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Review

Optimization of Green Infrastructure Practices in Industrial Areas for Runoff Management: A Review on Issues, Challenges and Opportunities

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Abstract: In urbanized lands, industrial areas are generally located close to residential and commercial areas due to ease of access for material and human resources. These industrial areas annually discharge large volumes of contaminated stormwater to receiving waters. Green Infrastructure (GI) practices, which were initially introduced as a land conservation strategy to enhance green space in urban areas, can provide benefits in source control of runoff generated in industrial areas with higher percentage of impermeable surfaces. Even though industrial areas across the world are currently looking at the applications of GI to reduce the impacts of excessive runoff and mitigate flash floods, several debates exist in optimization of these practices for such areas. In the current practice, optimal selection of GI practices for such areas are generally conducted based on expert judgement, and there are no systematic methodologies currently available for this process. This paper presents a review on various issues, challenges, and opportunities in the optimum applications of GI practices for industrial areas. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis conducted in this review by focusing on the applications of GI practices for industrial areas, helped to identify the existing research gaps for the optimization. Furthermore, the review showed the importance of engaging the multi-disciplinary stakeholders in the GI optimization process for industrial areas. In conclusion, the present review highlights the importance of introducing a systematic methodology for the optimum applications of GI practices for industrial areas to manage stormwater.

Keywords: green infrastructure; runoff management; industrial areas; optimisation

1. Introduction

The rapid advancement of industrialization has become one of the major threats to the natural environment over the years. Infrastructure development as a consequence of industrialization creates enormous pressures on natural green space in urban areas. The reduction of pervious surfaces associated with green space creates several adverse impacts on land surface characteristics, water cycle and the atmosphere. The impact of land use changes in urban planning has become a focal point of scientific interest since different land use types show different degrees of threats to the communities and ecosystems [1,2]. Industrial land use is known as the areas which are used for manufacturing or processing that can be zoned as light, medium or heavy industry [3]. According to the land surface characteristics, industrial areas can be divided into three major land use types as brownfields (abandoned or under-utilized industrial areas due to the presence of land contamination), existing industrial lands (areas that consists of considerably larger paved landscapes), and mixed land use of brownfields and existing industrial lands [4]. Most of these industrial areas are located within urban areas, surrounded by commercial and residential areas, due to easy access for human resources, transportation and materials supply [5]. Therefore, these areas increase the tendency of human exposure to various environmental impacts occurred by industrial activities.

Among the number of environmental problems present in industrial areas, water resource contamination, heat stress, and air pollution are identified as key concerns which can create severe long-term impacts for human and ecosystem health [6,7]. Industrial areas are identified as hot spots that generate highly polluted stormwater runoff, mainly consists of sediments, nutrients, and heavy metals due to the presence of large impervious areas [8].

During the past decade, Green Infrastructure (GI) has evolved as a successful measure in restoring urban green space across many countries around the world [9]. Though these practices have been earlier identified as a replacement for conventional stormwater management strategies, GI in broader terms can be defined as an "interconnected network of green space that conserves natural systems and provides assorted benefits to human populations" [10]. There are several different GI practices available that can provide these benefits. Some of the examples for widely applied GI practices are green roofs, trees, green walls, wetlands, bioretention, pervious pavements, infiltration trenches, retention ponds, sedimentation basins and vegetated swales [11,12].

While investigating numerous benefits of GI, researchers have identified that, apart from the application as a stormwater management strategy that manages both water quantity and quality within the water cycle, GI practices can also provide other important ecosystem services. Ecosystem services can be defined as "benefits of ecosystems to households, communities, and economies" [13]. Some of these other ecosystem services that GI practices provide are energy savings, air quality improvement, reducing greenhouse gases, reduction of urban heat island, improvement of community livability which includes aesthetics, recreation, and improvement of habitats amongst others [14]. GI practices play a significant role in the well-known Eco-Industrial Park (EIP) concept in industrial ecology. EIP is an industrial area that is designed to encourage businesses to share infrastructure as a strategy for enhancing production, minimizing costs, managing the environmental and social issues [15]. GI practices are widely used within the EIP planning to manage the issues related to stormwater, wastewater, air pollution, and energy consumption. Furthermore, GI can improve the social and community dimension of the industrial areas by providing measurements to enhance the community livability within and its surroundings [16]. However, there are numerous debates exist in ways of designing GI practices within industrial areas that can provide the optimum benefits to achieve the goals of the EIP concept [17,18]. Since there is a pool of different GI practices available that can produce several different combinations of interconnected networks of green space, it is a difficult task to assess which individual GI or combinations are the most suitable practices for a particular area. According to the definition of Ref. [19], it is always important to optimize the benefits that can be gained through designing ecologically sustainable industrial areas as a collective benefit rather than the individual benefits. Hence, innovative methodologies should be developed to identify ways of optimum selection and planning of GI practices within industrial areas that can provide more globalized benefits when it comes to runoff management and achieving other ecosystem benefits.

Even though the research on optimization of GI practices within the industrial areas is still in its infancy stage, there are several examples of the applications of the EIP concept, particularly in heavy industrial areas across the world. Some of the prominent international examples of EIPs are Kalundborg (Denmark), Forth Valley (Scotland, UK), Kawasaki (Japan), Rotterdam (The Netherlands), Map Ta Phut (Thailand), and North Texas (TX, USA) [20]. Majority of the development of these EIPs were gradually evolved in brownfield areas [21].

The first EIP in Australia is recorded as the "steel river' project which is located in Newcastle, New South Wales. This project included several GI practices to landscape streets, provide recreational and community livability benefits, and to manage the water resources within the site [22]. Some of the other leading examples for the applications of GI practices in heavy industrial areas in Australia are Kiwinana (Western Australia), Gladstone (Queensland) and Geelong (Victoria) [21]. The selection of different GI practices in these EIP is generally conducted through expert judgment and assessing the numerous other factors such as availability of funds, land area, and other resources. There is no systematic methodology currently available to identify the optimum GI practices for different industrial areas.

The applications and the importance of GI practices to improve the environmental quality of various land-use types are well discussed in the literature [23–25]. However, to date, the optimum planning of GI practices has not yet been discussed comprehensively for land use types such as industrial areas, which are complex and dynamic components in urban areas. Industrial areas are environmentally degraded areas which also consist of brownfield lands that are known as abandoned or underused sites that have tremendous opportunities for redevelopment by introducing urban green space [26].

The optimum planning of GI practices in such areas in the past and even now has been largely opportunistic, taking advantage of the funding opportunities, rather than looking at the reasons for implementing them in these areas and their actual long-term benefits [27]. From the selection of suitable GI practices to the sizing of these practices, various decisions should be made to achieve the sustainability in an optimum way. The decision-makers often find it difficult to assess the nature of these decisions due to multiple objectives associated with them [28]. Furthermore, each and every problem that GI provides solutions may be unique to each other and depends on the site conditions and objectives that have to be met through the implementation of them. Studies done by Ref. [29] and Ref. [30], identified several environmental, social and economic criteria to be considered when selecting optimum GI for runoff management and have presented decision matrices that provide decision aid on selecting them. Due to the multifunctionality of GI, the ecological and social objectives should be taken into consideration when optimum planning for GI [31]. Even though the primary focus of GI has been shifted towards the runoff management, the decision-makers today are focused on maintaining urban ecological networks through GI by maintaining a dynamic interplay of ecological and social systems [32,33].The ever-increasing knowledge base on ecosystem services of GI supports decision-makers on this process; however, holistic frameworks are required to link these ecosystem services for the GI planning in order to gain maximum environmental, economic and social benefits from their implementation [34,35].

One of the other significant problems in this process is the lack of the utilization of various tools and methods that can be used to support the GI optimization decision making. This paper provides a literature review of GI practices and their applications for stormwater management in industrial areas. The application of GI practices in industrial areas to manage runoff is discussed by focusing on the issues, challenges, and opportunities for their optimization. Multiple objectives associated with the decision making of GI optimization for industrial areas are also discussed in this paper.

Green Infrastructure (GI) Practices

Infrastructure systems are essential components in modern high-density cities. The Oxford dictionary defines the term infrastructure as "the basic physical and organizational structures and facilities (e.g., buildings, roads, and power supplies) needed for the operation of a society or enterprise" [36,37]. These infrastructure systems that are often referred to as traditional "grey" infrastructure consists of engineered networks of roads and services, which provide a range of services for the communities in urban areas [10]. The 'grey infrastructure' systems generally provide a single functionality for a community. However, with the constant pressure that has been forced by the urbanization upon traditional infrastructure, people have explored alternative systems that can provide multiple functions in cities within the same spatial area [38]. As a result of these efforts, the concept of GI was introduced, which comprises various elements that are capable of effectively responding to the environmental, economic, and social pressures that are forced upon the public by the urbanization.

Various scholars have provided different definitions for the term GI. Some of the definitions which are widely used in literature for GI are,

> "Green Infrastructure is an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations." [10]

> "Green Infrastructure is the network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services." [28]

> "Green Infrastructure is an approach to water management that protects, restores, or mimics the natural water cycle. Green infrastructure is effective, economical, and enhances community safety and quality of life." [39]

> "Green Infrastructure is a design strategy for handling runoff that reduces runoff volume and distribute the flows by using vegetation, soils and natural processes to manage water and create healthier urban and suburban environments." [40]

As evident from these different definitions, the more recent focus of GI practices has been shifted towards its applications as a stormwater management strategy. However, in summary, the underlying idea of all these definitions portrays that GI practices can provide multiple benefits that can contribute in developing resilient cities. GI practices can be implemented within urban areas in different scales from the local level through engineered structures to a broader level through landscaping [28]. The GI practices which are implemented at the local level are known as structural GI. Some of the examples of structural GI practices are wetlands, green roofs, rain gardens/bioretention systems, vegetated swales, permeable pavements, infiltration trenches, retention ponds, sedimentation basins, and green walls. At the broader level, GI practices are considered as non-structural components such as preservation and restoration of natural landscapes (e.g., forests and floodplains) [39,41,42]. The primary focus of the review presented in this paper will be on structural GI practices.

GI practices can be integrated into the existing features of the built environment such as streets, buildings, parking lots and landscaped areas [43]. One of the critical features of GI practices compared to traditional grey infrastructure is the cost-effectiveness during their operational period. Even though the initial installation costs of GI can be potentially high in redevelopment and retrofit settings, from their life cycle perspective, the long term operational and maintenance costs make them economically feasible than the conventional infrastructure. A study conducted by United States Environmental Protection Agency (USEPA) considering 17 projects which used local scale GI practices found that in the majority of instances, GI provided a cheaper and more environmentally friendly performance in managing stormwater compared to the conventional methods [43–45].

The costs and benefits of GI practices compared to grey infrastructure as a stormwater management strategy have been well discussed in the literature for various development types (e.g., residential, commercial, and industrial areas). Table 1 shows the cost savings associated with stormwater management GI practices used in various commercial and industrial facilities in USA and Canada [46]. These case studies have used combinations of several different types of GI practices for different facilities and have achieved a significant amount of cost savings. It is evident that even though investing in GI practices can be initially expensive when compared to the traditional infrastructure, they can be more favorable when looking at their long-term benefits [47,48].

Decision making in GI planning compared with grey infrastructure, involves multiple objectives [29,30,38]. In the planning principles of GI, stakeholder engagement has been identified as one of the important processes that are required to achieve the expected outcomes of implementing the GI practices [31,49]. These stakeholders may include public entities or individuals who own or manage the land in the areas which fall within the GI network and the people who invest in the future of the communities. The decisions for the initiation of GI practices can be immensely benefitted from these stakeholders by the integration of their knowledge, experience, and resources [50,51]. There are several tools available to evaluate the performance of GI practices (i.e., various ecosystem services) and the potential cost savings which also support the planning of GI [45].

Table 1. Cost Savings through Installing Green Infrastructure (GI) as Stormwater Management Strategies in commercial and Industrial Developments [46].

Location	Description of GI Used	Cost Savings through GI	Reference
Parking Lot Retrofit Largo, Maryland	One-half acre of impervious surface. Stormwater directed to central bioretention.	$10,500–$15,000	Ref. [52]
Old Farm Shopping Centre, Maryland	Site redesigned to reduce impervious surfaces, added bioretention, filter strips, and infiltration trenches.	$36,230	Ref. [53]
OMSI Parking Lot Portland, Oregon	Parking lot incorporated bio-swales into the design, and reduced piping and catch basin infrastructure.	$78,000	Ref. [53]
Light Industrial Parking Lot, Portland, Oregon	Site incorporated bio swales into the design, and reduced piping and catch basin infrastructure.	$11,247	Ref. [54]
Point West Shopping Center, Lexana, Kansas	Reduced curb and gutter, reduced storm sewer and inlets, reduced grading, and used porous pavers, added bioretention cells, and native plantings.	$168,898	Ref. [55]
Vancouver Island Technology Park Redevelopment British Columbia, Canada	Constructed wetlands, grassy swales and open channels, rather than piping to control stormwater. Also used native plantings, shallow stormwater ponds within forested areas, and permeable surfaces on parking lots.	$530,000	Ref. [56]

2. Role of GI Practices for Stormwater Management in Industrial Areas

The industrial sector plays a major role in a country's economy [57]. Several industrial areas are located within urban areas surrounded by residential and commercial areas due to the easy acquisition of materials and human resources. Contamination of surrounding water bodies from the runoff and flash floods generated due to the presence of larger impermeable areas are identified as significant issues related to water resources in the majority of these industrial areas [6,7,58]. In addition to these issues, some of the other impacts associated with the industrial areas are high energy consumption, GHG Emissions, threats to the natural ecosystems and habitats, and reduced community livability [59]. Lack of measures for the proper restoration of environmental quality within these areas can affect workers, surrounding communities and the ecosystems in the long term. Strategically planned GI practices have an enormous potential to meet the environmental demands forced by industrial areas by providing a diverse range of ecosystem services and by mitigating various impacts that occurred by the climate change [23,60,61].

2.1. GI practices for the Mitigation and Adaptation of Floods

At present, many leading cities across the world are looking at the opportunities to introduce GI practices in order to maintain resilient cities in terms of mitigating and adapting to rising impacts of climate change [41,62,63]. In an urban area, floods can be occurred due to two major reasons which are (1) the floods occur due to the problems in drainage systems when the system is disturbed or(2) the general flash floods which are typically occurred within an urban area. The land-use types such as industrial areas can be subjected to these two types of floods during storm events mainly due to the presence of higher percentage of impermeable areas and well as due to low urban green space [64]. Such urban floods can occur due to endogenic factors of the drainage basin that includes the aging infrastructure which has reached their capacity and therefore is unable to meet the demands of the runoff and changes of the river hydrology and the encroachment of impermeable surfaces [65–67].

GI practices, which are also introduced as Blue- Green Infrastructure (BGI) due to its capabilities in managing hydrological functions are currently incorporated as an integral component in urban planning across many cities around the world [68–70]. One of the leading examples could be given by taking Portland, Oregon as a case study. Portland is been identified as a city with one of the most mature and comprehensive GI programs in the country [71,72]. Oregon state government has invested 9 million US dollars for the GI investment and has made a saving of 224 million US dollars with the cost for combined sewer overflows including the operation and maintenance costs [73]. Another example could be drawn from the ABC waters program introduced by Singapore the government has introduced GI features such as rain gardens, bioretention swales, and wetlands to mitigate the impacts of urbanizations and flash flooding [74,75]. These practices implemented under the ABC waters program followed guidelines in order to achieve better surface water drainage, flood control, stormwater quality, and public health control. The assessment of the outcomes of this project has proven that there was a drastic change in the flood-prone areas of Singapore, from 629 ha (in 1989) to 56 ha (in 2011) [73]. Table 2 shows a summary of similar recent studies done by different regions across the world through the applications of GI practices.

As can be seen from Table 2, the majority of these studies are the applications of GI for the pluvial flood management in residential land use areas. In urban areas, the abandoned or underutilized industrial areas which are known as 'brownfields' are considered as major liabilities to a county's economy [76–78]. Sustainable brownfield redevelopment techniques are intended to achieve cleaner water, substantial energy savings, restoration of the ecosystems and increased diverse economic service and increased production efficiencies of these areas [79,80]. It is evident that GI practices can not only provide means of reducing the environmental threat posed to the neighborhood communities by these areas but also provide numerous economic benefits for the industries or individual businesses. However, there is yet limited information available on applications of GI practices in such areas due to the general lack of systematic knowledge on the optimal applications of these practices, shortage of awareness and the perspectives on the potential of integrating these strategies in such land areas [81]. The potential benefits of GI practices for such brownfields can only be understood if they are accepted as the vital land areas that can support applications of urban GI practices [61].

Table 2. Studies on flood mitigation effectiveness of GI practices [82].

Study	Location	GI Considered	Precipitation Peak Intensity/Duration/Frequency	Results
Ref. [83]	Urban community in Beijing, China	Expanding green space, concave green space, retention ponds, porous pavement and combinations	2.8 mm/min(peak)/24 h/10 years	GI projects is limited, BGI integrated throughout the community was highly effective in preventing flooding from precipitation events with 10-year recurrence interval
Ref. [84]	Guang-Ming New District, Shenzhen China	Swales, porous pavement and green roofs	4.3 mm/min (peak)/1–4 h/100 years	Effectiveness of GI was dependent on the percent coverage and storage capacity. Porous pavement was most effective at the study site since it provided the greatest area of coverage
Ref. [85]	Hexi watershed, Nanjing, China	Rainwater harvesting cisterns, porous pavement and combinations	Not specified/20 min/5 years	Porous pavement reduced induction area by 50%–75% in high hazard areas. Rainwater harvesting was able to provide limited additional mitigation benefits
Ref. [86]	Hypothetical, based on Cook County, IL, USA	Detention basins	0.25 mm/min (peak)/24 h/100 years	BGI dispersed throughout the landscape at high levels of coverage (>20%) effectively mitigated flooding
Ref. [87]	Residential area of Guangzhou, China	Bio retention, porous pavement, infiltration trench, rain barrel, vegetative swale, rain garden and green roofs	Not specified/2 hour/10 years	For the scenarios modeled, GI was effective for lower intensity storms (2 years), but less effective for the 10-year storm
Ref. [88]	Xingshi Village, Taiwan	Infiltration trench and basin, detention ponds, vegetated filter strip and swale, sand filter, constructed wetlands, green roof, rain barrel porous pavement, and bioretention	94.7 mm/ho/1 h/5 years × 1.5 to account for climate change	GI deployment throughout the watershed can be optimized to mitigate pluvial flooding

2.2. GI practices for Improving the Runoff Quality

In urban areas, stormwater can be generated from residential, commercial and industrial areas which are contributors for non-point source pollution. Among these different source categories, runoff generated from industrial areas has been identified with elevated levels of excess nutrients, sediments, heavy metals, hydrocarbons and other substances [89,90]. Furthermore, industrial runoff is the predominant contributor of Zinc (Zn) and Copper (Cu) loadings in receiving waters, and together with the commercial land, has the highest pollutant loading production of all stormwater sources [91].

Industrial activities such as material handling and storage, and equipment cleaning and maintenance, can interact with rainfall and build up the pollutants that can degrade the water quality of natural waterways [92]. Stormwater discharges from small to medium enterprises (SME) are largely unregulated and are not receiving treatment before entering the rivers or coastal waters. In Australia, 75% of the industrial areas are comprised of SME's which largely accounts for industrial stormwater pollution. According to a study done by City of Kingston, stormwater from approximately 4500 businesses drain into the Port Philip Bay, Australia [93].

Even though stormwater contamination has been identified as non-point source pollution for the majority of land-use types, industrial areas can also contribute to the point source discharges. The point source pollution in industrial areas can be attached to a single activity that has one clear source. Some of the examples are accidental discharges or deliberate disposal [93–95]. However, stormwater contamination through point sources is considered as not very difficult problem to mitigate in industrial areas since the source is identifiable whereas non- point source pollution is difficult to control due to their diffuse nature. Furthermore, past studies have highlighted that there exists a lack of guidelines to regulate the non-point stormwater pollution in industrial areas considering its harmful impacts compared to runoff of other land-use types [96,97].

The Milwaukee 30th Street Industrial Corridor restoration with GI could be taken as one of the examples in restoring GI in an industrial land area to mitigate impacts from runoff. This area has been highly utilized by manufacturing activities until the industry started declining in 1980s [98]. After the decline of the manufacturing industry, many industries along the 30th Street Industrial Corridor were downsized, and the area has remained with significant environmental issues such as severe flooding and environmental contamination that are affected for the surrounding communities [45,99]. To alleviate stormwater contamination and the flooding of this area, GI practices which promote detention and constructed wetlands are proposed that provide storage and delay of water entering into the sewer system [100]. With the area-wide development plan, sections of the corridor are planned to be developed into linear parks by promoting more urban green space. This has been intended to provide recreational opportunities and amenities for the area that could be beneficial for the residents of the adjacent residential area. Furthermore, these land areas were designed to connect with waterways through strategically planned bio swales, wetlands and infiltration-based GI practices [45,99]. A master plan for the restoration of Genetta Park in Montgomery Alabama, was initiated in 2010, to transform an unattractive industrial land into an attractive environmental amenity by implementing GI practices [80,101] The park area covered around 4-acre land area with Genetta stream traveling across the area. The land use of the area has been creating negative impacts for the Genetta stream by creating floods downstream, impaired water quality, reduced stream biodiversity and reduced groundwater recharge [80,101].

The need for environmentally sustainable strategies which support the efficient use of resources in industrial areas is becoming increasingly evident [47,102,103]. GI practices form an essential element in increasing the resilience of industrial businesses in the long term. Furthermore, GI practices demonstrate several financial advantages when compared to the traditional grey infrastructure due to their potential for reducing initial capital expenditure, ongoing operation and maintenance expenses. Moreover, strategically planned GI practices can also be used to recapitalize aging assets. Another important factor associated with GI practices is that since they leverage existing natural resources. As an example, the interconnected green space network provided by GI can support in the regeneration of urban forest with less energy and resources. The additional ecosystem services provided by this interconnected green space network such as energy conservation and cooling effects, can support for the industries in reducing costs for their energy consumption and support to reduce associated costs in longer term. In addition, GI practices offer numerous opportunities to enhance the communication within industries to effectively manage socio-political risks through the innovative collaboration of stakeholders [104].

Apart from the various benefits discussed, the implementation of GI practices within industrial areas has been also identified with the potential to treat wastewater discharged from the industrial plants by using them as source control treatment measures [105]. GI practices also provide opportunities to reduce the high potable water demands in industrial areas by promoting the reuse of water for activities such as cooling, cleaning the equipment, and product processing [106].

2.3. Treatment Efficiencies and Costs Associated with GI

GI practices incorporate various pollutant removal mechanisms such as e sedimentation, plant uptake, filtration, biofiltration, biodegradation and sorption [107]. Based on these treatment removal mechanisms GI demonstrates various treatment efficiencies that differ based on the case study it has been applied. Table 3 shows a summary of the treatment removal efficiencies of some of the popular GI applied for the pollutant removal from urban runoff. It is evident from these data that most of the GI supports in reducing TSS and Total Zn for a higher percentage. However, rain gardens have shown a tendency to export nutrients to the runoff which can be attributed to the characteristics of the filter bed and [108] suggest that the composition of filter media and hydrologic design of the system are the primary factors that can affect nutrient removal.

Table 3. Summary of pollutant removal efficiencies from various GI practices [109].

Constituents	Detention	Retention	Bioretention	Media Filter	Vegetated
	(Dry) Pond	(Wet) Pond	(Rain Garden)	(Sand Filter)	Swale/Buffer/Strip
TSS	66 to 80	54 to 94	63–91	81 to 90	46 to 92
TN	10 to 26	51		9 to 32	30
NO3-N	8 to 22	77	−128 to −559	−67 to −142	27
TKN	15 to 27	27	−31 to 18	36 to 53	31
TP	16 to 29	5	−494 to 76	39 to 44	−106
Ortho-P	−22 to 25	−266	−269 to −99	11 to 24	−218
Diss. P			−358 to −196		
Tot. sol. P			−350 to −317		
Tot. Cu	−29 to 58	89	−73 to −12	50 to 66	63 to 76
Tot. Pb	72	98	−30 to 98	85 to 87	68 to 92
Tot. Zn	65 to73	91		80 to 92	77 to 94
Diss. Cu	26 to 39	57		7 to 40	
Diss. Pb	29	76		31 to 40	
Diss. Zn	16 to 33	41		61 to 94	
Particulate Cu					49
Particulate Pb					57
Particulate Zn					74

The optimal sizing of a certain GI for stormwater management depends on the volume of the runoff generated, quality of runoff and the availability of space for the construction. A study done by [110], has proposed a methodology to optimally size GI treatment trains by considering their costs and treatment efficiency considering Total Suspended Solids, Total Nitrogen, and Total Phosphorous target pollutant reduction. It should be noted that each GI measure will incur their own costs including construction, operation, and maintenance costs that highly depend on the required treatment efficiency for an application.

3. Optimization of Green Infrastructure Practices for Industrial Areas: Issues, Challenges and Opportunities

It has been evident that during the past few years, GI practices have gradually become a vital component in sustainable urban planning. In the context of designing sustainable cities, applications of GI practices for several residential, commercial and industrial developments are well discussed in the literature [23,25,111]. However, the implementation of GI practices in the majority of these studies was conducted only based on trial and error or expert judgement without giving comprehensive attention to the land use type.

The uniqueness of different industrial land use types exhibits various types of environmental externalities and should be treated cautiously during the implementation of GI practices [61]. As an example, an industrial land use such as a brownfield area, the contaminated soils are generally capped with an impermeable surface. Therefore, it is recommended for the runoff to be directed away from those soils. Alternatively, contaminated soils can be excavated and treated separately with methods appropriate to the type of contamination, then replaced, if desired. However, even in such instances, the GI practices which promote infiltration may still not suitable. Thus, these land surface variations create the need for more careful selection and optimization of the best option for industrial areas from several different GI practices available, when compared with the other land use types.

Optimization of GI practices in industrial areas incorporates several challenges when compared to residential, commercial or open spaced areas, mainly due to the presence of land contamination. The presence of various industrial activities and considerably larger impermeable surfaces in industrial areas can lead to diffuse stormwater pollution and the selected GI practices for such areas should have the ability to limit these pollutants entering the receiving water bodies [112]. Some of the other challenges include the lack of financial resources for undertaking soil remediation for the GI implementation, risk of dealing with contamination (e.g. groundwater pollution), legal restrictions, and lack of tools and methodologies to identify optimum GI practices which are suitable for industrial areas [23,113].

There are several limitations in the application of GI practices for industrial land-uses, especially for the brownfield lands, due to the extent of the land contamination present. Several precautions may need to be taken before the implementation of GI for such land areas. The developers must be cautious if the brownfield lands are located in proximity to high groundwater tables or freshwater wells as the GI practices which promotes infiltration are not appropriate for such areas [80]. Guidelines were provided in Ref. [114] for the successful implementation of GI implementation on brownfield sites by maintaining a minimal environmental risk. Some of these guidelines include limitations of application of GI that promotes infiltration and increase the use of practices that reduces the runoff quantity through collection such as cisterns, green roofs or green walls, distinguishing the group of contaminants to minimize risks, application of impermeable liners of filter blankets coupled with traditional GI and keeping the clean stormwater away from the contaminated soils to reduce the further contamination. As can be seen from these guidelines, even though the application for GI for industrial areas or brownfield lands may be viable in improving the environmental quality, there might be a high cost, and technical expertise could associate that can hinder their implementation.

A study conducted by Ref. [115] analyzed the runoff quality of 20 industrial sites from North Carolina has found that runoff found in industrial areas has comparatively high concentrations of Zinc and Copper for almost all the sites despite their industrial activities. According to this study industrial runoff has reported high concentrations of heavy metals, volatile and semi-volatile organics apart from the conventional pollutants found in street runoff which are biochemical oxygen demand, BODs; chemical oxygen demand, COD; and oil and grease), nutrients (ammonia nitrogen, NH3; nitrate plus nitrite nitrogen, N03 + N02; total Kjeldahl nitrogen, TKN; total phosphorus, TP; and dissolved phosphorus), and solids (dissolved and suspended, TSS). Therefore, according to these results, it is evident that when selecting GI for industrial areas, it is important to select optimum practices that facilitate the treatment of these focused pollutants in runoff. Table 4 shows the various treatment mechanisms of GI practices that treat different types of pollutants according to their unique treatment mechanisms.

Table 4. GI Treatment Measures in GI Treatment Trains [116].

Treatment	Pollutants	Typical Treatment Measures
Primary Treatment	Gross pollutants and coarse sediments	Gross polluant traps, Sédimentation basins, Vegetated swales
Secondary Treatment	Fine sediments and attached pollutants	Vegetated swales, Infiltration trenches, Permeable pavement, Bioretention
Tertiary Treatment	Nutrients and dissolved heavy metals	Bioretention, Bio- infiltration systems, Wetlands, Retention ponds

As can be seen from the Table 4, the treatment measures that support infiltration such as bioretention, bio-infiltration systems and wetlands are recommended for the removal of heavy metals from urban runoff. Based on the Ref. [114] guidelines it is recommended to minimize the GI that support infiltration of runoff to the groundwater table especially for brownfield areas as the soils are contaminated in brownfield sites and runoff cannot be routed to such soils However, using measures with hinders the infiltration such as using impermeable liners as asphalt, are recommended where GI can be used as a secondary application to filter runoff from that impermeable area. It could be adding additional complexity to place more impervious surface down, but it could make previously un-useable land marketable and treat runoff from that property.

Furthermore, one of the major drawbacks of GI practices compared to grey infrastructure is the large land area required to achieve the intended environmental or socio-economic outcome. Hence the achievement of optimum results through GI implementation should be accomplished within existing land area constraints [117]. This creates a challenge in identifying the optimum GI practices for an industrial area to meet the environmental demand forced by the land use type. The other barriers in optimum application of GI practices in industrial areas are, lack of facilities for long term monitoring and evaluation, insufficient supporting and ongoing maintenance funds, failure of highlighting and addressing the real issues of the sites through GI practices, and ultimately a lack of success with project's objectives and the site sustainability [118].

Table 5 shows the analysis of strengths, weaknesses, opportunities, and threats (SWOT), in applications of GI practices within industrial areas for runoff management [104]. According to this SWOT analysis, the implementation of GI practices in industrial areas incorporates a unique set of issues including the additional financial resources, knowledge and expertise required for the optimal designing of GI for runoff management in areas such as brownfields, the time required for the maturation and provision of required functionality, the large physical footprint required for their construction, the lack of proper industry design standards and the challenges in obtaining the permits or regulatory approvals. Another layer of complexity is added to the problem due to the perspectives of the industrial landowners on GI practices as a sustainable solution. There can be issues raised due to their lack of interest in negotiating for the land areas for GI construction.

Table 5. SWOT analysis on applications of GI practices for industrial areas.

SWOT Analysis of GI Applications for Runoff Management for Industrial Areas			
Strengths (S)	**Weaknesses (W)**	**Opportunities (O)**	**Threats (T)**
Requires low initial expenses and operating expenses (only monitoring, feedback and control).	Often requires a large physical footprint to provide the expected runoff management outcomes.	Offers opportunities for innovative non-technical risk management by active local stakeholder participation in the design and operation of the GI solution	Can be susceptible to seasonal weather changes and extreme weather conditions
Is less sensitive to increases in the cost of raw materials, cost of power, power interruption, etc. when compared with grey infrastructure for runoff management.	Requires time for proper site investigation and performance maturation	Offers opportunities to partner with local landowners in the use of land areas	Can be subjected to unforeseen stresses over its lifetime
Appreciates over time as it grows more interconnected with the local environment.	May require time (years) to mature and to provide the required functionality	Apart from the runoff management benefit, provides nature's inherent with resource-efficiency and multi-functionality (water purification, urban cooling, air quality improvement, flood protection etc.) which can be highly beneficial for industrial areas.	Can pose challenges to obtain permits or regulatory approvals.

The weaknesses, opportunities and challenges identified in the Table 5 could be further classified into five categories as discussed in Ref. [119]. From a broader point of view, these categories can be identified as challenges related to design standards, financing, regulatory pathways, socio-economy, and innovation. There is a need for implementing design guidelines for the planning of GI that are tailor-made for specific cities and regions that addresses their own environmental risks and threats [120]. In the regulatory point of view integration of regulations that fully supports the multi-dimensional functions of GI still remains a key challenge in many urban areas across the world [121].

Moreover, there are particularly many different types of stakeholders involved in managing GI projects in industrial areas [122,123]. These stakeholders also play a significant role in identifying potential stresses forced upon the area and how the GI practices can be optimally utilized to overcome them. Although the multiple benefits of GI are well documented, public engagement could be challenging for industry owners who may have limited leisure time to participate in greening efforts especially when GI is located on their private lands [124]. In summary, there exists a wide range of opportunities for GI practices to provide resilience in industrial and business operations when they are optimally designed. However, the knowledge base on their optimal applications should be further enhanced to assess the ways of overcoming the potential challenges and barriers of their implementation.

4. Multiple Objectives in GI Decision Making for Industrial Areas

The rise of GI strategies has started in 1990's when the sustainability was becoming a national and international goal in the world. Thus, the growing interest of GI practices during this period was mainly concentrated around the objective of land conservation in urban areas in order to transform them into more sustainable cities [10]. However, the pressures forced upon land through urbanization and industrialization have provided the opportunity to look at the multifunctionality of GI practices not only as a land conservation strategy, but also as a means of providing wide range of ecosystem services. The ability of GI practices to provide several functions and ecosystem services within the same spatial area has been then identified with multiple objectives of different perspectives such as environmental, social and economic point of view [125]. In the current context, a major focus is given for the ecosystem services provided by GI practices in the decision making of GI planning process [31].

The are several objectives associated in decision making when selecting optimum GI practices for a site from the pool of different alternatives available [126]. The process in selecting potential GI practices for a site is further governed by the site-specific planning, environmental, institutional and regulatory constraints [127]. One of the major challenges faced by the decision maker during the GI selection process is to select the most cost effective and sustainable strategy for the site, which also provides benefits in terms of other multiple objectives considered [128]. Hence, it is always important to maintain the balance between environmental and economic goals of GI implementation while achieving the optimal implication among the multiple objectives [129]. Especially for industrial areas, these objectives can be further complex due to the higher environmental demands, impacts enforced by different GI practices on industry or business operations and the perspectives of variety of stakeholders associated in the project [103,104,112,130].

Stakeholder Participation in GI Decision Making

When optimizing GI practices for a particular area by considering their multiple objectives, several studies have highlighted the importance of stakeholder engagement due to the diverse nature of the problem [126,131]. These stakeholders may be engineers, planners and environmentalists who can directly or indirectly have an impact on the GI selection [132]. An engineer who represents a local government agency can have a higher preference for minimizing the costs of the GI strategy while a planner will prefer on improving the amenity of the area. Furthermore, an environmentalist may have an entirely different priority such as reducing the environmental impacts occurred by uncontrolled stormwater. Thus, to provide a reasonable balance between these conflicting objectives of different stakeholders, it is important to incorporate their preferences in the decision-making process [133,134]

GI planning requires knowledge from different disciplines such as landscape ecology, urban/regional planning, landscape architecture and engineering which rely on the partnership between different local authorities and stakeholders for its successful implementation. The preferences of these different stakeholders are elicited in the planning process to support the knowledge transfer and ensure environmental justice [31].

Several studies have highlighted the importance of stakeholder participation in GI planning for urban areas by considering their ecosystem services as multiple objectives that support decision making [30,125,126,130,131,135,136]. However, none of these studies have extensively studied the importance of stakeholder participation to identify the objectives or criteria relevant to the GI planning in industrial areas. The industrial areas are complex land use types which can include wide range of different GI practices with different impacts for water quality and quantity, air quality, which are subjected to different constraints and entailing variable costs. Unfamiliarity or lack of knowledge on stakeholders on the specific objectives for such areas could negatively influence the decision-making process of optimum GI planning [137,138]. It had been argued that transferring corporate and social responsibility (that includes environmental, economic and social performances) into industry's objectives is best undertaken through the stakeholder's point of view [139]. Hence, the strategies that promote sustainability for industrial areas such as GI practices should be given careful attention in terms of identifying their particular objectives and the influences of stakeholders for their optimum applications.

5. Summary and Conclusions

GI practices which were initially introduced as land conservation strategies, are currently becoming increasingly popular due to their stormwater management aspects and the provision of several other ecosystem services. In urbanized land uses, industrial areas are generally located close to residential and commercial areas due to the ease of access for material and human resources. These industrial areas can pose several threats to the environment and surrounding communities in the long term. GI practices can be implemented in industrial areas to mitigate major environmental problems that occur in these areas such as degradation of water resources through contaminated runoff and air pollution.

Several previous studies in the literature have highlighted the importance and the benefits that can be achieved for industrial areas by implementing GI practices. There are several different GI practices available which can provide different benefits for industrial areas with different associated costs for their implementation. Regardless of the wide acknowledgement of the applications of GI practices within industrial areas in the literature, there are no systematic methods available in the current practice to identify optimum GI practices suitable for such areas. In the current practice, the GI optimization for such land areas is performed through expert judgement and using simulation models which is an ad-hoc process. The analysis of strengths, weaknesses, opportunities and threats (SWOT) conducted for the assessment of the applications of GI practices within industrial areas further highlighted the lack of knowledge and research gaps in GI optimization for industrial areas.

Apart from the main objectives of implementing GI practices in industrial areas which is enhancing the overall environmental quality, there are several other multiple objectives associated in the optimization process. Another layer of complexity is added for the GI optimization process in industrial areas due to the views of various stakeholders who influence the process of GI implementation in such areas. When optimizing GI practices for an industrial area, all of these factors should be considered to identify the optimum GI practices which will ensure maximum benefits with minimum costs. The paper highlighted the importance of a systematic methodology to optimize GI practices for industrial areas which also require the involvement of multi-disciplinary stakeholders.

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