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Comprehensive Review on the Implications of Extreme Weather Characteristics to Stormwater Nature-based Solutions

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자연기반해법을 적용한 그린인프라 시설의 극한기후 영향 사례분석

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Abstract

The effects of climate change on green infrastructure and environmental media remain uncertain and context-specific despite numerous climate projections globally. In this study, the extreme weather conditions in seven major cities in South Korea were characterized through statistical analysis of 20-year daily meteorological data extracted fro m the Korea Meteorological Administration (KMA). Additionally, the impacts of extreme weather on Nature-based Solutions (NbS) were determined through a comprehensive review. The results of the statistical analysis and comprehensive review revealed the studied cities are potentially vulnerable to varying extreme weather conditions, depending on geographic location, surface imperviousness, and local weather patterns. Temperature extremes were seen as potential threats to the resilience of NbS in Seoul, as both the highest maximum and lowest minimum temperatures were observed in the mentioned city. Moreover, extreme values for precipitation and maximum wind speed were observed in cities from the southern part of South Korea, particularly Busan, Ulsan, and Jeju. It was also found that extremely low temperatures induce the most impact on the resilience of NbS and environmental media. Extremely cold conditions were identified to reduce the pollutant removal efficiency of biochar, sand, gravel, and woodchip, as well as the nutrient uptake capabilities of constructed wetlands (CWs). In response to the negative impacts of extreme weather on the effectiveness of NbS, several adaptation strategies, such as the addition of shading and insulation systems, were also identified in this study. The results of this study are seen as beneficial to improving the resilience of NbS in South Korea and other locations with similar climate characteristics.

Key words : Climate change adaptation; extreme weather; green infrastructure; nature-based solutions; urban resilience

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요 약

전세계적으로 기후변화로 인한 그린인프라와 환경기반시설의 영향 및 예측에 대한 연구는 활발히 진행되고 있다. 하지만 국가별 극한기후가 발생하는 시기나 패턴이 다르기에 국내에도 극한기후로 인한 그린인프라와 환경기반시설에 대한 연구가 필요하다. 따라서 본 연구에서는 국내 주요 7개 도시를 대상으로 기상청에서 제공하는 20년 동안의 극한기후에 대한 통계적 분석과 극한기후로 인한 자연기반해법(NBS)을 적용한 그린인프라 시설에 대한 영향분석을 수행하였다. 극한기후에 대한 통계분석 결과 지리적 위치, 지표 불투수성, 지역 기상 패턴에 따라 다양한 극한 기상 조건에 잠재적으로 취약한 것으로 분석되었다. 서울은 극한온도(영상, 영하)가 관측되었으며 부산, 울산 및 제주 에서는 강수량과 바람에 대해 극한기후가 발생하여 도시탄력성에 잠재적인 위협인자로 분류되었다. 온도는 도시 내 식생에 대한 회복력에 주요 요인으로 적용되며, 바이오차, 모래, 자갈, 우드칩 등 여재를 적용한 습지(CW)에서 극 영하온도에서 물리적 제거효율 및 영양염류 제거능력을 저하되는 것으로 분석되었다. 극한기후로 인한 영향을 저감하기 위해 그린인프라 시설 내 온도조절이 가능한 차광 및 단열 시스템적용과 같은 극한기후 별 대응전략 수립이 가능하다. 본 연구를 통해 국내와 기후특성이 유사한 지역에서의 극한기후 대응전략 수립에 도움이 될 것으로 판단된다.

핵심용어 : 기후변화 적응력, 극한기후, 그린인프라, 자연기반해법, 도시 탄력성

1. Introduction

Drastic changes in global climate patterns were observed throughout several decades. Consequently, these developments in climate patterns have resulted in detrimental impacts on environmental conditions in urban areas. It was previously reported that an increase in the global average temperature of +1.1°C from pre-industrial times to 2019 has resulted in higher frequencies of extreme weather events, particularly heat waves, flooding, and winter storms (UN Office for Disaster Risk Reduction, 2020). Previous studies also estimated, through the Clausius-Clapeyron relationship, that the intensity of extreme precipitation increases with global warming at about 7% per +1°C (Pall et al., 2007; Martinez-Villalobos & Neelin, 2023). Climate projection models from other studies, however, predict a precipitation increase of only 2% per +1°C (Richter & Xie, 2008). Despite these projections being indicative of the magnitude of climate change that could be expected in the following decades, its impacts on particular assets, such as Nature-based Solutions (NbS) remain context-specific, specifically in urban areas.

An extreme weather event was previously defined as the occurrence of a climatic condition near the upper or lower end of a spectrum of the observed climatic variables in a given span of time, more specifically the minimum and maximum values (Stephenson, 2008). Moreover, previous studies defined that a weather condition can be considered extreme if it is 10%, 5%, or 1% relative to a specific reference period (Seneviratne SI et al. 2012., Ummenhofer and Meehl, 2016). The occurrence of extreme weather events has also been found to be affected by external factors, such as carbon emissions. The continuously growing emissions of CO_2 have been confirmed to be a major contributing factor to the increase in global temperature (Friedlingstein et al., 2022; Lee & Cheong, 2018). In response to the continuous increase of CO_2 emissions globally, low impact development (LID) technologies such as constructed wetlands (CWs) became a major point of discussion in recent studies due to their potential as cost-effective carbon sequestration systems (Deverel et al., 2014; Maynard et al., 2011; Maziarz et al., 2019). Hence, reinforcing the extreme weather resilience of such technologies is seen as a vital contributor to attaining global carbon neutrality objectives. Extreme weather conditions caused by altered climate patterns also impose negative impacts on biodiversity. It was previously found that extreme heat and droughts can cause a decrease in crop production and quality (Gowda et al., 2018; Zhao et al., 2017). The size and health of harvested species in oceans and freshwater were also identified to be affected by rising temperatures (Cheung et al., 2013; Crozier & Hutchings, 2014). Thus, identifying the negative impacts and adaptation strategies that could be implemented is seen as a potential contributor to achieving global goals on sustainability and climate change adaptation. The attainment of Sustainable Development Goals (SDGs), particularly sustainable cities and communities, climate action, and life on land is presumed to be a benefiting endeavor in identifying such climate change impacts and adaptation strategies.

Amidst the uncertainties regarding the resilience of urban NbS to climate change, it is crucial to determine the characteristics of extreme weather conditions and the specific components of NbS that are negatively impacted by such events. This study aimed to characterize the extreme weather conditions in the major cities of South Korea were through statistical analysis of environmental data from the Korea Meteorological

Administration (KMA). In addition, a comprehensive review was conducted to determine the impacts of extreme weather on NbS and various types of environmental media. Furthermore, different extreme weather adaptation strategies developed and utilized globally were summarized and discussed in this study.

2. Materials and Methods

2.1 Extreme weather characterization

To assess the extreme weather characteristics in urban areas in South Korea, the extreme weather conditions in the country's major cities were characterized through an extensive statistical analysis of daily meteorological data from the KMA database. The studied cities were Seoul, Daejeon, Daegu, Gwangju, Busan, Ulsan, and Jeju, as the mentioned areas are seven of the most populated and impervious cities in the country. The extracted and analyzed meteorological data included daily maximum and minimum temperatures, relative air humidity, maximum wind speed, daily precipitation, and evaporation. The minimum and maximum values over a 20-year span, from January 1, 2003 to December 31, 2022, were obtained for each meteorological parameter. The selected span was used in the study to provides a relatively recent dataset that is more pertinent to current climate and weather patterns. The said span was also used in previously published articles on climate projection and extreme weather (Collins & Knutti, 2013; Nesbitt et al., 2022). In addition, a Pearson correlation analysis was conducted to investigate the relationships among the extreme meteorological variables obtained. The analysis aimed to provide insights into the complex interactions between meteorological data, identifying potential patterns and dependencies that may influence extreme climatic weather phenomena.

2.2 Comprehensive review

A comprehensive review of peer-reviewed scientific journal articles was conducted to determine the impact of extreme weather on LID facilities and various filter media used for such technologies. The reviewed articles were obtained from the Scopus and Google Scholar databases, in which general terms "extreme weather", "extreme climate", "environmental media" or "filter media", "low impact development" or "LID", "best management practices" or "BMP" were inputted. Individual keywords for environmental media, particularly "biochar", "sand", "gravel", "activated carbon", and "woodchip" were also inputted in addition to the general terms to obtain articles more relevant to the mentioned media. The search was restricted to articles published between the years 2000 and 2023 for a set of articles that is more relevant to modern climate trends. The obtained articles were screened for relevance based on the type of technology used, in which only studies focusing on nonpoint source pollution treatment systems were identified and included.

3. Results and Discussions

3.1 Extreme climatic occurrences in South Korean major cities

The magnitude in which extreme weather conditions occurred in the major cities analyzed varied according to several factors including geographic location, impervious surface area percentage, and local weather patterns. A summary of extreme values observed in the major cities in South Korea is shown in Table 1. The highest maximum and lowest minimum temperatures of 39.6 ˚C and -18.6 ˚C, respectively, were both observed in Seoul, which has the highest surface imperviousness among the studied cities at 50% (Yoon et al., 2016). The three nearest high temperatures to the recorded maximum were 36.2 ˚C, 35.7 ˚C, and 35.5 ˚C, which are 8.6%, 9.9%, and 10.4% lower than the observed maximum temperature, indicating the rarity of the extreme temperature occurrence. Moreover, the three nearest low temperatures to the recorded minimum were -18.0, -17.8, and -17.8, which were relatively close to the recorded 20-year minimum value. This indicates that severely cold temperatures tend to be a more frequent occurrence in Seoul. On the other hand, the lowest maximum temperature and the second highest minimum temperature were observed in Jeju, which has the lowest surface imperviousness at slightly above 20% (Moazzam et al., 2022). This observation indicates a directly proportional relationship between extreme temperature occurrence and surface imperviousness. Results also indicate that geographic location plays a vital role in the magnitude of precipitation extremes in the studied areas. It was noted that the three highest maximum precipitation depths in 1 hour were observed in Busan, Ulsan, and Jeju, which are all situated in the southern part of South Korea. The two highest maximum values for solar radiation/hr and total insolation were also observed in Busan and Jeju. As both temperature extremes were observed in Seoul, a potential vulnerability of NbS to extremely high and low temperatures in the said city is seen. Moreover, precipitation and solar radiation extremes were observed in cities from the southern part of the country, denoting possible vulnerabilities of NbS in those cities to extreme weather impacts, particularly increased plant mortality rate and facility overflow (Catalano de Sousa et al., 2016; Mantilla et al., 2023).

A Pearson correlation matrix of the environmental extremes obtained in this study is shown in Figure 1. A red cell indicates a strong correlation between the two variables corresponding to it, while a blue cell indicates a weak correlation between the two variables. It was observed that the minimum temperature has high correlations with several meteorological parameters, particularly precipitation extremes, maximum wind speed, average vapor pressure, and maximum solar radiation per hour. A strong positive correlation between daily minimum temperature and maximum wind speed, with a Pearson correlation coefficient (r) of 0.89, suggests that on days with lower minimum temperatures, higher wind speeds are often observed. This relationship may indicate the influence of temperature differentials on atmospheric circulation patterns (Ibebuchi & Lee, 2023; Jones & Lister, 2009). Additionally, there is a robust positive correlation of 0.84 between daily minimum temperature and maximum solar radiation per hour, implying that days with cooler nights tend to have higher daytime solar radiation levels, which is consistent with the expected relationship between temperature and solar insolation (Daut et al., 2012; Prieto et al., 2009). Maximum temperature, moreover, was revealed to have a negative correlation with several parameters, particularly precipitation and wind speed extremes. It reveals that higher maximum temperatures are associated with reduced precipitation amounts, a negative correlation that aligns with well-established meteorological principles (Trenberth & Shea, 2005; Wazneh et al., 2020). As temperatures increase, the atmosphere's capacity to hold moisture increases, leading to decreased cloud cover and a lower likelihood of precipitation events. This correlation also indicates that lack of precipitation may induce elevated air temperatures. The negative correlation between maximum temperature and precipitation amount is relevant because it highlights the importance of

Table 1. Summary of the observed extreme values for various meteorological parameters in the major cities of South Korea.

Parameter	Unit	City						
		Seoul	Daejeon	Daegu	Gwangju	Busan	Ulsan	Jeju
1Min. temperature	˚C	-18.6	-17.5	-13.9	-13.5	-12.8	-13.5	-5.8
2Max. temperature	˚C	39.6	39.4	39.2	38.5	37.3	38.8	37.5
Precipitation duration	hr	24	24	24	24	24	24	24
10-min. max. precipatation	mm	26.6	25	21.5	24	26.5	26.1	24.5
1 hr max. precipitation	mm	75	65.3	69	86.5	106	104.2	99.2
Daily amount of precipitation	mm	301.5	231.5	187	322.5	310	327.5	420
Max. instantaneous wind speed	m/s	28.3	26.8	33.3	28.8	42.7	33.2	60
Max. wind speed	m/s	14	16.4	17.1	14.6	26.1	18.3	39.5
Min. relative humidity	%	17.9	23.8	13.5	19.8	11.3	14.8	17.9
[3]Ave. relative humidity	%	99.8	99.9	99.8	99	100	99.8	99.4
Min. ave. vapor pressure	hPa	0.7	1.1	0.8	1.5	0.8	0.8	3.3
Max. solar radiation/hr	MJ/m^2	3.85	4.07	10.5	11	4.77	-	36.12
Total insolation	MJ/m^2	31.11	33	31.39	32.08	34.68	-	30.6
Total large evaporation	mm	9.3	8.1	9.2	7.2	8.1	-	10.6
Total small evaporation	mm	15	11.5	13.1	10.3	11.5	-	13.1

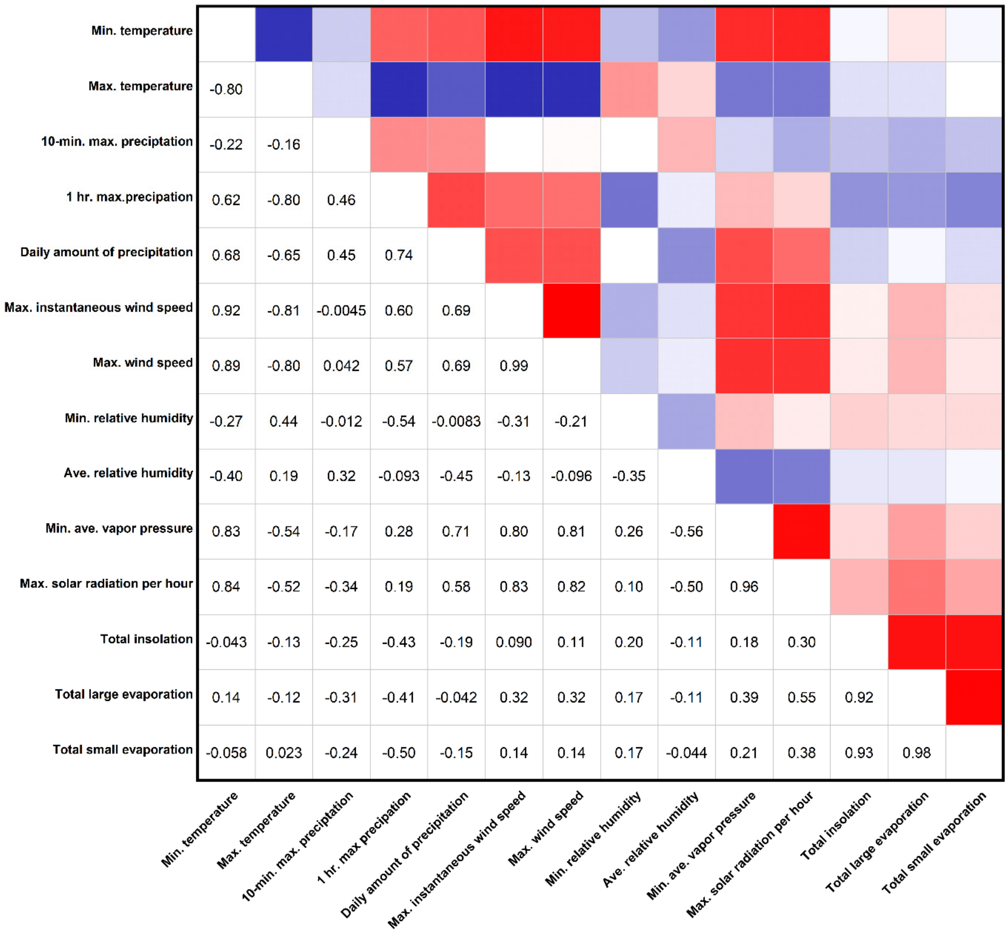
1-minimum; 2-maximum; 3-average

understanding how temperature fluctuations can affect local weather conditions. Conversely, a negative correlation between maximum temperature and maximum wind speed indicates that warmer conditions tend to be linked to calmer winds. This relationship is rooted in the stability of the atmosphere, as warmer, less dense air inhibits the development of strong winds, while cooler, denser air encourages vertical mixing and potentially stronger breezes (Wooten, 2011). Furthermore, minimum relative humidity was found to be independent of other meteorological parameters, as its correlations with other parameters were relatively low. These findings are seen as valuable in selecting NbS elements like vegetation, as they help anticipate potential wind-related stress on these components during extreme weather events.

3.2 Impact of extreme weather on filter media

A summary of the impacts of extreme weather on various types of environmental media is shown in Table 2. It was found that extreme values for relative humidity, drought, and air temperature impose impacts on environmental media that affect their removal performance and overall stability. A study by Zhang et al. (2022) indicated that high relative humidity resulted in biochar instability. It was observed in the same study that the CO_2 capture capacity of biochar was reduced by 63% after an increase in relative humidity from 9% to 88%. The results of the statistical analysis revealed that all the highest observed average relative humidity in the studied cities was close to 100%. Thus, the relationship between relative humidity, biochar stability, and CO_2 capture capacity suggests potential concerns about the stability and CO_2 storage performance of biochar used in urban areas in South Korea. Several studies also determined that extremely high air temperature results in a decrease in biochar stability, primarily due to elevated oxidative processes (Kumar et al., 2022; Lehmann and Sohi, 2008; Sohi et al., 2009).

Similar concerns were observed with regard to the impact of extreme weather on gravel, sand, and woodchip. It was determined in several studies that extremely low air temperature results in a notable



	Min. temperature	Max. temperature	10-min. max. preciptation	1 hr. max precipation	Daily amount of precipitation	Max. instantaneous wind speed	Max. wind speed	Min. relative humidity	Ave. relative humidity	Min. ave. vapor pressure	Max. solar radiation per hour	Total insolation	Total large evaporation	Total small evaporation
Min. temperature														
Max. temperature	-0.80													
10-min. max. preciptation	-0.22	-0.16												
1 hr. max.precipation	0.62	-0.80	0.46											
Daily amount of precipitation	0.68	-0.65	0.45	0.74										
Max. instantaneous wind speed	0.92	-0.81	-0.0045	0.60	0.69									
Max. wind speed	0.89	-0.80	0.042	0.57	0.69	0.99								
Min. relative humidity	-0.27	0.44	-0.012	-0.54	-0.0083	-0.31	-0.21							
Ave. relative humidity	-0.40	0.19	0.32	-0.093	-0.45	-0.13	-0.096	-0.35						
Min. ave. vapor pressure	0.83	-0.54	-0.17	0.28	0.71	0.80	0.81	0.26	-0.56					
Max. solar radiation per hour	0.84	-0.52	-0.34	0.19	0.58	0.83	0.82	0.10	-0.50	0.96				
Total insolation	-0.043	-0.13	-0.25	-0.43	-0.19	0.090	0.11	0.20	-0.11	0.18	0.30			
Total large evaporation	0.14	-0.12	-0.31	-0.41	-0.042	0.32	0.32	0.17	-0.11	0.39	0.55	0.92		
Total small evaporation	-0.058	0.023	-0.24	-0.50	-0.15	0.14	0.14	0.17	-0.044	0.21	0.38	0.93	0.98	

Fig. 1. Correlation of various extreme weather parameters in the major cities of South Korea from 2003 to 2022.

decrease in the nutrient removal performance of the aforementioned filter media. Environments with air temperature lower than 2 ˚C was revealed to result in a 9% decrease in total phosphorus (TP) removal efficiency of sand (Fowdar et al., 2021). A remarkable decrease in total nitrogen (TN) removal performance was observed in a constructed wetland in China, where the TN removal efficiency decreased from 91% at 15-20 ˚C to 18% at 3-6 ˚C (Xu et al., 2016). A similar trend in removal efficiency was found in the study by Akratos and Tsihrintzis (2007), where a decrease in total Kjeldahl nitrogen (TKN) removal efficiency of gravel was identified at air temperatures below 15 ˚C. Furthermore, some studies noted a decrease in the nitrate removal efficiency of woodchips in cold climatic conditions (Hoover et al., 2016; Maxwell et al., 2020).

Extreme weather conditions were also found to impact the physical properties of basalt, sand, and woodchip. It was previously determined that the ultimate compression strength of basalt was reduced by 10-17% after being exposed to high temperatures in Gelendzhik, Russia, where the maximum recorded air temperature was close to 30 ˚C over a 30-month span (Startsev et al., 2018). Moreover, air temperatures exceeding 32 ˚C were identified to reduce the thermal insulation capability of woodchips. An opposite behavior was observed in sand, in which severely low temperatures during winter reduced the thermal insulation capability of sand in green roofs, exhibiting a higher u-value (Scharf and Zluwa, 2017).

3.3 Impact of severe and extreme climatic conditions on LID technologies

As shown in Table 3, the results of the comprehensive review indicate that the impacts of extreme weather on LID technologies revolve around alterations in pollutant removal efficiency and survival rate of the vegetation used in the facility. Biochemical oxygen demand (BOD),

Table 2. Summary of the impacts of extreme weather conditions on various environmental media based on previous literature.

Filter media	Extreme weather parameter	Impact	Country	Reference
Biochar	High relative humidity	Increased relative humidity, leading to a decrease in biochar stability	United Kingdom	Zhang et al., 2022
	High air temperature	Increased biotic processes and litter content, leading to faster biochar degradation	USA	Lehmann and Sohi, 2008
	High soil temperature	Increased respiration rate of soil microorganisms resulting in high CO_2 production, altered soil aeration	India	Kumar et al., 2022
	Extreme drought	Decrease in plant growth due to oxidative stress	France	Tardieu et al., 2014
	High soil temperature	Decreased stability due to oxidative processes occurring on biochar	United Kingdom	Sohi et al., 2009
Basalt	High temperature	Decreased weight; increased pore size	Russia	Vankov et al., 2022
	High temperature	Decreased ultimate compression strength	Russia	Startsev et al., 2018
Gravel	Low water temperature (<15 ˚C)	Decreased TN removal efficiency	China	Xu et al., 2016
	Low air temperature (<15 ˚C)	Decreased TKN and ammonia removal efficiency	Greece	Akratos and Tsihrintzis, 2007
Sand	Low air temperature (<2 ˚C)	TP removal efficiency decreased from 69% to 60% on average	Australia	Fowdar et al., 2021
	Low air temperature	Reduced thermal insulation capability	Austria	Scharf et al., 2017
Woodchip	Low air temperature	Reduced nitrate removal rate	Spain	Maxwell et al., 2020
	Low air temperature (10-15˚C)	Reduced nitrate removal rate	USA	Hoover et al., 2016
	High air temperature	Reduced thermal insulation capability	France	Skogsberg & Lundberg, 2005

chemical oxygen demand (COD), and nutrients were identified as the pollutant parameters commonly tested in determining the effects of specific climatic conditions on LID pollutant removal performance. All studies focusing on constructed wetlands observed that extremely low air temperatures reduced the pollutant removal efficiency of the studied CWs. A study in China by Song et al. (2006) revealed that the ammonia removal efficiency of a free surface flow wetland during summer decreased by 22% in winter, where an average daily temperature of −0.1 ˚C was recorded. The reduction in removal efficiency of the CW during the seasonal change, however, was less for BOD and COD, where a decrease of 6% and 7% were noted, respectively. A similar trend in nitrogen removal efficiency was observed in a study in Lake Tahoe, USA where a decrease of 20–40% was recorded from summer to winter at a temperature range of −7.8 to −3.8 ˚C (Heyvaert et al., 2006; Varma et al., 2021). It was also found that the NH_4-N and COD removal efficiency of 14 free surface flow constructed wetlands in Finland were lowest in winter, in which the lowest observed daily minimum temperature was −15.1 ˚C (Postila et al., 2015). Furthermore, the same impact of extremely low temperatures on nitrate removal efficiency was determined on CWs studied in countries with

Table 3. Summary of the impacts of extreme weather on various NbS determined from previous literature.

NbS type	Extreme weather parameter	Material/Plant genus	Impact	Country	Reference
Constructed wetland	Low temperature	*Phragmites australis*	Reduced removal performance for BOD, COD, ammonia, and TN	China	Song et al., 2006
		Scirpus Juncus Lemna	Reduced TN uptake and storage	USA	Heyvaert et al., 2007
		-	Reduced removal performance for NH_4-N and COD	Finland	Postila et al., 2015
		Salix viminalis	Potential periodic freezing of the surface of vertical-flow beds	Denmark	Gregersen and Brix, 2001
		Canna Indica; Phragmites australis	Reduced TN removal efficiency	Italy	Mietto et al., 2015
		-	Reduced denitrification rate	USA	Poe et al., 2003
Green roof	High relative humidity	*Evergreen vine, Arachis pintoi (Perennial Peanut)*	Reduced thermal reduction performance	Hong Kong	Jim and Peng, 2012
	Extreme drought	*C. modestus and D. crassifolium*	Reduced survival on scoria substrate	Australia	Farrell et al., 2012
		S. spurium	Low plant survival rate	United Kingdom	Nagase and Dunnett, 2010
	Extreme drought and high temperature	*Arctostaphylos uva-ursi and Allium cernuum*	Increased plant stress and mortality	Washington, USA	Martin and Hinckley, 2007
Green wall	Low air temperature	*Thymus vulgaris*	Low plant survival rate	Sweden	Martensson et al., 2016
Permeable pavement	Low air temperature	-	Reduced capability in resisting deformation	China	Wang et al., 2021
	High air temperature	-	Increased vulnerability to cracking at temperatures above 40 ˚C	USA	US Department of Transportation Federal Highway Administration, 2012
Bioretention	Intensified precipitation	-	Changes in retention time resulting in ineffectiveness	USA	Johnson et al., 2022
		-	Overflow resulting in ineffectiveness	USA	Tirpak et al., 2021

Mediterranean and subtropical climates (Mietto et al., 2015; Poe et al., 2003). The observed decrease in pollutant removal efficiency of CWs in low temperatures may be attributed to reduced microbial and plant activity in the CWs. Several studies suggest that microbial activities are contingent on air temperature patterns. Particularly, low air temperatures were determined to hinder microbial processes in CWs, resulting in disrupted denitrification (Du et al., 2018; Ji et al., 2020; M. Wang et al., 2017).

The effects of extreme weather on green roofs and green walls were mostly related to plant growth and survival. In a study by Jim & Peng (2012), it was learned that environmental conditions with elevated relative air humidity reduce the thermal reduction performance of green roofs. The restrained green-roof cooling could be attributed to elevated relative humidity incurring a reduced vapor pressure gradient between the surface and air, and leading to suppression of evapotranspiration. Plant mortality and survival were also identified to be impacted by extreme drought. Farrell et al. (2012) observed lower survival rates for *C. modestus and D. crassifolium* in the scoria substrate after 113 dry days. A similarly low survival of *S. spurium* was observed on commercial green substrates in a study by Nagase & Dunnett (2010) in the United Kingdom. Furthermore, a combination of drought, lack of irrigation, and high temperature resulted in increased plant stress and mortality of *Arctostaphylos uva-ursi* and *Allium cernuum* on a green roof in the USA (Martin & Hinckley, 2007). Furthermore, permeable pavements were identified to be vulnerable to both extremely high and low air temperatures. It was found that under extremely cold conditions, permeable pavements tend to be less resistant to deformation, while a report in the USA indicated that permeable pavements can be vulnerable to cracking at extremely hot conditions, particularly temperatures above 40 ˚C (US Department of Transportation Federal Highway Administration, 2012; J. Wang et al., 2021). It was also confirmed that extreme precipitation events can cause ineffectiveness and overflow to bioretention cells (Johnson et al., 2022; Tirpak et al., 2021).

A majority of the reviewed studies were done in countries with temperate and Mediterranean climate types, where severely cold winters are experienced. With the extremely low temperatures in the major cities in South Korea ranging from -18.6 ˚C to -5.8 ˚C, NbS in those areas are presumed to be vulnerable to the identified negative impacts of climate change on such technologies. Thus, the magnitude to which these existing technologies are at risk should be further examined in future studies. In addition, the survival rate of the vegetation utilized in green roofs and walls in South Korea is seen as a potential concern in terms of the extreme weather resilience of the mentioned NbS.

3.4 Adaptation strategies to extreme weather conditions for green infrastructure

Numerous studies confirm that extreme weather conditions impose detrimental effects on the components and pollutant removal performance of NbS. With these concerns at hand, it is crucial to determine adaptation strategies that could help mitigate the risks and negative impacts of climate change and extreme weather. The adaptation strategies found in the comprehensive review focus on GI restoration, biodiversity development., and the addition of components to adapt to extreme weather conditions. A study by Moore & Schindler (2022) denoted that genetic and landscape heterogeneity can be beneficial in improving the resilience of landscapes and green infrastructure. Adding specific components was also determined to be a contributing factor in improving the resilience of CWs. Adding shading and reducing wind exposure on micro-scale CWs, for instance, was identified to be beneficial to plant resilience and regeneration (Zivec et al., 2023). As most of the concerns regarding the resilience of CWs to extreme weather revolve around low temperatures, applying insulations and heating systems to maintain the pollutant removal performance of CWs during seasonal changes was also studied in previous literature. It was identified in a study by Liang & Han (2019) that adding an insulation system to a CW in China resulted in a TN removal efficiency of 61%, which is relatively high compared to other recorded TN removal efficiencies of CWs in low temperatures. Diversity in terms of plant composition in green roofs is also seen as a potential adaptation strategy for green roofs to be more resilient to extreme weather. Kiss et al. (2018) indicated that a diversity of plant taxa, composed of species that survive extremely warm or cool conditions favor changing climatic conditions over time. It was also found that utilizing various life cycles of plants can be beneficial to improving the resilience of green roofs to drier or warmer conditions (Rainer and West, 2015). Furthermore, increasing the storage of wet and dry detention ponds with regard to newer design storms was identified as an adaptation strategy in increasing the resilience of non-vegetated NbS such as dry and wet detention ponds to intensified precipitation (Barber et al., 2023). Reinforcing such infiltration systems with diversion structures to bypass intense precipitation events was also found to address potential overflowing in the mentioned NbS type (Johnson et al., 2022).

4.Conclusions

Upon analysis of the extreme weather conditions in the major cities of South Korea, it was found that NbS in the studied cities are potentially vulnerable to varying extreme weather conditions, depending on geographic location, surface imperviousness, and local weather patterns. Extremely high and low temperatures can potentially impose threats to the resilience of NbS in Seoul, as both temperature extremes obtained were observed in the mentioned city. Furthermore, extreme precipitation and maximum wind speed values were observed in cities from the southern part of the country, particularly Busan, Ulsan, and Jeju. Thus, concerns about the survival and effectiveness of the vegetation utilized on the NbS in the mentioned cities are seen.

Through a comprehensive review, it was revealed that extremely low temperatures induce the most impact on the resilience of NbS and environmental media. It was found that extremely cold conditions reduce the pollutant removal efficiency of biochar, sand, gravel, and woodchip. Consequently, CWs were found to also be vulnerable to extremely low temperatures, as several studies indicated a reduction in nutrient removal efficiency and uptake in such facilities during cold conditions. Extreme heat and drought, moreover, were identified to impose threats on the survival rate of plants used in green roofs. Precipitation extremes were also found to have negative impacts on the effectiveness of permeable pavements and bioretention systems. In response to the impacts of extreme weather on NbS, several adaptation strategies were also identified in the comprehensive review. Adding specific components, such as shading and insulation systems, was found to be a potentially effective way of maintaining the performance of NbS during severe weather conditions. Diversity in the plant species being utilized in green roofs and green walls was also determined to be an adaptation strategy for droughts and high-temperature scenarios. It is recommended, therefore, that the identified adaptation strategies be further explored, in terms of their feasibility and applicability to NbS in South Korea. At length, the results of this study are seen as potential contributors to improving the resilience of GIs in South Korea and other countries with similar climate characteristics.

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