptation. Results revealed that rain gardens have high potential of mitigating UHI and regulating microclimate conditions. Overall, LID technologies and green space expansion presented temperature regulating benefits on areas with high rates of imperviousness.

4. Conclusion

The application of LID technologies are one of the vital options for non-point source control and UHI effects in urban areas. Compared to the IT influent pollutant loads, the influent stormwater samples collected from RG and tree box filters exhibited 33% and 53% lower pollutant loads. According to the LID facilities' treatment, such as the RG, IT, and Tree box filters were capable of removing pollutants in stormwater runoff. The KNU was found to have a low pollutant load, when compared to the typical

Korean stormwater pollutant loads, implying limitations on vehicular transport, no classes during the vacation, and low anthropogenic activities. The LID facility not only demonstrated NPS pollution removal but also an environmental cooling impact, suggesting that nature-based systems help to decrease UHI conditions in an urban area. Ultimately, this study can be used as a reference for evaluating urban the benefits of LID in alleviating environmental issues such as non-point source pollution, stormwater management, and UHI.

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