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Degradation and biodiversity of rain gardens in the tropics

Lina Altoaimi*
Shruthakeerthi Karthikeyan**
Akshitha Vadlakunta***
Yuting Wang****
Abdul Tha'qif bin Abdul Terawis*****

Abstract

Rain gardens are commonly applied as a nature-based stormwater management method in urban areas, yet the long-term impacts, possible degradation, and effects on biodiversity as a type of green infrastructure remain underexplored. By comparing two rain gardens in Singapore– one of the earlier prototypes in a neighbourhood managed by a local town council in Central Singapore at Potong Pasir, and a more recent one managed by the National Parks in the West at Jurong Lake Gardens, the ecological and aesthetic functions are investigated. Thus, the rain gardens are explored through the lenses of both functional and aesthetic degradation. Quantitative methods, including the Shannon Biodiversity Index, Green View Index, Colourfulness Index, and surface heat mapping, are applied. Observational methods, including spatial configurations of the rain gardens, plant health, and soil conditions, were also explored to understand the extent of degradation. Common challenges encountered in rain gardens included poor or improper maintenance, poor aesthetic and visual engagement, as well as improper design. Through the findings, comprehensive design and maintenance suggestions are provided for designers and planners to improve existing rain gardens and extend the lifespan and function of future gardens. Rain garden lifespans can be lengthened to reap long-term benefits like effective stormwater management and habitat creation for local biodiversity. Maintenance suggestions build upon existing grey infrastructure and nature-based solutions routine maintenance protocols, tackling the four key functions of a rain garden: sedimentation, filtration, infiltration, and bioretention. Design suggestions are drawn from the data analysed, including potential tree planting configurations and the use of groundcover to reduce surface temperature.

Keywords: design maintenance, ecosystem services, green infrastructure, landscape degradation, rain gardens

1. Introduction

Water Sensitive Urban Design (WSUD) is a nature-based solution for combating climatic risks such as flooding, environmental pollution and high urban heat (Chen et al, 2022), whilst also creating aesthetic benefits for urban populations (Healthy Land and Water, 2020). One example of a WSUD feature often used in small-scale urban spaces is a rain garden. The Public Utilities Board (2024) defines rain gardens as "vegetated land depressions" designed to hold and filter stormwater runoff. As illustrated in Figure 1, surface runoff is first filtered through a layer of mulch and plants, then infiltrates into bioretention soil. A layer of pea stone and a layer of gravel filter out excess sediment. Usually, a perforated pipe within the gravel layer carries excess filtered water to a catchment area.

*(Corresponding author), Landscape Designer and Independent Researcher, Singapore lina74@u.nus.edu
**Architect and Independent Researcher, Singapore e1352732@u.nus.edu
***Architect and Independent Researcher, Singapore e1351837@u.nus.edu
****Landscape Designer and Independent Researcher, Singapore e0959199@u.nus.edu
*****Landscape Designer and Independent Researcher, Singapore thaqifterawis@u.nus.edu
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Rain gardens are regarded as an efficient stormwater management measure while also being low-cost and environmentally sustainable. However, inadequate maintenance can render them ineffective (Vineyard et al., 2015). This can lead to both the aesthetic and functional degradation of the rain garden. Aesthetic degradation refers to the human perception that the rain garden is no longer able to fulfil scenic, care and knowledge, and ecological value requirements. Functional degradation refers to a decline in the hydraulic and ecological performance of the rain garden. There is a general shortage of research which assesses the degradation of rain gardens, especially using aesthetic metrics such as the Green View Index, Colourfulness Index, or plant health and ground coverage assessments. This also indicates a lack of studies on the visual and aesthetic qualities of rain gardens.

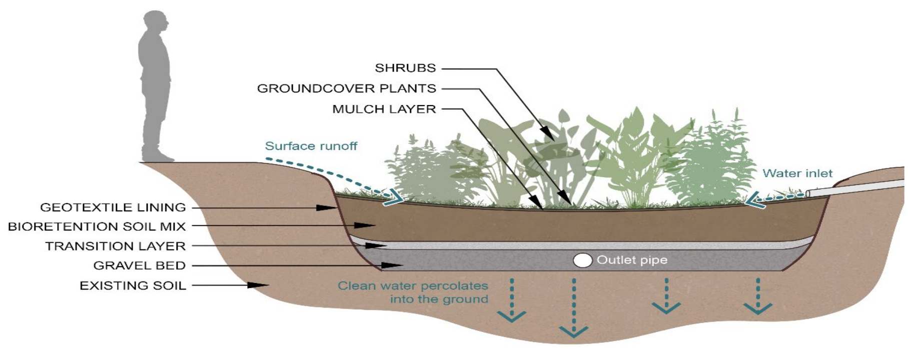

Figure 1 Layers and functions of a rain garden (Original illustration, adapted from Massachusetts Department of Environmental Protection (2006))

The objective of this study is to understand the aesthetic and functional degradation of rain gardens and its implications using both qualitative and quantitative methods, including the aesthetic metrics of Green View Index and Colourfulness Index, to then provide recommendations for extending existing and future rain garden life spans. Three main research questions are listed as follows:

1. How can rain garden degradation be measured and comparatively assessed?
2. What environmental, maintenance, and design factors affect the degradation of rain gardens?
3. How may research inform existing rain garden maintenance practices, and improve future rain garden designs for longevity of functions?

Two rain gardens in Singapore are selected for a comparative study: a rain garden at Potong Pasir and a rain garden located in Jurong Lake Gardens, due to differences in their maintenance, planting strategies, and age. In this comparative study, the Shannon Biodiversity Index of the plant species at the respective rain gardens will be measured to understand plant diversity. The Green View Index and Colourfulness Index will also be used to quantify plant growth and floral colours in the rain gardens, from a human perspective. Additionally, surface temperature will be taken within and around the rain garden to understand shading conditions. Finally, analysis focusing on observations of spatial configurations, plant health, and groundcover conditions will be conducted and compared to the quantitative data collected.

2. Literature Review

2.1. Spatial Design and Function of Rain Gardens

Rain gardens originated as an alternative for stormwater drainage in the 1990s for a development project which aimed to reduce the costs of drainage systems by mimicking natural water flows and retention (Green Building Alliance, n.d.). Rain gardens are typically advised to include a soil mix of 50%-60% sand, 30%-40% silt or loam topsoil, and 10%-20% organic matter or compost (ibid.). Multilayered planting within these gardens can lower the Urban Heat Island effect of a space (Shi et al., 2024). Furthermore, Ge et al. (2023) explain how the public may perceive the thermal comfort of a space to be more regulated if multilayered planting is implemented. Rain gardens also provide a cooling effect during the nighttime as it facilitates water transpiration (Shi et al., 2024). The pollutant-capture capacities of rain gardens depend on the plant species and soil quality within the garden; Singapore National Parks Board suggested plant palette was tested to remove up to 95% of Nitrates and 100% of Phosphates (Loh, 2012). Through a variety of plant species, rain gardens have been found to benefit ecosystem restoration projects, as they provide habitats for pollinators and other animal species (Morash et al., 2019; Dunnett & Clayden, 2007). When implemented on the larger urban scale, improved nature-space connectivity and ecosystem resilience are observed (Hanumesh et al., 2024).

From the cited literature, the studies conducted either assess rain gardens independently as a single variable or made a comparison between rain gardens on their planting palettes. These studies do not typically evaluate rain gardens in the context of WSUD. Instead, some of the sources determine the perceptive value of rain gardens in comparison to more conventional landscape features such as streetside planting and turfed areas. They recommend high maintenance requirements for the rain gardens and their surrounding spaces. Thus, one key focus of this study is to provide design guidelines for both new and existing rain garden projects to improve their effectiveness, longevity and sustainability.

2.2. Aesthetic Degradation of Rain Gardens

Dobbie and Farrelly (2023) explain the human perception of rain gardens to be dependent on four aesthetic lenses: scenic, care and knowledge (e.g. maintenance), identity of the space, and the perceived ecological value. They suggest that the aesthetics of function, i.e. the perceived function of a space, is equally as important as the four other lenses. Users of a space often perceive rain gardens to be a positive addition, in comparison to regular tree-lined streets (Dobbie, 2016). Furthermore, the educational function of a rain garden is suggested to add value to the space and increase public acceptance of rain garden installation and use (Church, 2015). Varying colours and textures of the plant palette of a rain garden is highly important to improve the scenic aesthetics and provide an identity for the space (Doğmuşöz, 2024). Overall, the sources assess the perceptive value of rain gardens as a comparison to more conventional street planting or turfed areas and suggest high maintenance requirements for the spaces.

Based on the above literature, the aesthetic degradation of rain gardens can be defined through the aesthetic lenses identified by Dobbie and Farrelly (2023), focusing specifically on the lenses of scenic, care and knowledge, and perceived ecological value. When the rain garden is perceived as no longer being able to fulfil the above functions, it is considered aesthetic degradation. Focus will be placed on analysing how biodiversity plays a role in this aesthetic degradation, specifically, plant species that are both intentionally planted as part of the rain garden function and design, as well as plants that have emerged during the rain garden's lifespan, such as weeds, which were not part of the design intent. The Shannon Biodiversity Index will be used in this paper to quantify the biodiversity at the chosen sites.

There is a lack of studies on the implications of the Green View Index (GVI) and Colourfulness Index (CI) on rain gardens, which are useful methods of quantifying visual greenery and plant diversity. Currently, studies on GVI and Colourfulness Index tend to focus on urban streetscapes rather than rain gardens specifically (Zhu et al., 2023; Ma et al., 2023). Furthermore, another metric for rain gardens that is understudied is surface temperatures. Although Chen et al. (2024) studied the effect of rain gardens on surface temperatures, they only accounted for the surface temperature of the rain garden and surrounding impermeable pavement rather than the surface temperature of different materials, shaded and unshaded conditions and the effect of plant palette on rain garden temperatures. Therefore, this study aims to tackle these gaps in knowledge through the comparison between two rain gardens of different ages and site contexts, to understand how degradation occurs over time.

2.3. Functional Degradation of Rain Gardens

The degradation of Water Sensitive Urban Design (WSUD) features often results in degraded stormwater quality, with increased pollutant loads reaching the receiving catchment (Xiao et al., 2017). When assessing the hydraulic performance and water quality impact of different WSUD features, bioretention basins, which are functionally similar to rain gardens, perform well and hence, are preferred over other filtration features when water quality is the primary concern (Liu et al., 2022). While the effectiveness and performance of rain gardens or similar features are well documented, the same is not true for their degradation. However, similar to a constructed wetland, the lifespan of a rain garden is influenced by factors such as filter media, type of runoff pollutant, inflow water quality, management level, etc. (Guo et al., 2018). A case study of a bioretention basin in Westbury Place, Brisbane, showed that the overgrowth of weeds and grass in the basin resulted in many issues, including clogged filter media, a lack of filtering plants, and no inlet scour protection (Tara & Thrupp, 2018). The outlet was also prone to blockage. As a result, the Brisbane City Council replaced all the vegetation as well as replenished the system to reinstate its functionality. Thus, based on the existing literature on the degradation of Water Sensitive Urban Design ('WSUD') landscape features similar to the rain garden, the functional degradation of rain gardens can be defined as the gradual decline in their hydraulic and ecological performance, leading to a decrease in their lifespan.

The performance of a rain garden, especially infiltration, does not decline abruptly. Research indicates that infiltration-based blue-green infrastructure can lead to a significant reduction in flooding despite low saturated hydraulic conductivity and weed growth, provided that the infiltration cells have been designed and installed effectively (William et al., 2019). However, there is still a lack of research on how this degradation can be alleviated or alternatively planned to increase the lifespan of a rain garden. Furthermore, though there is a general understanding that the efficiency of rain gardens reduces over time without appropriate maintenance and replacement of filter media (William et al., 2019), a comparison of such a feature with more recent rain gardens would offer insight into better planning and design for longevity of rain gardens and propose alternative uses for the WSUD feature over its lifetime.

2.4. Rain Garden Improvement Methods and Techniques

In general, Bąk and Barjenbruch (2022) describe maintenance methods of rain gardens to include the upkeep of the rain garden irrigation, pruning of invasive vegetation, removal of dead plant matter and rubbish, replenishing the mulch layer, preventing erosion and accumulation of sediment, and management of the surrounding landscape. Meanwhile, based on existing literature, techniques for improving rain garden effectiveness can be categorised into digital simulations, infrastructural techniques, and planting techniques. Digital techniques can be utilised through simulation modelling and computer algorithms. For example, Li et al. (2020) ran a hydrology simulation, simulating the effects of water volume and nitrogen regulation of rain gardens to improve their design parameters. Similarly, McGuire et al. (2021) conducted a simulation using green stormwater infrastructure models to understand various stormwater variables in relation to rain garden catchment.

Infrastructural techniques involve engineering solutions such as installing a cap orifice in the underdrain pipe to control water outflow and constructing a two-stage tandem rain garden that can better reduce surface runoff (Guo & Luu, 2015; Tang et al., 2024). Lastly, various studies have investigated planting techniques and their effect on rain gardens. Yuan et al. (2017) studied how vegetation types affect the hydrological performance of rain gardens, concluding that a mixed variety of forb-rich perennials were most effective in reducing surface runoff. Likewise, Johnston et al. (2020) show vegetation types can change the bioretention capabilities of rain gardens, determining that plants with higher leaf area and rooting mass such as shrubs and prairie vegetation were most effective in improving soil-water storage and soil drainage.

3. Methodology

3.1. Data Collection Methodology and Site Selection

Following site selection, both quantitative methods– Shannon Biodiversity Index, Green View and Colourfulness Indices, and surface temperature– and observational data– spatial configurations of the sites, plant health, and groundcover and soil conditions– are collected. As suggested in Figure 2, the parameters across the two categories are interdependent; for example, observed issues with plant health may affect the Shannon Biodiversity Index through observed plant death, while surface temperature may be influenced by different soil conditions, such as compacted soil versus loose soil. Similarly, the spatial configurations of the rain gardens may affect the Green View and Colourfulness Indices through visibility of different vegetation. Following the data collection a comparative analysis between the two rain gardens will be made. From the analysis, design suggestions for new rain gardens and maintenance suggestions for existing rain gardens will be discussed. The methodology of this study is represented in Figure 2.

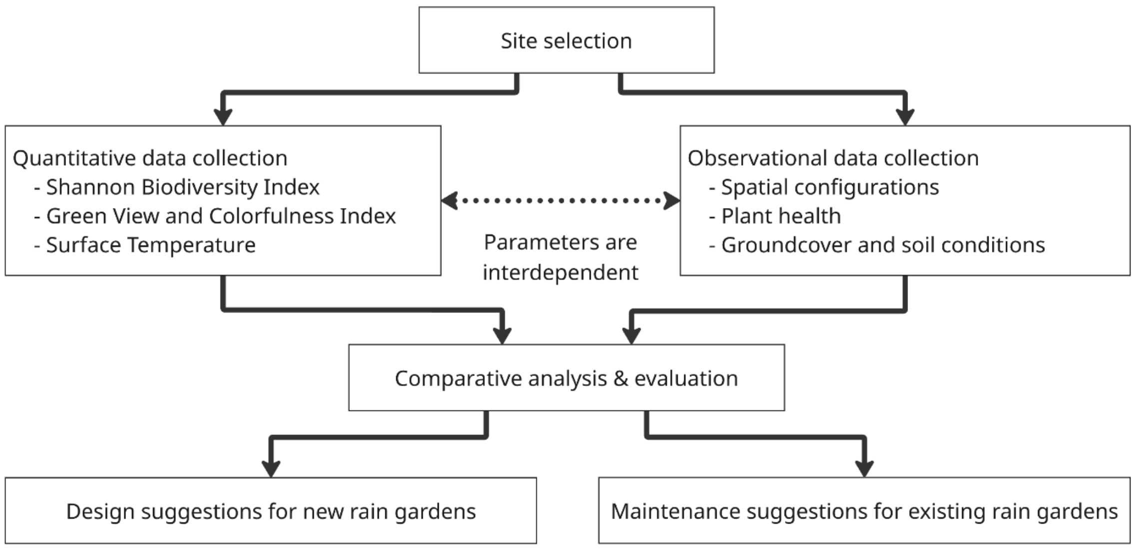

Figure 2 Methodology for data collection and analysis

Two rain gardens from different sites were chosen for this study. The first rain garden is located within Lakeside Garden at Jurong Lake Gardens, spanning approximately 478 square meters, and the second is located at Potong Pasir Avenue 3, where the rain garden and the swale together span over 700 sqm, in that particularly the rain garden spanning over 100 sqm. Both rain gardens are located in Singapore and were built as part of the Active, Beautiful, and Clean Waters programme– 'ABC Waters'– which promotes the integration of sustainable water management within urban landscapes (Public Utilities Board, 2024). The two rain gardens were chosen for several notable differences that will aid in the investigation of rain garden degradation and allow for comparative discussions between them.

First, the differing socio-economic and governing contexts of the two rain gardens suggest reason for comparative study. Because of the recent rejuvenation of the Chinese and Japanese Gardens within Jurong Lake Gardens (National Parks Board, 2024), the gardens are likely to receive more attention in terms of higher footfall and maintenance, compared to the Potong Pasir rain garden, which resides in a mature residential estate. The differing socio-economic contexts of a public park in the case of Jurong Lake and a small neighbourhood park connector in the case of Potong Pasir have implications on the use and perception of the gardens; the image of the Jurong Lake rain garden may be reflected in a national lens, while the Potong Pasir rain garden fulfils neighbourhood functions, as it is incorporated in a community learning trail (The Institution of Engineers Singapore, 2016). Additionally, another important difference to take into context is the differing governing authorities; while the rain garden in Jurong Lake Gardens is managed by the National Parks Board– 'NParks'– the rain garden at Potong Pasir is managed by the Jalan Besar Town Council. The differing management authorities have implications on funding available for the upkeep of the respective rain gardens, and it can be assumed that less funding is provided to the neighbourhood-scale Jalan Besar Town Council than the national-scale NParks.

Second, through initial observations, the differing planting strategies and age of either rain garden suggest different outcomes of aesthetic and functional roles of the gardens. The current planting palette of the Potong Pasir rain garden only consists of ground cover, while the Jurong Lake rain garden has more shrub coverage. The Potong Pasir rain garden is older than the Jurong Lake rain garden by approximately 14 to 17 years; the Potong Pasir rain garden was initiated between 2006 to 2008, at a similar time as the launch of the ABC waters programme (Public Utilities Board, 2024), while the Jurong Lake rain garden was constructed between 2022 and 2023.

Finally, design strategies implemented for the rain gardens differ in purpose and in connecting to the wider ecological and hydrological contexts, as seen in figures 3 and 4, providing basis for comparison of rain garden performance and intended function. The Potong Pasir rain garden was implemented using a 3P strategy– People, Public, and Private; it serves educational functions as well as hydrological and ecological functions to collect, filter, and convey stormwater, as well as to enhance biodiversity (The Institution of Engineers Singapore, 2016). On the wider scale in figure 3, the rain garden at Potong Pasir is connected to a series of vegetated swales and other rain gardens along Kallang River that filter stormwater before discharging into a canal (Public Utilities Board, 2024, p. 84-85). The Jurong Lake rain garden, a more recent project, intends to restore the landscape heritage of the freshwater swamp forest on site; thus, site-specific habitat zoning plans encapsulate different deconstructed freshwater swamps (Ecotones and Habitats, 2019). The specific rain garden chosen for this analysis is within the shaded woodland zone near Jurong Lake, as seen in figure 4. On the wider scale, Jurong Lake Gardens integrates a network of bioretention basins and rain gardens designed to manage approximately 20% of surface runoff, thereby alleviating pressure on conventional drainage infrastructure (AECOM, n.d.). Therefore, the differing spatial and design qualities of the two rain gardens provided reason for comparative assessment.

Figure 3 Satellite image of Potong Pasir rain garden and wider context (Google Earth, 2025a)

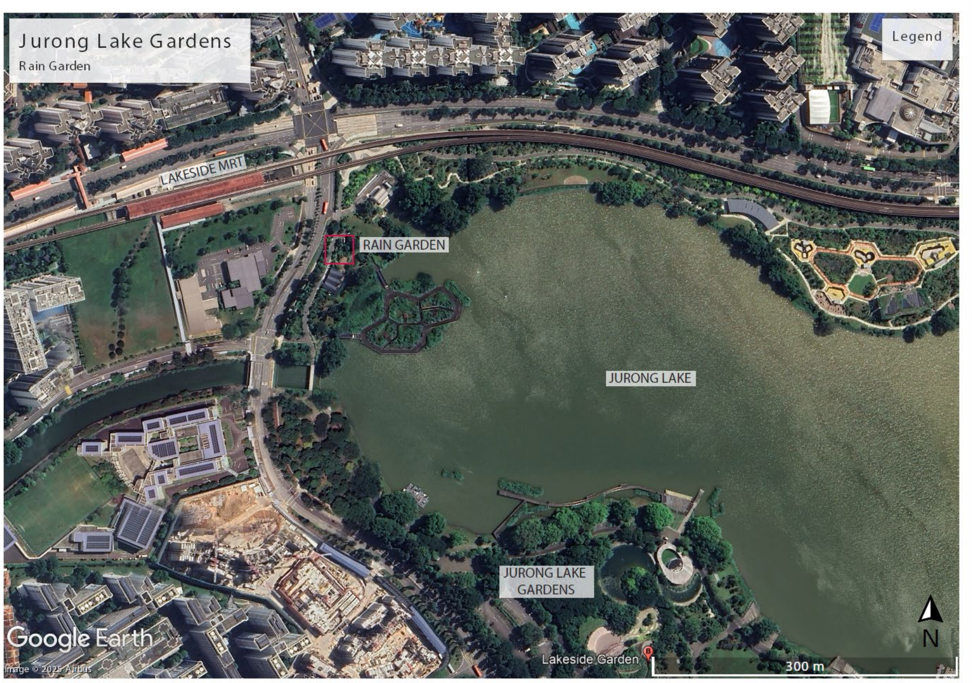

Figure 4 Satellite image of Jurong Lake rain garden and wider context (Google Earth, 2025b)

3.2. Hypotheses

Based on the literature review and site selection, the following were the hypotheses for the study:

1. The newer rain garden (Jurong Lake Garden) would be less visually degraded due to routine maintenance and early care, as opposed to the Potong Pasir rain garden. The rain garden in a larger public park, therefore, will be in better condition than the one in a residential neighbourhood. (Xiao et al., 2017)

2. The newer rain garden, due to its age and location, will have a wider variety of species suited for water filtration, whereas most of the intended plant palette would have been replaced for the Potong Pasir rain garden.
3. The newer rain garden would have higher GVI and CI due to diversity in species and more closely planted groundcover, lowering surface temperatures (Doğmuşöz, 2024).

3.3. Quantitative Data-Biodiversity, GVI & CI, and Surface Temperature

First, the Shannon Biodiversity Index was calculated to measure the diversity of plant species by sampling two quadrats on each rain garden site. At Potong Pasir, the plants generally consisted of ground cover, hence two 1x1 meter quadrats were sampled. At Jurong Lake, the plants were mostly shrubs, hence two 3x3 meter quadrats were sampled. For both sites, one quadrat in an edge or corner of the rain garden and one quadrat in the core or centre of the rain garden were sampled, such that the different conditions can be considered. The Shannon index is calculated for each quadrat using the formula below:

$$H' = - \sum_{i=1}^{S} p_i \ln(p_i)$$

Where:

S indicates the total number of species in the community, i.e. species richness.

p_i indicates the proportion of the i-th species. This is calculated as the number of individuals of species i divided by the total number of individuals in the community, pi = ni / N.

ln as the natural logarithm.

A higher value in the Shannon Biodiversity Index indicates greater diversity for both richness and evenness of the species. This metric gauges the distribution and diversity of the flora of selected rain gardens. Since plant selection plays an essential role in water filtration and quality (Chaves et al., 2025; Laukli et al., 2022), the index allows us to determine the functionality of both sites.

After calculating biodiversity metrics, the Green View Index (GVI) and Colourfulness Index (CI) of the overall spaces are quantified based on images taken from eye-level around each of the rain gardens. The GVI aims to compute the greenery along the rain gardens and is defined as the ratio of vegetation area within human view to the total human view area, given as a percentage (Zhu et al., 2023). Next, the CI aims to complement the GVI by analysing the level of ecosystem service that can provide scales with trait diversity; the more diversity of a trait is present, it results in more service provided (Behm et al., 2022). Hence, in this case, rain gardens with a diverse disposition of plant growth form and floral colours can be associated with a higher delivery of aesthetic ecosystem services as compared to gardens with single-growth forms and colours. 10 images were taken at eye-level at Potong Pasir, while 14 images were taken at Jurong Lake to account for the larger area, then, using those images, the GVI and CI were calculated by a Grasshopper code shown in appendix A. The code calculates the GVI and CI as a percentage of the images processed; the higher the value, the better the GVI or CI score. This allows us to understand and quantify the visual diversity of spaces, as a higher GVI value suggests that more vegetation is in view, and a higher CI value represents more contrasting colours in the vegetation.

Measuring the surface temperature allows the identification and understanding of the effects of UHI on the site (Lau & Lin, 2023). These measurements under different shade conditions and materials provide a distinguished identification of disparities between the two rain gardens to focus design suggestions. Additionally, it allows for further inferences about the environment for plant growth, medium compaction, which affects water filtration, and thermal comfort. The measurements of surface temperature were collected using a thermal image sensor FLIR TG165 under various conditions, including unshaded barren ground, unshaded ground cover, shaded ground cover, plant surface, paved surface and the centre of the rain garden.

3.4. Observational Data-Spatial Configurations, Plant Health, and Groundcover Conditions

The spatial configuration of each rain garden is mapped out to understand the clustering of plants, canopies, and groundcover. Overlapping canopies are noted, as unintentional shading of the rain garden may affect performance. As Puppala et al. (2022) highlighted that the GVI does not report on the health of plants; observational data is collected on site to identify issues with plant health. Potential issues of plant death, stunted growth, and pest infestations are noted and discussed in relation to the spatial clustering of plants within the rain garden. Invasive and spontaneous-growing species and their effects are explored as well. Similarly, groundcover conditions are noted, where patches of exposed soil and rocks are investigated in relation to quantitative data such as surface temperature. Soil quality and erosion are also noted and their implications on rain garden performance are discussed.

4. Results

4.1. Quantitative Data-Biodiversity, GVI & CI, and Surface Temperature

The data collection method was designed to capture representative samples of plant diversity across different spatial conditions within each rain garden. By sampling both central and peripheral zones, the method accounted for potential microhabitats and differences that could influence species distribution. The use of different quadrat sizes tailored to vegetation type (shrubs vs. ground cover) ensured scale and accuracy in capturing species composition and abundance. This analytical approach allowed a nuanced interpretation of biodiversity in relation to ecological function, thus supporting a better understanding of how plant diversity may influence hydrological performance across different rain garden designs. Sampling biodiversity responds to the hypothesis that the newer rain garden is expected to have a wider variety of species suited for water filtration.

While initial results suggest higher species evenness and diversity at Potong Pasir, with a Shannon Index of 1.62, compared to Jurong Lake Gardens of 1.2, this changes significantly when weeds and unintended species are excluded, as seen in table 1. Potong Pasir's index drops to 0, leaving only one species, whereas Jurong Lake Gardens rises to 1.66, indicating a more purposeful planting palette due to its increased diversity. Figure 5 illustrates the plant configurations at Potong Pasir, and figure 6 illustrates that of Jurong Lake, based on species listed in tables 1 and 2.

Table 1 Species Identified at Jurong Lake Gardens Rain Garden and Potong Pasir Rain Garden-Species Considered as Weeds are Highlighted in Red

Jurong Lake Gardens Rain Garden		
Species	**Quadrat 1 (Corner)**	**Quadrat 2 (Center)**
Cheilocostus speciosus (J. Koenig) C. Specht	-	5
Pandanus amaryllifolius Roxb.	-	9
Calathea lutea	21	2
Rhapis multifida	3	12
Osmoxylon lineare	-	14
Thalia geniculata (red-stemmed)	-	12
Arostichum speciosum	9	-
Axonopus compressus	1320	-
Phyllanthus debilis	-	338
Spermacoce latifolia	-	1125
Cyperus mindorensis	-	450
Hydrocotyle sibthorpioides	-	56
Phyllanthus urinaria	240	-

Cyanthillium cinereum	120	-
Overall Shannon Index	**0.76**	**1.20**
Shannon Index without weeds	**0.136**	**1.66**
Potong Pasir Rain Garden		
Species	**Quadrat 1 (Corner)**	**Quadrat 2 (Center)**
Commelina diffusa	93	-
Cyperus mindorensis	105	294
Axonopus compressus	50	56
Nelsonia sp	20	130
Solanum sp	35	-
Phyllanthus urinaria	2	37
Medicago lupulina	5	2
Spermacoce ocymoides	97	162
Eragrostis tenella	145	185
Overall Shannon Index	**1.40**	**1.62**
Shannon Index without weeds	**0**	**0**

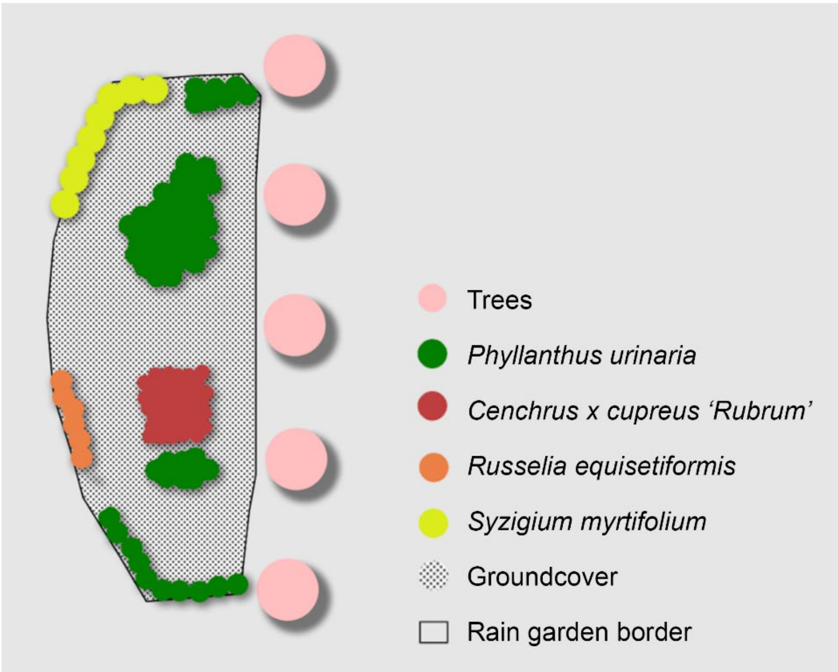

Figure 5 Potong Pasir rain garden plant configuration

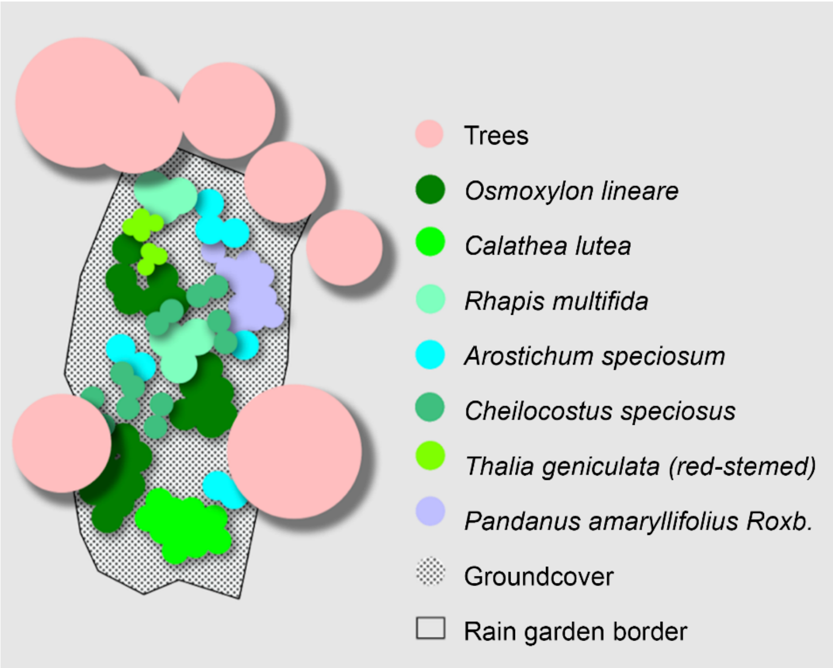

Figure 6 Jurong Lake rain garden plant configuration

For the Green View Index (GVI) and Colourfulness Index (CI), data collection relied on capturing multiple eye-level images that reflect the everyday human experience of the rain garden (appendix B and C), ensuring consistency in perspective across both sites. These images served as the visual dataset for further analysis, and to respond to the third hypothesis that the newer rain garden is expected to have higher GVI and CI values. The computational approach by processing the images through a Grasshopper script (appendix A) minimised human bias and allowed for objective comparison of GVI and CI. The GVI and CI percentages for each of the images and the averages are represented in table 2.

Table 2 Green View Index (GVI) and Colourfulness Index of Jurong Lake Gardens and Potong Pasir Rain Gardens

Image No.	GVI (%)		Colourfulness (%)	
	Jurong Lake Gardens	Potong Pasir	Jurong Lake Gardens	Potong Pasir
1	26.86	73.15	35.65	48.44
2	29.39	45.49	33.16	44.12
3	30.26	33.01	32.41	46.40
4	34.61	16.48	33.82	40.26
5	49.82	30.59	40.30	55.86
6	34.18	29.77	37.42	61.03
7	30.36	40.38	35.48	50.69
8	40.04	40.09	38.71	45.63
9	45.83	26.22	37.30	37.08
10	35.07	24.95	38.30	39.15
11	40.67	-	43.41	-
12	38.04	-	41.92	-
13	42.62	-	35.32	-
14	35.29	-	39.81	-
Average:	**36.64**	**36.02**	**37.36**	**46.89**
Std Deviation, σ:	**6.36**	**14.77**	**3.16**	**7.12**

While both the GVI and the CI are on average higher for Potong Pasir as compared to Jurong Lake Gardens, there is a higher variance in the values as seen in figure 7, compared to those at Jurong Lake in figure 8. This indicates that GVI and CI are unevenly distributed across the rain garden at Potong Pasir, while the distributions and variation are more even at Jurong Lake.

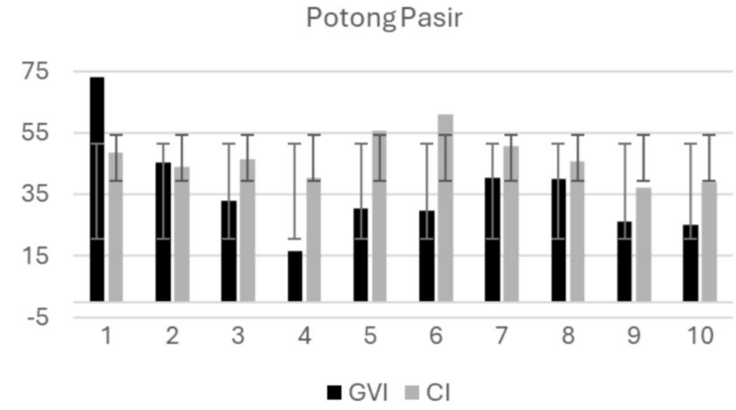

Figure 7 Graph showing GVI and CI of the Potong Pasir rain garden with standard deviation

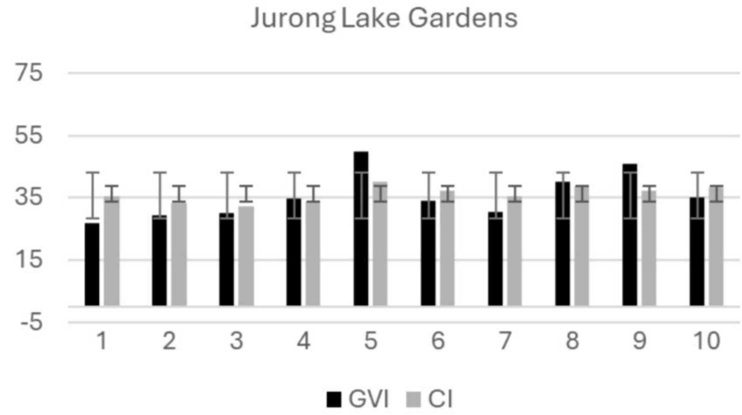

Figure 8 Graph showing GVI and CI of the Jurong Lake rain garden with standard deviation

Surface temperature data was collected systematically across different material and shade conditions to capture a comprehensive thermal profile of each rain garden. Both rain gardens were visited in mid-March 2025, with surface temperatures measured between 12-2 pm during the peak heat period. Although mild rain occurred prior to data collection at both sites, the similar weather conditions ensure a valid comparative analysis. By targeting consistent surface types under comparable conditions, the method minimised external variability and ensured reliability. The analysis approach involved comparing temperature ranges across both sites to identify microclimatic differences and infer their implications on thermal comfort and hydrological performance. This comparative approach underscores how planting design and material choices influence heat retention, which may help inform better landscape strategies.

The Jurong Lake rain garden recorded a higher average surface temperature of 51.36°C, compared to 41.14°C at Potong Pasir. Despite having more shade, the newer Jurong site showed higher temperatures, likely due to sparse ground cover at its core, as shown in figure 10 (iii). In contrast, Potong Pasir's established ground cover appears to lower surface temperatures by around 20°C on average, as shown in figure 9 (iii).

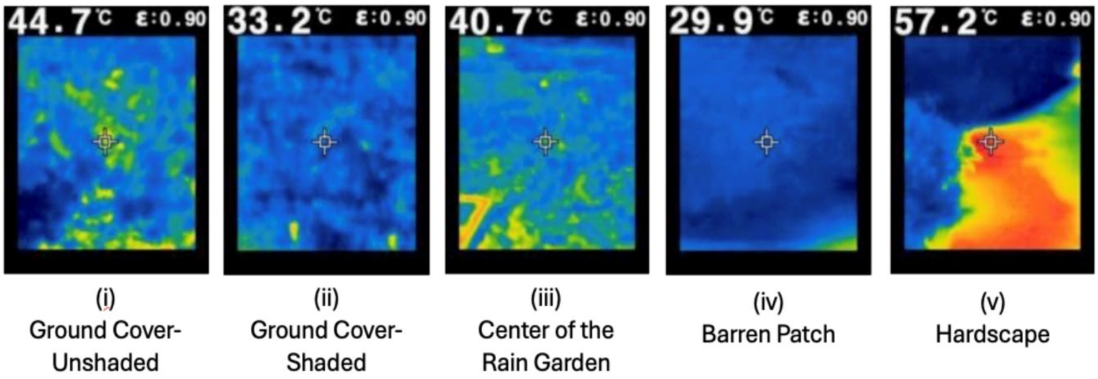

Figure 9 Surface temperature images of Potong Pasir rain garden

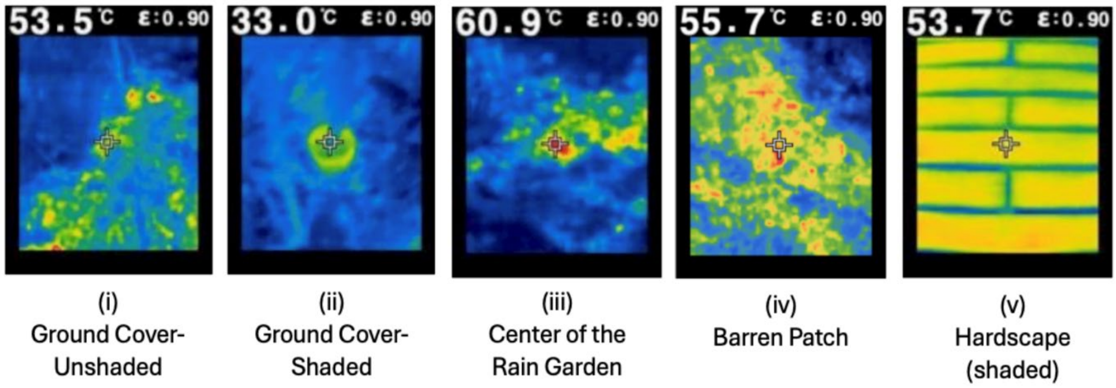

Figure 10 Surface temperature images of Jurong Lake Gardens rain garden

4.2. Observational Data-Spatial Configurations, Plant Health, and Groundcover Conditions

Spatial observations were gathered through on-site walkthroughs, focusing on visual assessment of planting structure, soil conditions, and infrastructure performance, such as inlet function. Selected patches were examined to represent broader patterns across the rain gardens. The analysis approach involved linking these qualitative observations, such as overgrowth, soil patchiness, and clogged inlets, to broader maintenance and design outcomes. By correlating spatial layout and vegetation health with signs of neglect or poor establishment, the analysis provides insights into how site conditions impact long-term performance of rain gardens. This aims to respond to the first hypothesis statement that the newer rain garden is expected to be more visually diverse and less degraded due to routine maintenance and early care.

Both rain gardens showed signs of poor maintenance, including overgrown plants, dried patches, and clogged inlets. As seen in figure 11, Potong Pasir mostly has even ground cover, while patchy ground coverage was observed at Jurong Lake, shown in figure 12, indicating inadequate early-stage care, which is critical for healthy vegetation establishment. This has likely contributed to weed growth in parts of the rain garden. There is also an overall lack of visual harmony within either garden; without seasonal bloomers or focal plants, rain gardens fail to serve their educational or recreational role. The general observations also reflect an overarching theme of disconnect from the communities using the rain garden. Without interpretive signage, benches, or pathways, rain gardens feel like passive infrastructure rather than public green assets.

Figure 11 Site images of Potong Pasir rain garden

Figure 12 Site images of Jurong Lake Garden rain garden, showing patchy ground cover

Infections like leaf blotching and stem browning, shown in figure 13, indicate inadequate pest control and mulch renewal, contributing to habitat degradation and visual neglect. This weakens ecosystem resilience and may even reduce community engagement. Despite Potong Pasir's higher GVI at (73%), uneven plant coverage results in visual imbalance, which users often perceive as neglect or poor design (Church, 2015).

(a) (b)

Figure 13 Poor plant conditions at **(a)** Jurong Lake Gardens, and **(b)** Potong Pasir

Poor soil quality and unsuitable plant selection were observed to compromise key rain garden functions. Sediment buildup and root blockages hinder infiltration, leading to surface pooling and increased mosquito breeding risk. The absence of proper elevation zoning (inflow-mid-outflow) disrupts water movement and filtration. This, along with compacted soil, limits percolation and thus reduces microbial activity and weakens plant anchorage.

5. Discussion

The following discussion aims to evaluate the conditions of the two rain gardens through comparison across the various parameters. Existing routine maintenance and design guidelines will be explored alongside possible inadequacies in current practices. By deducting and analysing likely reasons for different aspects of degradation at both rain gardens, detailed design and maintenance suggestions are provided.

5.1. Comparative Discussion

A summarised comparison between the Jurong Lake rain garden and the Potong Pasir rain garden is shown in Table 3 below, addressing the first research question on how rain garden degradation may be measured and comparatively assessed.

Table 3 Summarised Comparison Between Jurong Lake Gardens and Potong Pasir Rain Gardens

Parameter	Jurong Lake Gardens rain garden	Potong Pasir rain garden
Shannon Biodiversity Index	***1.66*** The diversity and evenness of species are high. As a newer rain garden, the shrubs and plants for filtration are maintained. However, there is a notable lack of ground cover.	***0*** The original plant palette of the rain garden has been replaced with weeds; as a result, the distribution of rain garden-specific plant species is missing.
Avg. Green View Index (GVI)	***36.64%, with a σ: 6.36*** The GVI is similar for both rain gardens. However, the standard deviation indicates evenness in the different views of the garden.	***36.02%, with a σ: 14.77*** The GVI is similar for both rain gardens. However, the higher standard deviation shows more variation in the level of greenness in various views.
Avg. Colourfulness Index (CI)	***37.36%, with a σ: 3.26*** Despite the higher species diversity, JLG has comparatively lower CI due to the lack of flowers in flowering species and surrounding objects.	***46.89%, with a σ: 7.12*** Potong Pasir rain garden has a higher CI with a greater standard deviation. The presence of buildings and other elements gives it an edge despite the lack of a diverse planting palette.
Avg. Surface Temperature	***51.36 °C*** The lack of ground cover contributes greatly to its increased average surface temperature. Thus, the JLG rain garden is less effective in mitigating UHI.	***41.14 °C*** Weed growth in the old garden has contributed to a dense ground cover that helps lower the overall surface temperature of the garden and its surrounding surfaces, contributing to reducing the area's UHI.
Spatial Configuration	Lacks visual harmony Over-shading by large tree canopies	Lacks visual harmony Lacks water-filtering shrubs and plants Connected to bioswales and series of other rain gardens
Plant Health	Leaf blotching Stem browning	Leaf blotching Leaf defoliation
Ground Cover Conditions	Low Ground Cover Compacted soil High sediment content	High Ground Cover Loose soil Low sediment content

To address the second research question– what environmental, maintenance, and design factors affect the degradation of rain gardens– a comparative discussion of the two rain gardens' conditions is explored. Although the rain garden at Jurong Lake Gardens was constructed at least 14 years after the rain garden at Potong Pasir, it appears to have degraded faster, as highlighted in the results discussion parts 5.1 – 5.3. This may be attributed to a few challenges that were identified based on the results of the study, which include low diversity in species selection, overshading of trees in the surrounding landscape, and heat retention due to soil compaction. In addition to these challenges that could have increased the rain garden deterioration rate, another challenge rain gardens may face is the lack of visual identity, resulting from its degradation.

The quicker degradation of the rain garden at Jurong Lake Gardens may be attributed to poor plant selection. According to the results of the Shannon Biodiversity Index, the Jurong Lake rain garden scored lower when weeds are included in the count. While the Jurong Lake rain garden scores higher than the Potong Pasir rain garden when weeds are removed from the count, the plant diversity in the Jurong Lake rain garden is extremely concentrated in one location, causing the score in one quadrat to not be significantly higher than the score of 0 in the Potong Pasir rain garden. These results demonstrate that, regardless of the presence of weeds, rain gardens appear to perform better with higher plant species diversity that is more evenly dispersed throughout the rain garden. This is supported by Yuan et al. (2017), who suggest that planting more diverse species rather than monocultures or restricting plant mixtures can improve the hydrological performance of rain gardens in terms of stormwater detention and retention capabilities. Furthermore, it appears that forb-rich perennials are effective in slowing surface runoff and increasing stormwater detention time due to their higher leaf area and deeper rooting mass (Ibid.), such as weeds like Commelina diffusa, Cyperus mindorensis and Eragrostis tenella in the Potong Pasir rain garden. Another benefit of the deeper rooting systems of such plant species is improved biofiltration and nutrient removal of nitrates and phosphates (Loh, 2012). Additionally, a diverse planting palette also strengthens the plants' resistance to disease and insect infestations (Ibid.). Apart from forb-rich perennials, prairie vegetation is also similarly effective in providing these benefits, a category that the weed species fall into as well (Yuan et al., 2017). Hence, it appears that the lack of diversity in plant species selection may have reduced the hydrological performance of the Jurong Lake Gardens rain garden over time, as there are lesser forb-rich perennials or prairie vegetation planted, thus contributing to its degradation.

As part of the biodiversity evaluation conducted during the assessment of the Shannon Biodiversity Index, the current plant configuration of both rain gardens is evaluated in figures 5 and 6. In figure 6, the growth of the tree canopies have likely shaded the vegetation within the rain garden at Jurong Lake, in comparison to figure 5 where the trees have been planted further away. Thus, the spatial layout and design of not just the rain garden but also its surroundings play a crucial role in its performance and degradation. This highlights a potential challenge in which trees planted too close to the edges of a rain garden may cause overshadowing, preventing sunlight from reaching the plants within the rain garden and affecting their growth. Furthermore, this is supported by observations of plants such as the Rhapis multifida in the Jurong Lake rain garden, which may have deteriorated due to the lack of sunlight. Therefore, improper tree planting near a rain garden may cause the issue of overshading from trees as the canopies expand, affecting plant growth in the rain garden and affecting its performance over time.

The higher surface temperatures observed within the rain garden at Jurong Lake Gardens, especially in areas without ground cover, could result in soil compaction, which in turn can appear higher in temperature. This is observed in figure 9(iii), where compacted soil and larger rocks were found at the core of the Jurong Lake rain garden, measuring upwards of 60ºC surface temperature when under direct sunlight. Soil compaction may significantly impact the performance of rain gardens as it can reduce the level of moisture in the soil, affecting plant health, and affect the soil's ability to retain water (Kelishadi et al., 2018). Without ground cover covering the soil in the rain garden this increases exposure to sunlight, thus resulting in soil compaction. As Attah and Etim (2020) show, high temperatures can influence soil compaction, which also decreases its moisture level. With less access to water in the soil, this may negatively impact the health of plants in the rain garden and exacerbate the decline of the rain garden. Moreover, heat also reduces the water retaining capacity of soil, thus less water is saturated within it (Kelishadi et al., 2018), which may impact the rain garden's bioretention functionality.

Lastly, both rain gardens scored approximately 36 GVI, while Jurong Lake scored 37 CI and Potong Pasir scored 46 CI (where 100 indicates the highest value). As Jurong Lake scored lower on CI, it may represent a lack of a clear visual identity. This may affect a rain garden's ability to provide cultural ecosystem services, such as aesthetic and educational services, while also decreasing spatial identity. According to Doğmuşöz (2024), varied textures and colours of the plants in a rain garden help to increase aesthetics and form a spatial identity. Thus, this absence may cause monotony and decrease the strength of the rain garden and its surrounding area's identity. The higher standard deviation in the GVI results of the Potong Pasir rain garden also suggests a visual imbalance in the greenery, which may further impede its aesthetic values. Additionally, without seasonal bloomers or focal plants, the rain garden at Potong Pasir also fails to serve enhanced educational and recreational purposes, especially since it is used in educating students from nearby schools. This lack of visual identity and reduced educational value may also reduce the impact of rain gardens as sites for engaging with communities on biodiversity and water management.

5.2. Suggestions for Planners and Designers

This section explores the third research question of how research may inform existing maintenance practices and future designs of rain gardens. Based on the data collection and analysis of the two rain gardens, the following are suggested maintenance and design guidelines to increase the lifespan of rain gardens and to design for longevity.

Table 4 suggests the basic routine maintenance in ensuring that conventional system components in grey infrastructure remain highly functional. The above maintenance for grey infrastructure is largely done by Town Councils for areas within Housing & Development Boards (HDB) estates (Housing & Development Board, 2024) and by contractors employed by developers or property owners of private developments (Public Utilities Board, 2018).

Table 4 Routine and Remedial Maintenance on Infrastructures to Manage Stormwater-Text Marked with an Asterisk Indicates Practices Observed to be Inadequate on Site

Conventional system component	**Routine maintenance**
Pipelines and storage basins	Inspecting surface above pipelines for sinkholes, wet spots and tree growth
Inlets / outlets / manholes	Removal of litter and debris Cleaning of screens to remove moss Cutting grass, removing weeds
Nature-based solutions practice	**Routine maintenance**
Sedimentation	Cutting grass, removing weeds Removal of litter and debris Pruning trees, maintaining vegetation
Filtration	*Cleaning and removing build-up of geotextile or filter
Infiltration	Cleaning gutters Cleaning and removing build-up of geotextile or filter
Bioretention	*Assessing vegetation for disease, infection or poor growth *Maintaining plant density *Mulching and replacing top layer of soil
Nature-based solutions practice	**Remedial / Occasional Maintenance**
Sedimentation	Reseeding areas Repairing erosion damage Realigning riprap Re-levelling uneven surfaces
Filtration	Removal or control of tree roots Replacing geotextile or filter
Infiltration	Clearing sediment deposits Replacing geotextile or filter Repairing cracks, depressions
Bioretention	Fixing holes in filter media Maintaining erosion protection *Removal of invasive species Repairing cracked or disturbed inlets

However, Rain Gardens – a Nature Based Solution (NBS) make the focus of this study. The maintenance of rain gardens depends on their location and ownership. The Potong Pasir rain garden is located within HDB estates. It is maintained by the respective Town Council – Jalan Besar

Town Council – which manages the common property in public housing areas (Housing and Development Board, 2024). The JLG rain garden falls under the care of the National Parks Board (NParks), which is responsible for the upkeep of ecological features that promote stormwater management and enhance biodiversity (National Parks Board, 2024).

In table 4, the entries marked with an asterisk indicate maintenance practices that were observed to be either inadequate or entirely absent during field observations. As a result, the following design recommendations have been proposed to address these maintenance gaps and to inform future iterations of rain garden implementation in the tropics. These suggestions are grounded in field observations and aim to enhance the long-term functionality and resilience of rain gardens, contributing to the objectives of the study on the degradation and performance decline of such systems across the nation.

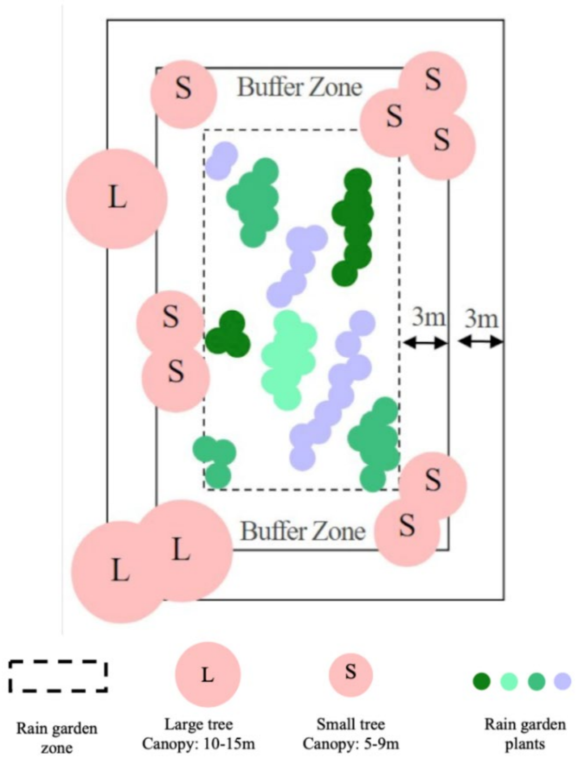

Figure 14 Design suggestions to prevent over-shading by trees

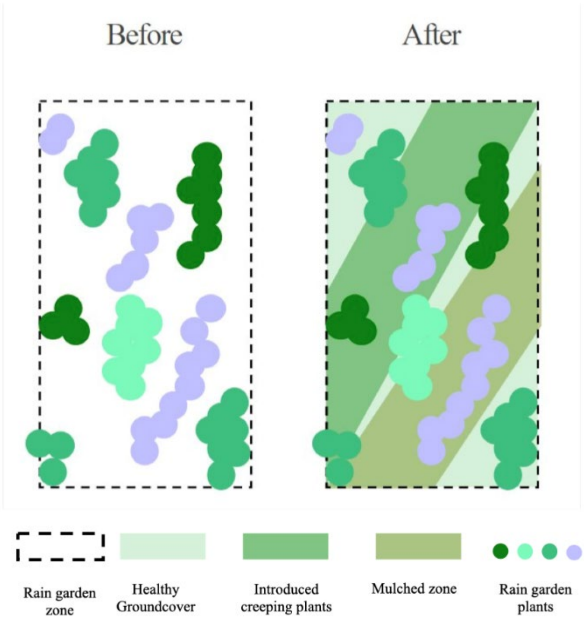

Figure 15 Design suggestions to improve temperature regulation

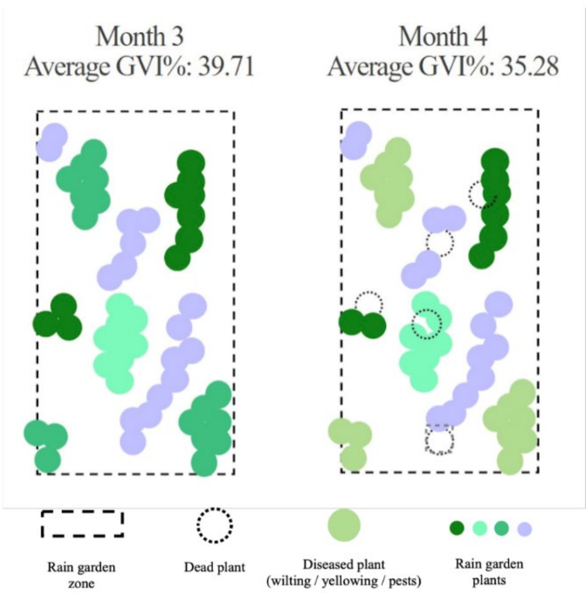

Figure 16 Design suggestions for weed and pest control, and for easier regular visual assessment

Table 5 Design Suggestions Based on Field Observations, Correlating with Figures 14, 15, and 16 Above

Fig. No	Reason	Recommendations / suggestions
14	**Preventing over-shading by trees.**	
	Rhapis multifida in JLG rain gardens were suspected to die over time due to the over-shading of trees that grew larger over time (refer to fig. 6).	Planting large trees at a minimum of 3 meters away from rain garden zones. Smaller trees can be planted just within the buffer zone. No trees should be planted within rain garden zones.
15	**Improving surface temperature regulation**	
	JLG rain garden was observed to have higher surface temperature on bare grounds and areas with a lack of ground cover (refer to fig. 7 and 8).	Applying mulch – of 50% sand, 30% loam and 20% compost (Green Building Alliance, n.d.)– and planting creeping groundcovers to reduce surface temperature. Introduce phase-based maintenance (see table 4).

	The quick degradation of this rain garden could indicate a lack of initial maintenance.	Year 1 to year 2: Routine health screening of plants Year 3 onwards: Increased remedial maintenance
16	**Improving surface temperature regulation**	
	Potong Pasir rain garden is a place of learning for students (Ying, 2019). Overgrowth and infestation were observed on some plants (refer to fig. 13).	Introduce community weeding activities – spearheaded by Jalan Besar Town Council – to remove invasive species Monthly image inspection through the measurement of GVI for early identification of plant issues and preparation of plant disease mitigation methods.

Thus, to enhance the longevity and functionality of rain gardens in the tropics, it is quintessential to address key design and maintenance challenges identified during field observations of this study. These strategies aim to mitigate degradation over time and contribute to more resilient, low-maintenance rain gardens in urban environments.

5.3. Limitations

Various methodological and interpretive constraints limited the study. Methodological constraints include the small sample size in which only two rain gardens were compared, and the data collected was limited to the rain gardens themselves, not incorporating the surroundings and conditions of the wider context (e.g. swales and catchment linked to the rain garden). The study was also limited by time-based and seasonal variables; there was limited time to assess rain garden performance, hence the majority of the data collected was static. Similarly, there was a lack of control over environmental variables, such as seasonal changes which affected the spontaneous vegetation growing during the monsoon season. In the results for the surface temperature on hardscape material at Jurong Lake Gardens, there may be some inconsistencies due to significant shade cast on the hardscape and edges of the rain garden.

Both rain gardens are situated in public spaces, making it accessible for the visual analysis methods employed in this paper. However, the study was limited from exploring various sub-soil parameters, such as monitoring filtration and infiltration of water, measuring extents of water purification, and inspecting sub-soil qualities, due to the limited access to the rain garden ground. Interpretive constraints of this study included potential observer bias in qualitative observations, such as when noting plant health and ground coverage. Potential bias may have also been translated into the images captured for GVI and CI calculations.

6. Conclusion

Rain garden degradation was measured through both quantitative measurements of biodiversity, Green View Index, Colourfulness Index, and surface temperature, as well as qualitative assessments of the spatial configurations, plant health, and groundcover conditions. The various measurements allowed for a rich comparative assessment. The study thus concludes that tackling key issues that accelerate rain garden degradation through maintenance and design suggestions allows rain garden lifespans to be lengthened and reap long-term benefits like effective stormwater management and habitat creation for local biodiversity. Common challenges encountered in rain gardens included maintenance issues, poor aesthetic and community engagement, as well as improper design. Maintenance suggestions tackled four key functions of a rain garden: sedimentation, filtration, infiltration, bioretention. Design suggestions included tree planting configurations and using ground cover to reduce surface temperature and visual inspections. This, in turn, allows for improved visual quality and a higher greenery in view.

Further studies are suggested to account for more diverse rain garden planting palettes in the tropics, and a longer time frame to monitor rain gardens and their degradation from their installation date, while also factoring in more data regarding the user experience of the rain garden. User experiences can link back to the assessment of GVI and CI to understand the visual perception of rain gardens and may be incorporated through usage data of rain gardens, community engagement analyses, and user perception surveys. This is encouraged to be carried out as a longitudinal study with standardised data collection methods, including regular biodiversity surveys as well as plant and soil quality monitoring, and statistical testing for comparison between rain garden conditions. Future studies should continue to employ mixed-method approaches to capture the relationship between ecological and socio-economic dimensions of rain gardens, especially as the governmental and managerial contexts of rain gardens heavily affect the conditions, as shown in this paper.

References

AECOM. (n.d.). *Jurong lake garden phase 2 development*. https://aecom.com/projects/jurong-lake-garden-phase-2-development/

Attah, I. C., & Etim, R. K. (2020). Experimental investigation on the effects of elevated temperature on geotechnical behaviour of tropical residual soils. *SN Applied Sciences*, *2*(3). https://doi.org/10.1007/s42452-020-2149-x

Bąk, J., & Barjenbruch, M. (2022). Benefits, inconveniences, and facilities of the application of rain gardens in urban spaces from the perspective of climate change–A review. *Water*, *14*(7), 1153. https://doi.org/10.3390/w14071153

Behm, J. E., Bélouard, N., Gleditsch, J. M., Phillips, P. M., & Swartz, T. M. (2022). Trait-based approaches for understanding how biodiversity generates sustainable benefits in urban vegetated green infrastructure. *Current Opinion in Environmental Sustainability*, *57*, 101204. https://doi.org/10.1016/j.cosust.2022.101204

Chaves, M. T. R., Moreira, J. G. R., Correia, K. P., Eloi, W. M., & Farias, T. R. L. (2025). Vegetation adaptability in a tropical urban rain garden: A study in northeast Brazil. *Urban Forestry and Urban Greening*, *107*, p.128810. https://doi.org/10.1016/j.ufug.2025.128810

Chen, C.-F., Chen, Y.-W., Lin, C.-H., & Lin, J.-Y. (2024). Field performance of 15 rain gardens in different cities in Taiwan. *The Science of the Total Environment*, *947*, 174545-174545. https://doi.org/10.1016/j.scitotenv.2024.17454

Chen, N., Tang, X., & Liu, W. (2022). Urban disaster risk prevention and mitigation strategies from the perspective of climate resilience. *Wireless Communications and Mobile Computing*. https://doi.org/10.1155/2022/4907084

Church, S. P. (2015). Exploring green streets and rain gardens as instances of small scale nature and environmental learning tools. *Landscape and Urban Planning*, *134*, 229-240. https://doi.org/10.1016/j.landurbplan.2014.10.021

Dobbie, M. F. (2016). Designing raingardens for community acceptance. *Cooperative Research Centre for Water Sensitive Cities*. Melbourne, Australia.

Dobbie, M. F., & Farrelly, M. A. (2023). Affordance and the aesthetic experience of raingardens. *Research Square*. https://doi.org/10.21203/rs.3.rs-2903208/v1

Doğmuşöz, B. B. (2024). Plant selection for rain gardens in temperate climates: The case of Izmir, Turkey. *Journal of Design for Resilience in Architecture and Planning*, *5*(1), 18-34. https://doi.org/10.47818/DRArch.2024.v5i1117

Dunnett, N., & Clayden, A. (2007). *Rain gardens, managing water sustainability in the garden and designed landscape.* Timber Press.

Ecotones and Habitats. (2019). Landzine international landscape award. https://landezine-award.com/jurong-lakeside-garden/

Ge, M., Huang, Y., Zhu, Y., Kim, M., & Cui, X. (2023). Examining the microclimate pattern and related spatial perception of the urban stormwater management landscape: The case of rain gardens. *Atmosphere*, *14*(7), 1138. https://doi.org/10.3390/atmos14071138

Google Earth. (2025a). Potong Pasir Neighborhood. 1°20'01"N 103°51'54"E. 1,300m.

Google Earth. (2025b). Jurong Lake Gardens. 1°20'38"N 103°43'19"E. 1,100m.

Green Building Alliance. (n.d.). Rain gardens. https://gba.org/resources/green-building-methods/site-solutions/rain-gardens/

Guo, C., Li, J., Li, H., Zhang, B., Ma, M., & Li, F. (2018). Seven-year running effect evaluation and fate analysis of rain gardens in Xi'an, Northwest China. *Water*, *10*(7), 944. https://doi.org/10.3390/w10070944

Guo, J. C. Y., & Luu, T. M. (2015). Operation of cap orifice in a rain garden. *Journal of Hydrologic Engineering*, *20*(10). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001184

Hanumesh, M., Mohan, M., & Anand, P. (2024). Enhancing urban resilience and biodiversity: Integrating rain gardens and green corridors. In *Innovations in the Development of Sustainable Infrastructure:*

Proceedings of the International Conference on Technological Innovations in Multidisciplinary Engineering and Sciences. (pp. 52-65). Springer Nature.

Healthy Land and Water. (2020). *Water sensitive urban design*. Water by Design. https://waterbydesign.com.au/wsud#:~:text=Urban%20development%20using%20conventional%20approaches,water%20supply%20and%20sewage%20management

Housing and Development Board. (2024, June 21). *Four Tengah BTO projects awarded top-tier Active, Beautiful, Clean Waters certification*. https://www.hdb.gov.sg/about-us/news-and-publications/press-releases/21062024-Four-Tengah-BTO-Projects-Awarded-Top-tier-Active-Beautiful-Clean-Waters-Certification

Johnston, M. R., Balster, N. J., & Thompson, A. M. (2020). Vegetation alters soil water drainage and retention of replicate rain gardens. *Water*, *12*(11), 3151. https://doi.org/10.3390/w12113151

Kelishadi, H., Mosaddeghi, M. R., Ayoubi, S., & Mamedov, A. I. (2018). Effect of temperature on soil structural stability as characterized by high energy moisture characteristic method. *Catena*, *170*, 290-304. https://doi.org/10.1016/j.catena.2018.06.015

Lau, T.-K., & Lin, T.-P. (2023). Investigating the relationship between air temperature and the intensity of urban development using on-site measurement, satellite imagery and machine learning. *Sustainable Cities and Society*, *100*, pp.104982–104982. https://doi.org/10.1016/j.scs.2023.104982

Laukli, K., Gamborg, M., Haraldsen, T. K., & Vike, E. (2022). Soil and plant selection for rain gardens along streets and roads in cold climates: Simulated cyclic flooding and real-scale studies of five herbaceous perennial species. *Urban Forestry and Urban Greening*, *68*, p.127477. https://doi.org/10.1016/j.ufug.2022.127477

Li, J., Liu, F., & Li, Y. (2020). Simulation and design optimization of rain gardens via DRAINMOD and response surface methodology. *Journal of Hydrology*, *585*. https://doi.org/10.1016/j.jhydrol.2020.124788

Liu, A., Egodawatta, P., & Goonetilleke, A. (2022). Ranking three water sensitive urban design (WSUD) practices based on hydraulic and water quality treatment performance: Implications for effective stormwater treatment design. *Water*, *14*(8), 1296. https://doi.org/10.3390/w14081296

Loh, B. (2012). A selection of plants for bioretention system in the tropics. *Centre for Urban Greenery and Ecology*. https://www.nparks.gov.sg/-/media/cuge/pdf/rtn-04-2012---a-selection-of-plants-for-in-the-tropics.pdf

Ma, L., Guo, Z., Lu, M., He, S., & Wang, M. (2023). Developing an urban streetscape indexing based on visual complexity and self-organizing map. *Building and Environment*, *242*, 110549. https://doi.org/10.1016/j.buildenv.2023.110549

Massachusetts Department of Environmental Protection. (2006). Bioretention areas & rain gardens. *Massachusetts Clean Water Toolkit*. https://megamanual.geosyntec.com/npsmanual/bioretentionareasandraingardens.aspx

McGuire, M. P., Grimley, D. A., Phillips, A. C., Stillwell, A. S., William, R., Shen, J., & Schneemann, M. (2021). Retrofitting urban land through integrative, subsoils-based planning of green stormwater infrastructure: a research framework. *Environmental Research: Infrastructure and Sustainability*, *1*(3). https://doi.org/10.1088/2634-4505/ac27bd

Morash, J., Wright, A., LeBleu, C., Meder, A., Kessler, R., Brantley, E., & Howe, J. (2019). Increasing sustainability of residential areas using rain gardens to improve pollutant capture, biodiversity and ecosystem resilience. *Sustainability*, *11*(12), 3269. https://doi.org/10.3390/su11123269

National Parks Board. (2024). NParks completes Jurong Lake Gardens with opening of rejuvenated Chinese and Japanese Gardens. https://www.nparks.gov.sg/news/news-detail/nparks-completes-jurong-lake-gardens-with-opening-of-rejuvenated-chinese-and-japanese-gardens

Public Utilities Board. (2018). *Code of practice on surface water drainage* (6th ed.). https://www.pub.gov.sg/Documents/CoP_On_Surface_Water_Drainage.pdf

Public Utilities Board. (2024). Active, beautiful, clean waters design guidelines (5th ed.). https://www.pub.gov.sg/-/media/Images/Feature/Content-Pages/Resources/Publications/Pdfs/ABC_Waters_Design_Guidelines.pdf

Puppala, H., Tamvada, J. P., Kim, B., & Peddinti, P. R. T. (2022). Enhanced green view index. *MethodsX*, *9*, 101824. https://doi.org/10.1016/j.mex.2022.101824

Shi, L., Maruthaveeran, S., Yusof, M. J. M., Zhao, J., & Liu, R. (2024). Exploring herbaceous plant biodiversity design in Chinese rain gardens: A literature review. *Water*, *16*(11), 1586. https://doi.org/10.3390/w16111586

Tang, S., Song, Y., Wang, Y., Jia, Z., Gao, X., Cheng, N., & Lu, T. (2024). Optimizing stormwater runoff treatment: The role of two-stage tandem rain gardens. *Environmental Research*, *262*. https://doi.org/10.1016/j.envres.2024.119831

Tara, N., & Thrupp, C. (2018). Maintenance of WSUD Assets – "The good, the bad and the ugly." In *Proceedings of the 9th Australian Stream 1 Management Conference, Brisbane City Council*. https://asnevents.s3.amazonaws.com/Abstrakt-FullPaper/51644/9ASM-Full-Paper.pdf

The Institution of Engineers Singapore. (2016). ABC waters at potong pasir–A case study [PDF]. https://www.ies-crm.com/professional/registry/abc/ABCWaters_Potong-Pasir_IES_Case%20Study%20slides.pdf

Vineyard, D., Ingwersen, W. W., Hawkins, T. R., Xue, X., Demeke, B., & Shuster, W. (2015). Comparing green and grey infrastructure using life cycle cost and environmental impact: A rain garden case study in Cincinnati, OH. *Journal of the American Water Resources Association*, *51*(5), 1342-1360. https://doi.org/10.1111/1752-1688.12320

William, R., Gardoni, P., & Stillwell, A. S. (2019). Predicting rain garden performance under back-to-back rainfall conditions using stochastic life-cycle analysis. *Sustainable and Resilient Infrastructure*, *6*(3-4), 143-155. https://doi.org/10.1080/23789689.2019.1660549

Xiao, Q., McPherson, E. G., Zhang, Q., Ge, X., & Dahlgren, R. (2017). Performance of two bioswales on urban runoff management. *Infrastructures*, *2*(4), 12. https://doi.org/10.3390/infrastructures2040012

Ying, B. X., (2019), Potong Pasir: The idyllic town imbued with community spirit. *Edgeprop Singapore*. https://www.edgeprop.sg/property-news/potong-pasir-idyllic-town-imbued-community-spirit

Yuan, J., Dunnett, N., & Stovin, V. (2017). The influence of vegetation on rain garden hydrological performance. *Urban Water Journal*, *14*(10), 1083-1089. https://doi.org/10.1080/1573062X.2017.1363251

Zhu, H., Nan, X., Yang, F., & Bao, Z. (2023). Utilizing the green view index to improve the urban street greenery index system: A statistical study using road patterns and vegetation structures as entry points. *Landscape and Urban Planning*, *237*, 104780. https://doi.org/10.1016/j.landurbplan.2023.104780

Appendix

Appendix A– Grasshopper (Rhinoceros 3D) script for calculating Green View and Colourfulness Indices

```
# Source: https://github.com/kowalski93/Green-View-Index-for-QGIS/blob/main/greenviewindex/calculate_green_view_index_algorithm.py
import os
import clr  # Add the clr import to access .NET libraries
clr.AddReference("System.Drawing")  # Import the System.Drawing assembly
from System.Drawing import Bitmap, Graphics, Color  # Import Bitmap, Graphics, and Color classes

input_folder = InputFolder  # Folder containing the images
output_folder = InputFolder  # Folder for saving masked images (optional)

write_masked = False  # No longer saving masked images
algorithm = "Li"  # Algorithm to extract vegetation pixels: "Li" or "Dong"

# Function to resize the image to 1000x1000 pixels
def resize_image(img, target_width=1000, target_height=1000):
    resized_img = Bitmap(target_width, target_height)
    graphics = Graphics.FromImage(resized_img)
    graphics.DrawImage(img, 0, 0, target_width, target_height)
    graphics.Dispose()
    return resized_img

# Function to calculate Excess Green Index (ExG) for vegetation detection
def calculate_exg(img):
    width, height = img.Width, img.Height
    exg_values = []

    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
            r, g, b = pixel.R, pixel.G, pixel.B
            exg = 2 * g - r - b
            exg_values.append(exg)

    return exg_values, width * height

# Function to apply Li et al. or Dong et al. vegetation algorithms
def apply_vegetation_algorithm(exg_values, algorithm, width, height):
    vegetation_mask = []
    for exg in exg_values:
        if algorithm == "Li":
            # Li et al. algorithm: simple threshold for ExG
            vegetation_mask.append(255 if exg > 50 else 0)
        elif algorithm == "Dong":
            # Dong et al. algorithm: Example HSV-based threshold (not included in Rhino)
            # Replace with a direct RGB-based rule for compatibility
            vegetation_mask.append(255 if 50 < exg < 150 else 0)
    return vegetation_mask

# Function to calculate Sky View Factor (SVF)
def calculate_svf(img):
    width, height = img.Width, img.Height
    sky_pixels = 0
    total_pixels = width * height

    # Assume sky pixels are those with high R, G, B values (near white or light blue)
    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
            r, g, b = pixel.R, pixel.G, pixel.B

            # Simple threshold to identify sky pixels
            if r > 200 and g > 200 and b > 200:  # Example for white or light blue
                sky_pixels += 1

    # Calculate SVF as the percentage of sky pixels
    svf = (sky_pixels / total_pixels) * 100
    return svf

  # Function to calculate colourfulness
def calculate_colourfulness(img):

    width, height = img.Width, img.Height
    rg = []  # To store rg values for all pixels
    yb = []  # To store yb values for all pixels
    # Calculate rg and yb for each pixel
    for x in range(width):
        for y in range(height):
            pixel = img.GetPixel(x, y)
```

```
            r, g, b = pixel.R, pixel.G, pixel.B
            rg.append(r-g)
            yb.append ((r + g) / 2 - b)

        # Calculate the mean values
            Urg = sum(rg) / len(rg)
            Uyb = sum(yb) / len(yb)

        # Calculate the standard deviations
            Qrg = (sum((value - Urg) ** 2 for value in rg) / len(rg)) ** 0.5
            Qyb = (sum((value - Uyb) ** 2 for value in yb) / len(yb)) ** 0.5

     # Compute the colourfulness metric
    colourfulness = (Qrg ** 2 + Qyb ** 2) ** 0.5 + 0.3 * ((Urg ** 2 + Uyb ** 2) ** 0.5)

    return colourfulness

# Function to process images and calculate GVI and SVF
def process_images(input_folder, write_masked, algorithm):
    all_files = [f for f in os.listdir(input_folder) if f.endswith(".jpg")]
    results = []

    for file in all_files:
        filepath = os.path.join(input_folder, file)
        img = Bitmap(filepath)

        # Resize the image to 1000x1000
        resized_img = resize_image(img, target_width=100, target_height=100)

        # Calculate Excess Green Index
        exg_values, total_pixels = calculate_exg(resized_img)

        # Apply vegetation classification
        vegetation_mask = apply_vegetation_algorithm(exg_values, algorithm, resized_img.Width, resized_img.Height)

        # Calculate GVI as the percentage of vegetation pixels
        green_pixels = sum(1 for value in vegetation_mask if value == 255)
        gvi = (green_pixels / total_pixels) * 100

        # Calculate Sky View Factor (SVF)
        svf = calculate_svf(resized_img)

        # Calculate Colourfulness
        colourfulness = calculate_colourfulness(resized_img)

        results.append((file, gvi, svf, colourfulness))

    return results

# Main execution
results = process_images(input_folder, write_masked, algorithm)

# Output results to console or Grasshopper panel
for file, gvi, svf, colourfulness in results:
    print(f"Image: {file}, GVI: {gvi:.2f}%, SVF: {svf:.2f}% , Colourfulness:{colourfulness:.2f},")
```

Appendix B– Images taken at Jurong Lake rain garden used to process Green View and Colourfulness indices

Appendix C– Images taken at Potong Pasir rain garden used to process Green View and Colourfulness indices

CRediT Authorship Contribution Statement

Lina Altoaimi: Writing - Review & Editing, Writing - Original Draft, Investigation, Methodology, Project Administration. Shruthakeerthi Karthikeyan: Writing - Review & Editing, Writing - Original Draft, Investigation, Formal Analysis. Akshitha Vadlakunta: Writing - Review & Editing, Writing - Original Draft, Conceptualization, Investigation. Wang Yuting: Writing - Review & Editing, Writing - Original Draft, Investigation, Data Curation. Abdul Tha'Qif bin Abdul Terawis: Writing - Review & Editing, Writing - Original Draft, Investigation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that this study has received no financial support.

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Data Availability

Data will be made available upon request.

Ethics Committee Approval

An ethics committee approval was not required for this study.

Resume

Lina Altoaimi is a graduate of the Bachelor of Landscape Architecture programme at the National University of Singapore. Her research interests include spatial degradation and transformation, as well as the influence of policy on urban spaces. She is currently pursuing independent research projects exploring architectural degradation and related policies in the tropical built environment.

Shruthakeerthi Karthikeyan is an architect and designer trained in SPA, JNAFAU, India. Her research interests include urban green spaces, relationships between climate change and heritage, and urban hydrology. She is currently pursuing her Master's in Landscape Architecture (MLA) at the National University of Singapore.

Akshitha Vadlakunta is an architect trained at Manipal School of Architecture and Planning. She is currently pursuing her Master's in Landscape Architecture (MLA) at the National University of Singapore. Her research interests focus on speculative and adaptive landscape strategies, including climate-resilient design, experimental ecologies, and the role of public space in shaping future urban living.

Wang Yuting is a graduate from National University of Singapore with a Bachelor's degree in Landscape Architecture and winner of the Lee Kuan Yew Gold Medal for best performing graduate in her course. Currently, she is pursuing the Environmental Technology MSc at Imperial College London, specialising in Urban Sustainable Environments.

Abdul Tha'qif bin Abdul Terawis is a graduate from National University of Singapore with a Bachelor's degree in Landscape Architecture. His research interests lie in simulation-based design and its applications in the landscape. He is currently undertaking independent studies on therapeutic plant-based interventions within transitional spaces of HDBs to promote well-being among the elderly.