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RESEARCH ARTICLE

Interlocking Elements to Control Erosion in Natural and Urban Ecosystems

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ABSTRACT

Advancements in comprehending soil erosion alleviation, relevant to both natural terrains and urban settings, have experienced notable growth in knowledge and products. Nevertheless, the increasing influence of climate change-driven forces, extreme weather events, and human-caused actions have resulted in reduced attainment of the desired results in erosion mitigation efforts. This paper aims to investigate how interlocking elements contribute to the reduction of soil erosion in natural landscapes and urban green spaces. This will be achieved by analyzing published materials, patents, installation instructions, manuals, and reports from organizations. Furthermore, we delve into novel interlocking products and emerging strategies like soft solutions and ecologically engineered blocks designed to effectively address soil erosion within vegetated habitats while enhancing the system's capacity to adapt and withstand shifts in climate, curbing soil loss, and diminishing the speed of water runoff, consequently mitigating the potential for erosion. Geotechnical engineering and other erosion control solutions like biobased interlocking components and interlocking permeable blocks offer promise in safeguarding natural landscapes and urban infrastructure from erosion-related impacts. The geotextiles market, for instance, which was valued at over $7 billion in 2022, is anticipated to experience an annual growth rate of 6.6% from 2023 to 2030. This growth can be attributed to increasing environmental concerns related to soil erosion and the rapid urbanization occurring in developing countries. However, continuous progress in the economic viability and sustainability of these techniques and products is crucial to effectively achieve erosion mitigation goals in the face of a shifting climate.

Keywords: Climate change, Erosion mitigation, Interlocking elements, Urban green space.

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1. Introduction

At the human lifespan level, soil represents a non-renewable resource that cannot be regenerated [1]. Soil erosion stands as a prominent global concern that greatly impacts both the environment and public health [2]. For instance, water-induced soil erosion impacts approximately 11 billion hectares of land globally, emerging as a pervasive and significant challenge to soil quality and quantity [3]. The implementation of soil erosion control measures contributes to the preservation of soil resources and facilitates ecological restoration efforts [4]. Researchers believe that there is a synergy between the measures for soil erosion mitigation and ensuring ecological integrity and cultural ecosystem services [5]. Water-induced soil erosion, mainly by rainfall and surface runoff, may be observed in four different types of soil loss, including splash erosion, sheet erosion, gully erosion, and rill erosion. The presence of vegetation plays a vital role in mitigating soil erosion [6] by intercepting rainfall, diminishing its force, and preventing splash erosion.

Additionally, vegetation aids in slowing down runoff, minimizing sheet erosion, and providing stability to the soil through its root system [7]. In addition to soil degradation and the subsequent decline in fertility, water erosion leads to various detrimental consequences. One of these is water pollution resulting from the release and transportation of substances. While some soil particles settle at the base of slopes, the majority is carried by water into the hydrographic network, forming a significant portion of the sediment runoff, commonly known as bed load.

The accumulation of sedimentary load contributes to siltation in both natural and man-made watercourses and constructed structures [8]. The expansion of soil erosion has been attributed to alterations in land cover and inadequate management practices during land cover transitions [9]. Commercial fertilizers and pesticides contain chemical substances that adhere to soil particles and eventually contaminate surface water and groundwater, posing a significant risk to water resources. The elevated levels of nitrogen and phosphorus present in these substances contribute to the eutrophication of numerous water reservoirs, negatively impacting their usability for a wide range of applications [8]. Soil erosion is a worldwide environmental issue that detrimentally impacts the ecosystem services, safety, and economy of urban areas. The process of urbanization, driven by the demand for additional space and addressing population growth, exacerbates natural soil erosion processes. This acceleration of erosion poses a significant challenge for modern cities, especially in the context of climate change [10]. Moreover, water-induced erosion plays a role in the process of global warming as it leads to the release of carbon dioxide (CO_2) into the atmosphere through the oxidation of soil carbon [11].

Soil erosion mitigation in both natural lands and urban areas has been investigated for a long time, and many advancements in knowledge and products have been achieved. However, climate change, extreme weather events, and anthropogenic interventions have resulted in a decline in the attainment of desired results of erosion mitigation efforts. It is crucial for every erosion and flood control method to be designed to function properly immediately after installation and to harmonize with the surrounding environment, including both natural and human habitats. Therefore, the design and materials of these systems should ensure the sustainability of the system and facilitate appropriate interaction with the local fauna and flora over the long term. A blend of inert materials and living organisms, coupled with a meticulous engineering approach, will ensure the stability of such systems amidst changing climate conditions [12]. A synergy between engineered and nature-based stormwater solutions has paved the way for a systematic approach to urban water management, allowing for the effective integration of multidisciplinary techniques and desired technological advancements. By incorporating engineered blue-green-gray stormwater systems, it becomes possible to merge urban waterways with functional vegetation, as well as geo-or bio-based filtering materials and associated technologies. This collaborative effort brings together urban planners, designers, environmental specialists, water management experts, and material experts, along with landscape designers knowledgeable in vegetation. This eco-friendly innovation represents a comprehensive system for sustainably managing the quantity and quality of urban stormwater, combating both flooding and erosion [13].

Incorporating interlocking components presents compatible structures for seamless integration with plant cover in both natural landscapes and urban green spaces, fostering a harmonious relationship between vegetation and non-living materials at a local level. Interlocking elements reinforce vegetation cover, especially on steep slopes, where the vegetation provides essential ecosystem services and serves as a valuable protective and scenic layer on the hard blocks. Ensuring long-term durability and sustainability of such integrated system necessitates the implementation of a well-engineered design that takes into account site-specific hydrological and geotechnical conditions [14].

The objective of this paper is to examine the contribution of interlocking elements in mitigating soil erosion in natural landscapes and urban green spaces by reviewing published resources, patents, installation guides, manuals, and organizational reports. Additionally, we explore innovative interlocking products and emerging techniques for managing soil erosion in vegetated areas.

2. Materials and Methods

2.1. Erosion Control Systems Using Interlocking Elements; Synergy of Engineering and Plants

Erosion control systems are essential in mitigating the damaging effects of erosion on landscapes, infrastructure, and ecosystems. In recent years, a novel approach to erosion control has gained prominence: the use of interlocking elements in combination with plants. This innovative approach harnesses the synergy between engineering techniques and the natural resilience of plants to create effective erosion control systems.

Traditional erosion control measures, such as retaining walls and riprap, have often relied solely on rigid structures and non-living materials. While these methods can be effective, they may lack the ability to adapt to changing environmental conditions and can create a harsh visual impact on the landscape. Recognizing the limitations of these traditional approaches, researchers and engineers have turned to interlocking elements and vegetation to develop more sustainable and aesthetically pleasing erosion control systems.

Interlocking elements, typically made of materials like concrete, plastic, or natural stone, are designed to fit together like puzzle pieces. These elements form a stable and interconnected framework that enhances the structural integrity of erosion control systems. By using interlocking elements, engineers can create flexible yet sturdy barriers that can withstand the forces of water flow, preventing soil erosion and sedimentation.

The synergy of engineering and plants lies in the incorporation of vegetation into the interlocking element systems. Plant roots play a vital role in stabilizing soil and preventing erosion [15]. When plants are integrated into erosion control systems, their root systems interlock with the interlocking elements, reinforcing the overall structure and enhancing its ability to resist erosion.

The benefits of combining interlocking elements and vegetation in erosion control systems are manifold. Firstly, the presence of plants adds a layer of aesthetic appeal, making these systems visually appealing and blending them harmoniously with the natural environment. Moreover, the vegetation component enhances the ecological value of the system by providing habitat for various organisms, improving biodiversity [16], and contributing to the overall health of the ecosystem. Additionally, the use of interlocking elements and vegetation allows for increased adaptability and resilience to changing environmental conditions. The interlocking structure can accommodate the natural movements of the soil, expanding and contracting without compromising stability. The plants, in turn, contribute to soil moisture regulation [17], absorb excess nutrients, and reduce the velocity of water runoff, thus minimizing erosion risk.

On the other hand, Soil erosion leads to a decrease in soil productivity and significant environmental harm due to the depletion of valuable soil resources [18]. These negative impacts are sedimentation, muddy runoff, nutrient loss, water pollution [19], soil aeration loss, and physical impacts on structures, waterways, and lands. Moreover, water-induced soil erosion plays a role in exacerbating global warming as it leads to the release of carbon dioxide (CO_2) into the atmosphere [20] through the oxidation of soil carbon [11]. The significant increase in soil erosion rates caused by rainfall and runoff, resulting from human-induced changes in land cover, has also led to the widespread mobilization of large amounts of soil organic carbon (SOC) on a global scale [21].

Water-induced soil erosion, known as raindrop splash erosion, is initiated by the impact of raindrops that dislodge soil particles. Another form of erosion, sheet erosion, involves the movement of soil particles within the shallow water flow as it drains from the land. Rill erosion takes place when flowing water becomes concentrated in small channels, while gully erosion occurs when these channels grow in size and depth. Lastly, channel erosion arises from the substantial volumes and high velocities of water flow [7]. However, the presence of vegetation plays a crucial role in mitigating soil erosion caused by rain. Vegetation intercepts rainfall, diminishing its energy and preventing splash erosion. Additionally, it effectively slows down the runoff process, minimizing sheet erosion.

Moreover, the roots of vegetation serve as anchors, reinforcing the soil and enhancing its stability [7]. The detrimental effects resulting from water-induced soil erosion processes can be categorized as either on-site damage or off-site damage [8]. The secondary consequences of erosion-related off-site damage primarily involve eutrophication of water bodies and contamination of neighboring fields [22], sediment accumulation in reservoirs and waterways [23], as well as property destruction in urban areas [8], and structural failures of dams and other structures caused by surface runoff and the transportation of suspended sediments [22]. On-site issues resulting from water-induced soil erosion include the degradation of soil's physical, chemical, and biological properties, nutrient loss, potential loss of cropland, and decreased agricultural productivity [24]. Rainfall and irrigation are the main external propellants for water erosion. For instance, A rise in precipitation by 4%–18% would result in a substantial increase in runoff by 49%–112% and soil loss by 31%–167% [25].

A variety of soil erosion control methods, such as terracing [11], [26], [27], gravel grains [2], dry and vegetated stone walls [26], [28], check dams [29], [30], lining systems, mass gravity wall systems, natural or geosynthetic fiber blankets, geogrids, and steel wire products, can be combined to create a wide range of solutions that may incorporate soil bioengineering [12]. However, Soil bioengineering is primarily employed for slopes with low to moderate risk levels of erosion. In contrast, high-risk slopes necessitate the implementation of conventional and combined engineering measures, which are considered more suitable and continue to be the preferred method for slope stabilization [15]. In addition, any erosion protection systems, regardless of their nature or type, must be specifically designed to function effectively immediately upon installation. For instance, the efficacy of a soil bioengineering technique in terms of hydraulics relies on the growth of vegetation, which is initially minimal upon installation but gradually improves over time [31]. These systems should possess the capability to seamlessly integrate with the surrounding environment, ensuring flawless harmony is achieved [12]. Fig. 1 demonstrates that incorporating vegetation cover into lining systems substantially enhances surface stability, offering an efficient approach to erosion control (Fig. 1).

Soil bioengineering techniques are commonly integrated into heavy duty linings and rolled erosion control systems. Heavy duty linings (hard armor systems) comprise systems such as articulated concrete blocks (ACBs), gabions, rock mattresses, rip rap, and so on, while rolled erosion control systems (light systems) encompass erosion control blankets (ECBs) [32], turf reinforcement mats (TRMs) [33]–[35], flow transition mats [29], geocells, and other similar solutions [12], [29].

Further to the discussed erosion and flooding control systems, engineered blue-green-gray systems refer to integrated infrastructure designs that combine natural and engineered elements to manage stormwater effectively in urban environments. These systems incorporate features such as green spaces, vegetation, water bodies, permeable surfaces, and filtration technologies to mitigate soil erosion and flooding, enhance water quality, and promote sustainable urban water management. More specifically, implementing these systems can bolster the resilience of urban areas against the impacts of extreme weather events and climate change [13]. For example, permeable interlocking concrete pavers (PICP) demonstrated the highest effectiveness in reducing rainwater runoff, achieving a significant reduction of 46% [36]. In addition, findings from an experimental study revealed that the PICP herringbone pattern outperformed the stretcher pattern. The herringbone pattern exhibited a slightly higher skid resistance value and a greater infiltration rate, which is particularly crucial during heavy rainfall events [37]. Interlocking concrete blocks, on the other hand, performed considerable runoff infiltration and purification and soil stabilization on a loose sand layer via increasing permeability on the system up to 30% [38].

Researchers revealed synergies between soil erosion mitigation measures and ecological integrity and other ecosystem services like landscape values [10], regulating services, and provisioning services [5], [22]. Therefore, erosion control systems utilizing interlocking elements and incorporating plants represent a promising approach that combines the strengths of engineering and nature. By harnessing the stability of interlocking structures and the protective properties of plants, these systems offer effective

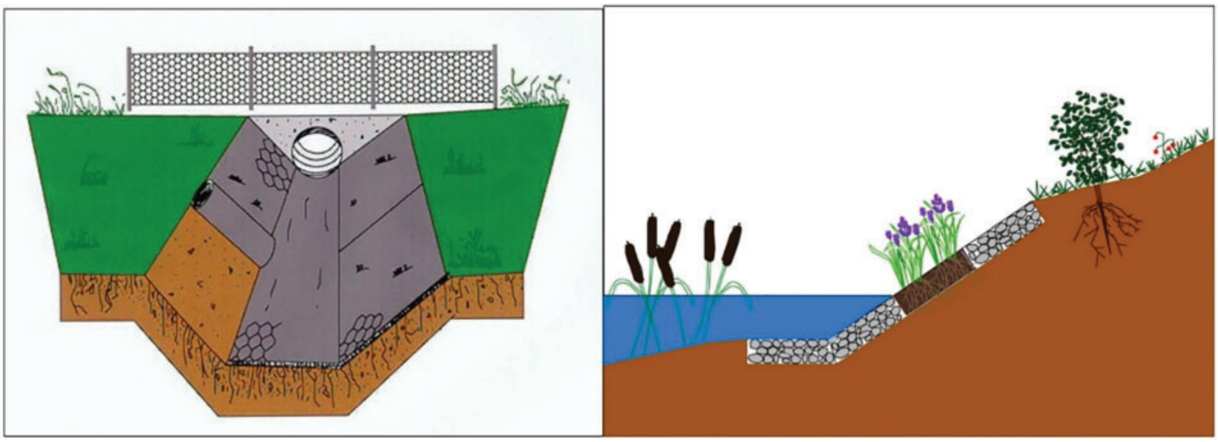

Fig. 1. Common approaches involving lining systems, adapted from [12].

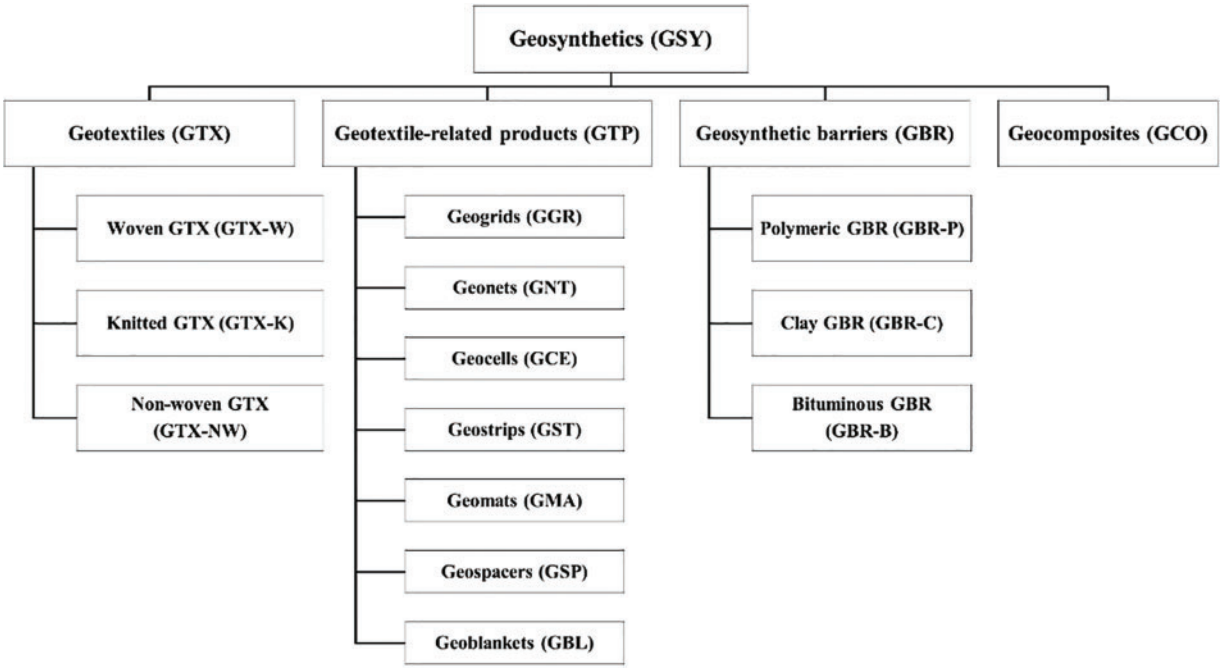

Fig. 2. Classifications and sub-classifications of geosynthetics, modified after [45].

erosion control, aesthetic integration with the environment, ecological benefits, and adaptability to changing conditions. This synergistic approach represents a significant step forward in sustainable and environmentally conscious erosion control practices in natural areas and urban green spaces.

2.2. *Geotechnical Engineering in Soil Erosion Mitigation*

Geotechnical engineering plays a crucial role in mitigating soil erosion, a pressing environmental issue that poses significant challenges worldwide. Geotechnical engineering offers effective solutions to combat soil erosion by employing various techniques aimed at stabilizing soil surfaces, controlling runoff [28], and managing sediment transport. These techniques leverage the principles of soil mechanics, hydraulics, geology, and ecology to develop erosion control measures that minimize the erosive impact of water and promote sustainable land management practices. Geotechnical engineers work in collaboration with hydrologists, environmental scientists, and other professionals to analyze soil properties, hydraulic conditions, and catchment characteristics to develop effective erosion control strategies.

A range of geotechnical techniques can be employed to mitigate water-induced soil erosion. These include the construction of erosion control structures [39], implementation of surface water management systems, establishment of vegetation cover [40], and utilization of erosion-resistant materials. Establishing vegetation cover through techniques like reforestation, grass seeding [41], and erosion control blankets helps stabilize soil surfaces, enhance infiltration, and reduce the erosive impact of rainfall and flowing water [42]. Erosion-resistant materials, such as geosynthetics and erosion control mats, provide a protective layer that prevents soil displacement and erosion [43]. The category of geosynthetics (Fig. 2) encompasses various types, such as geotextiles, geomembranes, geogrids, geosynthetic clay liners (GCLs), geofoams, geonets, geocells, geobags, and geocomposites [44].

Geosynthetics offer flexibility and environmental compatibility while facilitating the growth of vegetation and enhancing the long-term resilience of grass covers against

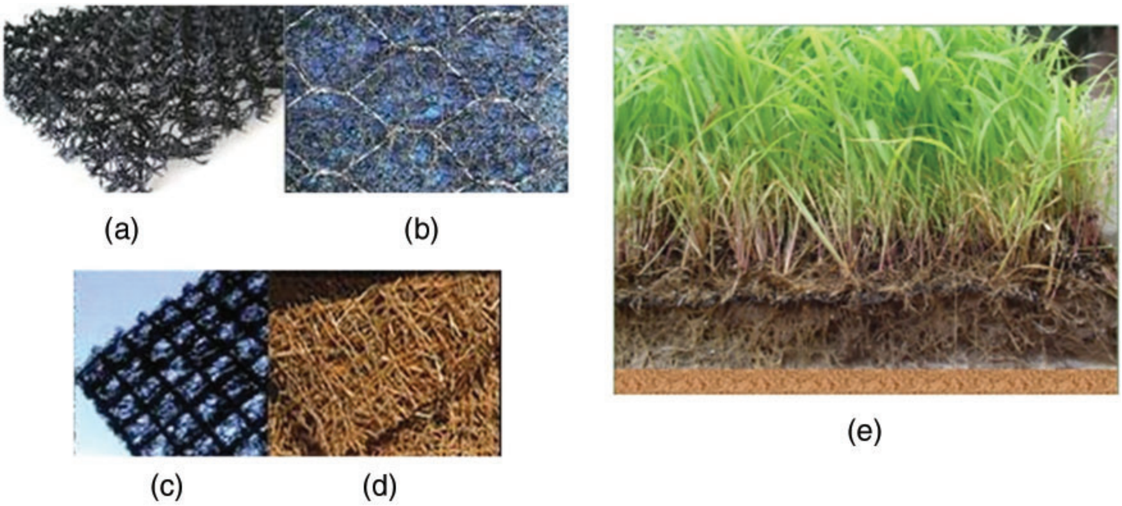

Fig. 3. Illustrations of geosynthetics employed in erosion control: (a) geomat, (b) steel mesh reinforced geomat, (c) geogrid reinforced geomat, (d) geoblanket and (e) subsequent vegetation growth, adopted from Rimoldi *et al*. [46].

Fig. 4. Methods for eco-engineered shorelines (a) hard, (b) hybrid, and (c) soft, adapted from Morris *et al*. [51].

hydraulic loads caused by floods and water flow [46]. By reinforcing the root zone of the grass (Fig. 3), geosynthetics help protect against the initiation of concentrated erosion that can lead to head-cut development and breaches during overtopping flow. In the case of higher flow rates, the presence of vegetation can delay breaches, allowing ample time for downstream areas to be evacuated [46], [47]. The reinforced grass exhibits considerably greater resistance to prolonged flow velocities compared to unreinforced grass. Furthermore, the presence of vegetation reinforcement extends the time before failure occurs. Typically, a robust grass cover can withstand flow velocities of 4.5 ms^{-1}, 3.2 ms^{-1}, and 2.8 ms^{-1} for durations of 1 hour, 5 hours, and 10 hours, respectively. However, when the grass is reinforced with a 20 mm thick TRM, these velocities typically increase to 6.0 ms^{-1}, 5.5 ms^{-1}, and 5.0 ms^{-1} [48].

Therefore, geotechnical engineering contributes to the development of sustainable erosion control measures that protect soil resources, preserve water quality, and foster long-term environmental sustainability. The application of these techniques plays a vital role in promoting resilient landscapes and ensuring the preservation of ecosystems and critical infrastructure [49]. For instance, retaining walls are introduced as a protective measure for slope repair in natural and urban areas [50]. From another perspective, eco-engineered solutions are categorized into three kinds: hard (e.g., modified ACBs), Hybrid (e.g., rock sill with saltmarsh), and soft (e.g., restored oyster reefs using oyster mats and interlocked bagged shell oyster reef for saltmarsh vegetation protection) eco-engineering [51] (Fig. 4).

Urban spaces, coastal regions, slopes, and riverbanks are prone to significant degradation due to erosion, particularly when there is insufficient vegetation. The fundamental approach to managing soil erosion involves preventing or minimizing the displacement of soil caused by erosive agents like water. The incorporation of geotechnical techniques in erosion and sediment control systems has presented substantial benefits, whether used independently or in combination with traditional natural materials. Geotextiles, when placed on the soil surface, contribute to surface stabilization by restraining movement and preventing the dispersion of soil particles susceptible to erosion caused by rainfall or running water [32]. Moreover, these geotextiles can also facilitate or enhance vegetative growth. The implementation of geotextiles actively manages soil displacement to control erosion, while sediment control or retention involves the capture and filtration of eroded soil that is transported by runoff. Consequently, innovative geotextile materials have been developed with the objective of revegetating barren soil or providing support for vegetation in soil prone to erosion. These materials serve as long-term, non-biodegradable support, as well as temporary, biodegradable support for newly planted seedlings [49]. Moreover, the combination of a hybrid habitat consisting of reno mattresses and eelgrass brings together the advantages of both components within

Fig. 5. ECO block samples: (A) Untested and brand new, (B) after enduring 75 freeze-thaw cycles for extreme weather conditions applications, (C) after being submerged for six months, adopted from Sella *et al*. [53].

a system. While complex artificial structures like reno mattresses offer habitat for aquatics and invertebrates, it is crucial to complement their use with natural vegetation to obtain more erosion mitigation [52].

Besides, the integration of ecological design, encompassing concrete composition, texture, and overall design, synergistically contributed to the enhanced capabilities of the ecologically engineered articulated concrete block mattresses (ECO ACBMs). Following a two-year monitoring period, notable ecological improvements were observed on the ECO ACBMs. Consequently, the adoption of Nature-Inclusive Design (NID) holds the potential to encourage a more sustainable and adaptable approach to the development of urban and coastal areas. The incorporation of a biological layer into ACBMs has the potential to extend their expected lifespan, decrease maintenance requirements, and enhance structural stability while effectively absorbing hydrodynamic forces [53]. More specifically, minor adjustments made to the ACBM, such as incorporating grooved and rough surfaces, result in enhanced habitat quality for macroinvertebrates (Fig. 5), which play a significant role in the diet and growth of recreational and ecologically valuable plants and animals [54]. The ACBMs offer a cost-effective alternative to traditional riprap, resulting in approximately 50% cost savings. The current price range for ACBMs is estimated at $10 to $18 per square foot of area [55].

2.3. Biobased Interlocking Elements: Role of Nature to Protect Ecosystems

Biobased interlocking elements play a crucial role in utilizing nature to protect ecosystems. These elements, made from organic materials, provide innovative solutions for ecological preservation and erosion prevention. By incorporating natural processes and materials, such as plants and organic structures, they contribute to the sustainability and resilience of ecosystems [56] in both natural areas and urban green spaces. Biobased interlocking elements help mitigate the negative impacts of human activities, promote biodiversity, enhance water management [57], and create habitats for various species. Their use highlights the importance of integrating nature's principles into design and construction practices to foster the protection and restoration of ecosystems. Moreover, this approach offers a financially feasible opportunity for generating income (for marginal farmers) and ensuring food security while also contributing to slope stabilization in the highland region [58]. The incorporation of vegetation and biobased elements in ecological restoration and erosion mitigation of constructed sites (e.g., roads) demonstrated a satisfactory level of efficacy and cost-effectiveness, making it a valuable technique for developing countries [56]. For instance, a robust vegetation cover emerges as a critical factor in enhancing infiltration and mitigating runoff, while the integrated geogrid exhibited consistently low erosion rates in a steep slope (0.6 g m^{-2} at 45° slope) [59]. However, in addition to their fundamental functions, geosynthetics (e.g., geotextiles, geocomposites, geogrids, geobags, geomats, and geocells) can fulfill additional roles including containment, absorption, surface stabilization, and vegetation reinforcement [60].

The utilization of erosion control matts on topsoil has the potential to decrease soil water evaporation, preserve soil moisture, and moderate soil temperature fluctuations. Consequently, it creates favorable soil conditions for vegetation establishment and growth [61]. In other words, these erosion control elements foster a favorable microclimate that enhances vegetation growth and development [62].

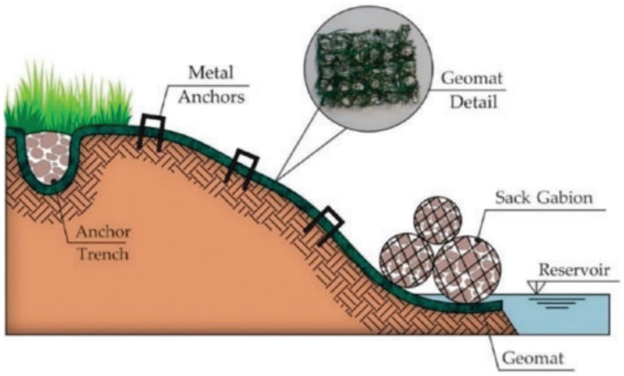

Fig. 6. Schematic representation of erosion control techniques utilizing geomats and sack gabions, depicting their arrangement and setup, adapted from da Luz *et al*. [57].

The geotextile minimizes sediment deposits [58] and contributes to the rapid growth of the seeded plants, resulting in a well-developed vegetation cover. The restoration of vegetation on steep slopes can mitigate adverse impacts, particularly during the early stages of construction sites like roads and railways (Fig. 6). The successful reestablishment of vegetation can enhance the visual appeal of the road environment, contributing to its natural aesthetics [56]. The application of geotextile on mine site reclamation programs proved an acceptable capability for these elements in water-induced soil erosion/sediment mitigation. The installation and seeding of the geotextiles by the end of the dry season showed a significant reduction in soil loss rate by 56.6%–97.3% through the absorption of rain and concentrated runoff flows. The correlation between the effectiveness of the biological geotextiles in minimizing soil loss and the geotextile's percentage cover and flexibility was direct and apparent [63]. In addition, Pineapple Leaf Fiber (PALF) geotextile with a water absorption capacity of 163% decreased the sedimentation rate to 21.44 g m^{-2} per hectare, effectively inhibiting substantial mass runoff flow from the topsoil during heavy rain [64].

Furthermore, the low biodegradation rate of geotextiles not only protects the vegetation cover during the initial establishment of plants or grass against erosion forces but also, as the biodegradation process occurs, releases nitrogen-rich organic compounds from the geotextiles into the soil, acting as potent fertilizers that stimulate the growth of the vegetation cover [65], [66]. Consequently, the thriving vegetation on the bank (e.g., ditches, roads, and slopes) provides effective protection and assumes the role previously fulfilled by the integrated geotextiles [65]. The integration between geotextiles and vegetation cover enhances the erosion mitigation capacity of vegetation cover even in heavy rainfall events at steep slopes. The vegetation cover without geotextile performed a soil loss reduction effectiveness (SLRE) of 39.6% at more than 60% slope, while the integration of geotextiles and vegetation scaled up the SLRE to 75%–98% [67]. However, certain geotextiles may experience a reduction in tensile strength in high humidity conditions, necessitating the use of fast-growing vegetation specifically tailored for such erosion control elements [68], [69]. The proper utilization of geotextiles in conjunction with native and non-invasive plant species offers a practical approach to enhance total soil organic carbon (SOC) and soil microbial biomass carbon (SMB-C), as well as enriching nutrient levels such as nitrogen and phosphorus while simultaneously promoting the growth of microbial populations [70].

On the other hand, geotextiles exhibit exceptional water retention capacity and resistance to scouring [71]. During heavy rainfall, they can achieve a maximum water content of 227%, effectively reducing soil temperature and increasing moisture levels during the summer season, where the vegetation cover and biomass of the geotextile-treated group were 3.9 times and 4.1 times higher, respectively, compared to the control group [72]. Besides, the application of geotextiles in soil conservation in temperate climates revealed a great reduction in soil loss (0.09 tons per hectare of sediment yield per year), while the adjacent bare land showed 0.45–14 tons per hectare [73], [74]. Nevertheless, certain geotextiles exhibit a detrimental effect on runoff flow during intense rainfall events, leading to an 8%–16% increase in runoff discharge [74]. This negative impact is correlated with the nature of the geotextiles or due to the addition of some stabilizers to erosion control elements like earth bricks [75].

2.4. Permeable Pavements for Erosion and Runoff Control

Interlocking permeable pavements serve as effective solutions for erosion and runoff control. These pavements feature interlocking units with porous surfaces, allowing water to permeate through the pavement and infiltrate into the ground. By reducing surface runoff, interlocking permeable pavements help minimize erosion and alleviate the burden on stormwater systems. The interlocking design enhances stability and load-bearing capacity, making them suitable for various applications such as driveways, walkways, and patios. Additionally, these pavements contribute to environmental sustainability by promoting natural water filtration, groundwater recharge [76], pollutant removal, and vegetation cover stability [77]. With their functional and aesthetically pleasing design, interlocking permeable pavements offer a durable and eco-friendly solution for erosion and runoff control (Fig. 7). These permeable pavement systems (PPSs) offer possibilities for addressing the effects of urbanization on receiving water systems by enabling on-site treatment and management of stormwater. These systems enhance the quality of stormwater by decreasing stormwater temperature and reducing pollutant concentrations and loadings of suspended solids, heavy metals, polyaromatic hydrocarbons, as well as certain nutrients even in cold climates [78].

Permeable surfaces and rooting soils go beyond mere additions to urban areas; they offer a fresh approach to urban construction. By incorporating natural functions into the built environment, these elements infuse life into the typically rigid urban landscapes intended for human activity [77]. For instance, rain gardens are excavated sections of land adorned with grasses and perennial flowers within the landscape. The gardens serve as a collection point for rainwater originating from roofs, driveways, or sidewalks, enabling the water to infiltrate the surrounding soil [80], introducing biodiversity to urban

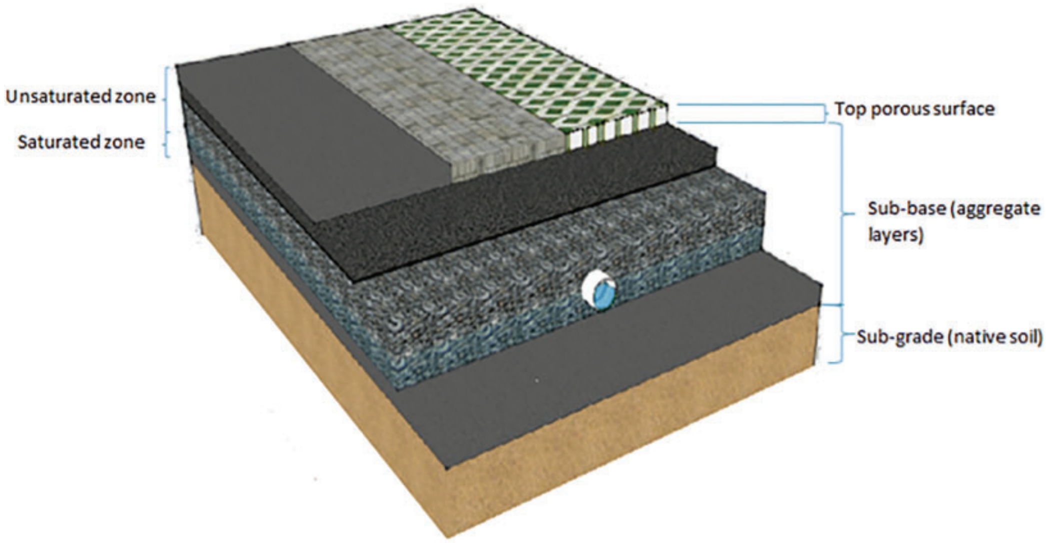

Fig. 7. A common eco-friendly PPSs profile, adapted from Kuruppu *et al*. [79].

spaces, revitalizing them, and prolonging the treatment and restoration of excess stormwater. In essence, permeable surfaces and rooting soils provide a transformative outlook on urban structures, blending nature's functions to enhance stormwater management [77].

From pollutant removal point of view, although permeable surfaces (like permeable interlocking concrete pavement (PICP)) are effective in removing ammonia-nitrogen and orthophosphate-phosphorus, removal efficiency of nitrite-nitrogen and nitrate-nitrogen needs to be improved [81]–[83]. However, the average removal efficiency of grass paving interlocking concrete block pavement (porous pavement) compared to impermeable pavement surfaces are as follows: total phosphorus (52%–60%), nitrites (60%–65%), nitrates (60%–65%), total suspended solids (92%–95%) [84]. Furthermore, the effectiveness of permeable pavement systems in eliminating microbial content of runoff, such as total coliforms, *E. coli*, and fecal Streptococci, was found to reach as high as 99% [82]. The infiltration rate and pollutant removal rate are also influenced by the thickness of bedding sands and the sub-base gravels in a permeable system, where the optimal thickness of bedding sands (5 cm) and sub-base gravels (20 cm–30 cm) can lead to a removal rate of 79.8%–98.6% for suspended solids and 72.2% for total phosphorus of stormwater [85].

The efficiency of pollutant removal from stormwater by grass paving interlocking concrete block pavement reaches higher levels after a while, as planting soil and additives (like organic materials) have negative impacts on the removal efficiency [84]. These findings indicate that both the specific type of permeable pavement, incorporated vegetation and the underlying media play a crucial role in influencing runoff reduction and infiltration in different climate conditions [86]. Researchers believe that optimal infiltration performance of PICP sites can be achieved by situating the system above sandy in situ soils, designing it with a spacious storage capacity, and ensuring a fines-free surface [87]. They also believe that the hydraulic performance of modular forms of permeable pavement systems (PPSs; interlocking concrete paving systems and grid systems) surpasses that of monolithic forms (porous asphalt and porous concrete), thanks to the voids present between the pavers, while PPSs in monolithic forms are prone to easy clogging [79], [88]. In addition to this, the extremely severe winter weather conditions cause the PPSs to transform into impermeable slabs in the short term [89]. Overall, the ability of a permeable pavement to sustain its high surface infiltration performance throughout its lifespan is crucial for ensuring all the significant environmental advantages it offers. The high infiltration performance relies on two essential necessities: careful design and selection of materials for each layer to ensure sufficient drainage properties [90], and regular maintenance and monitoring to ensure that all layers maintain effective drainage properties [91], thus delivering satisfactory infiltration performance during time [92]. For instance, regenerative air and vacuum trucks partially restore surface permeability, resulting in improved surface infiltration for approximately 50% of the cleaned surfaces right after maintenance [93].

The high infiltration performance would also result in the enhancement of both the volume and quality of streamflow in natural and urban areas, while it is influenced by the development situations and land cover texture, which varies based on the population growth of each sub-watershed [94]. Therefore, permeable pavements help alleviate the effects of urbanization on surface waters by reducing pollutant loads. This is achieved through the sequestration of pollutants and the reduction of stormwater volume through exfiltration. The hydrologic and water quality performance of permeable pavements is mainly influenced by the loading ratio (LR) of pollutants, microbes, and sediments [95]. Additionally, the surrounding land use types impact the durability and effective functioning of the permeable elements' performance [96].

From an urban climate perspective, it was found that grass interlocking pavers significantly enhance evaporation rates, surpassing previous concrete pavements by more than 243% due to the transpiration effect of the vegetation cover. Conventional concrete or stone pavers, which are directly exposed to solar energy [97], have a detrimental impact on the local climate of neighborhoods, particularly during the summer season. Evapotranspiration acts as a mitigating factor for the urban heat island, reducing the impact of heat waves, and also serves as a proxy for measuring vegetation water use in green cities [98]. Hence, the advancement of grass pavers could effectively tackle some of the escalating concerns related to urban climate in the era of climate change. In addition, the incorporation of recycled materials in the production of eco-friendly permeable pavements has demonstrated significant environmental advantages when contrasted with conventional PPSs in the construction and built environment sectors [99]. Moreover, the utilization of waste recycling materials such as sawdust and laterite in interlocking paving units plays a crucial role in reducing the environmental impact of the concrete construction industry. Additionally, it leads to substantial cost savings in the construction of PPSs. As an illustration, a cost reduction of 10.1% per m^3 of concrete was attained by employing a combined 10% optimal sawdust replacement for cement and 10% laterite partial replacement for sand in an interlocking pavement system [100].

2.5. *Riprap Placements; Ecological Consequences and Alternative Elements*

In constructed and natural areas, riprap placements, which involve the use of large stones, rocks, or concrete blocks for waterways protection and erosion control, can have significant ecological consequences. Although riprap shields the soil from erosion in regions characterized by strong or concentrated water currents, specifically when it comes to fortifying the banks of channels and ditches [101], the installation of riprap in all terrestrial/aquatic ecosystems often involves altering natural habitats, disrupting aquatic ecosystems, and impeding the movement of wildlife. This can lead to a loss of biodiversity and ecological functionality. Nonetheless, within specific natural aquatic settings, the stacking of large boulders results in notable gaps or "pore" spaces. Strikingly, engineers have revealed that these voids exert a significant influence on the structure's stability [102], while concurrently serving as crucial habitats for benthic organisms. This underscores the substantial biological impact of pore spaces in such environments [103]. However, in appropriate situations, it is worth contemplating the utilization of spurs (also referred to as groins) as a viable substitute for continuous riprap in order to enhance the stability of a river. These structures aid in preserving a predominantly natural riparian zone while simultaneously establishing unique aquatic habitats in both their upstream and downstream areas [104]. On the other hand, by integrating toe supports with preexisting riprap structures in steep slopes and banks, a substantial improvement in the overall stability of the ripraps can be achieved, particularly when facing overtopping conditions [105]. In undegraded areas, particularly in remote regions, it is recommended to consider the adoption of soft stabilization techniques. These methods involve actions such as planting native species or incorporating embedded plant-based elements to enhance stability [104]. The careful selection and strategic combination of plant species play a vital role in effectively reducing soil erosion and controlling the flow rate of runoff. One specific example is the synergistic pairing of Ruzi and Vetiver grasses (from Poaceae family) with lateritic soil, which has been shown to yield optimal results in terms of runoff rate and soil loss, particularly on slopes up to 33% [106].

Additional alternatives to traditional riprap include rolled erosion control products (RECP), geocells, precast concrete products (PCCPs) [107], geobarrier systems (GBS) [108], ECO ACBMs [53], and A-Jack interlocking armors. The interlocking A-Jacks offer several advantages that enhance the stability of the armor, especially in specific hydraulic conditions. These benefits include their suitability for regions with limited riprap resources and the potential for vegetation growth between the blocks [109]. In addition, noteworthy ecological improvements were observed with the use of ECO ACBMs, particularly in terms of increased species richness and diversity values [53]. RECP, comprising TRMs, high-performance TRM, and ECBs, serve the purpose of establishing onsite vegetation. Subsequently, the vegetation cover plays a crucial role in continuing the mitigation of erosion [107]. PCCPs encompass tri-lock concrete blocks, ACBMs, and three-dimensional concrete units. Among the alternatives, PCCPs show great potential in replacing large class riprap due to their superior durability compared to RECP or geocells [107]. Each of the traditional riprap alternatives presents both advantages and limitations. However, these alternatives frequently offer additional benefits, such as facilitating vegetation growth within the revetment system, reducing greenhouse gas (GHG) emissions, and providing a safer installation process [107].

To address these ecological consequences, alternative elements and approaches are being explored. Bioengineering techniques, such as the use of vegetated slopes, living shoreline projects, and biodegradable erosion control materials, are gaining attention. These techniques aim to provide erosion control while promoting habitat creation, water filtration, and improved aesthetics. By incorporating natural elements and organic materials, they can help restore ecological balance and enhance biodiversity. One notable example is the utilization of geotextiles, particularly on slopes with low to medium gradients (up to 15%). These materials have proven to be highly effective in enhancing infiltration rates, reducing inter-rill run-off, and minimizing erosion rates [110].

Other alternatives to riprap in urban areas include the use of green infrastructure practices, such as constructed wetlands, rain gardens, and permeable pavements. These approaches not only provide erosion control but also offer additional benefits such as stormwater management, improved water quality, and urban heat island mitigation. They can contribute to creating more sustainable and resilient urban environments. Hence, the ecological consequences of riprap placements can be significant. However, alternative elements and approaches, such as bioengineering techniques and green infrastructure practices, offer promising solutions to mitigate these consequences and promote ecologically sustainable urban development.

2.6. *Patents, Advancements, and Installation Guides*

In recent years, there have been significant advancements in the development and implementation of interlocking elements to control erosion, particularly in the field of civil engineering and environmental conservation. Erosion poses a serious threat to landscapes, infrastructure, and ecosystems, making effective erosion control methods essential.

Interlocking elements are designed to stabilize soil and prevent erosion by using materials that lock together, creating a cohesive and resilient structure. These advancements have proven to be more sustainable, cost-effective, and environmentally friendly than traditional erosion control measures.

One major innovation is the use of geosynthetic materials, such as geotextiles and geogrids, which are synthetic fabrics or grids made from durable polymers. These materials offer high tensile strength and resistance to degradation, enabling them to withstand erosive forces while promoting vegetation growth. Additionally, they are lightweight, easy to install, and adaptable to various terrains, enhancing their widespread application.

Another significant development involves the integration of natural interlocking elements, like interlocking concrete blocks, gabions, and vegetation-based solutions, into erosion control strategies. These methods work in harmony with the environment, allowing for better integration into landscapes and ecosystems. Vegetation, for example, acts as a natural erosion deterrent by stabilizing soil with its root systems and reducing surface runoff.

Advancements in technology have also played a role in improving erosion control. Computer modeling and simulation tools enable engineers and environmentalists to analyze erosion patterns and design more effective interlocking systems based on specific site conditions. This data-driven approach enhances the precision and efficiency of erosion control efforts [111]–[113].

More specifically, patents and progress in this area have focused on novel designs and materials for interlocking elements. Some patents describe intricate patterns or shapes that maximize interlocking capabilities, enhancing overall stability, while others explore the use of environmentally friendly materials, such as recycled plastics [114] or bio-based composites [115], to promote sustainability and reduce the ecological impact of erosion control measures. As an illustration, a patented erosion control item is employed in the USA, utilizing recycled plastic bottles made of High-Density Polyethylene (HDPE). This product effectively functions on slopes with angles ranging from 10 to 45 degrees and offers effortless assembly. To establish a robust plant root system, it is recommended to use the product at an ideal plantation rate of 50%–70% for soil erosion control [114]. Yet another product available is the employment of HDPE grids designed to facilitate slope stabilization and minimize soil erosion. These grids consist of hexagonal cells with permeable sides, function as a sequence of check dams, effectively dissipating the energy of rapidly flowing water [116], also enabling water and plant roots to pass through, thereby enhancing the overall interlocking and infiltration capability of the grid. This versatile product is well-suited for mitigating soil erosion and controlling runoff in various settings, such as natural areas, urban slopes, landscapes, embankments, shorelines, and channels [117], [118]. Moreover, another innovation presented a block design that incorporates mold for creating the interlocked structure. The mold is adaptable for on-site use during block fabrication and permanently becomes an integral part of the block. The block is manufactured as a unified piece, featuring openings that extend from its top surface to the bottom, formed as an extension of the mold, achieving interlocking through the utilization of plastic sockets [119]. Erosion control mat, on the other hand, acts as a ballast and soil confinement. The invented product absorbs the impact of high waves and concentrated water flow. The mat is made of a non-buoyant, heavy, and flexible material with pores allowing water inflow and vegetation growth. It can also serve as ballast for underlying erosion control materials. The mat has a modular design, with interlocking square or rectangular panels featuring connection elements, enabling them to form a checkerboard pattern. Some panels may have beveled edges to improve water flow [120].

Certain organizations have established suitable assessment procedures to offer a structure for creating, building, operating, and upkeeping environmentally sustainable and energy-efficient initiatives. LEED (Leadership in Energy and Environmental Design), for example, is a globally recognized green building certification program developed by the United States Green Building Council (USGBC) to evaluate various aspects of a building's performance, including energy efficiency, water usage, indoor environmental quality, materials selection [121], and sustainable site development. Among all the LEED credits, 35% are associated with climate change, 20% have a direct impact on human health, 15% influence water resources, 10% affect biodiversity, 10% pertain to the green economy, and the remaining 5% impact community and natural resources [122]. Of all LEED elements, sustainable sites, materials/Resources, and possibly innovation in design and regional priority credits hold significant importance in the assessment of soil erosion control projects [14]. In addition, organizations such as the Minnesota Pollution Control Agency (MPCA) and the Erosion Control Technology Council (ECTC) have established standard specifications for erosion control methods and products (Table I), aiming to ensure the implementation of the most effective erosion prevention practices [123], [124]. For instance, ECBs that incorporate vegetation cover were classified into four groups based on their design and fabrication. These groups include ultra short-term, short-term, extended-term, and long-term, each with functional lifespans of 3, 12, 24, and 36 months, respectively [124].

According to other manuals, the responsibility lies with the designer to choose Best Management Practices (BMPs) for erosion control plans [125] that are suitable for the specific site conditions [126] and can be divided into three main categories of erosion management, sediment management, and runoff redirection [127]. When evaluating BMPs, ACB systems stand out as a superior choice compared to other erosion control methods like cast-in-place concrete bulkheads, slope paving, gabions, soil cement, roller-compacted concrete, or rock riprap. The key advantage of ACB systems lies in their ability to support the ecosystem's habitat while delivering serviceability, aesthetics, pedestrian safety, sustainability, cost-effectiveness, and

TABLE I: ECTC Standard Specifications for ECBs and Mulch Control Nets, Modified after Refs. [123], [124]

Product type and description	Material composition	Maximum gradient (H:V)	C factor	Minimum tensile strength (kN/m^2)
1. Ultra Short-Term; lifespan of 3 months				
1.1. Mulch control nets	Photodegradable synthetic mesh/woven biodegradable natural fiber netting.	5:1	<0.10	0.073
1.2. Netless rolled ECBs	Natural or polymer fibers mechanically interlocked/chemically adhered to form a RECP.	4:1	<0.10	0.073
1.3. Single-net ECBs/Open weave textiles	Processed degradable natural or polymer fibers mechanically bound together by a single rapidly degrading, synthetic, or natural fiber netting/open weave textile of processed rapidly degrading natural or polymer yarns.	3:1	<0.15	0.73
1.4. Double-net ECBs	Processed degradable natural or polymer fibers mechanically bound together between two rapidly degrading fiber nettings.	2:1	<0.20	1.09
2. Short-Term; lifespan of 12 months				
2.1. Mulch control nets	Photodegradable synthetic mesh/woven biodegradable natural fiber netting.	5:1	<0.10	0.073
2.2. Netless rolled ECBs	Natural or polymer fibers mechanically interlocked/chemically adhered to form a RECP.	4:1	<0.10	0.073
2.3. Single-net ECBs/Open weave textiles	An ECB composed of processed degradable natural, or polymer fibers mechanically bound together by a single degradable synthetic or natural fiber netting to form a continuous matrix/open weave textile composed of processed degradable natural or polymer yarns.	3:1	<0.15	0.73
2.4. Double-net ECBs	Processed degradable natural or polymer fibers mechanically bound together between two degradable, synthetic, or natural fiber nettings.	2:1	<0.20	1.09
3. Extended-Term; lifespan of 24 months				
3.1. Mulch control nets	Slow degrading synthetic mesh or woven natural fiber netting.	5:1	<0.10	0.36
3.2. ECBs/Open weave textiles	An ECB composed of processed slow degrading natural, or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix/an open weave textile composed of processed slow degrading natural or polymer yarns.	1.5:1	<0.25	1.45
4. Long-Term; lifespan of 36 months				
4.1. ECBs/Open weave textiles	An ECB composed of processed slow degrading natural, or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix/an open weave textile composed of processed slow degrading natural or polymer yarns.	1:1	<0.25	1.82

flexibility [14]. ACB systems offer permanent solutions and allow for rapid and straightforward installation, making them highly suitable even for large-scale erosion control projects [128].

Furthermore, community awareness and collaborative efforts have led to the development of erosion control guidelines and best practices. By combining the expertise of engineers, scientists, and local stakeholders, comprehensive erosion management plans can be implemented, addressing both short-term and long-term erosion challenges.

Therefore, advancements in interlocking elements for erosion control have changed the way we approach landscape protection and environmental conservation. By embracing innovative materials, natural solutions, technological tools, and community engagement, erosion mitigation efforts have become more effective, sustainable, and tailored to the needs of each unique landscape. These advancements offer hope for preserving our natural resources and safeguarding our infrastructure from the damaging effects of erosion.

3. Results and Discussion

In the quest to mitigate erosion across the diverse landscapes of both natural and urban ecosystems, the exploration of interlocking elements has revealed a nuanced and integrated approach that blends scientific ingenuity with ecological resilience. This article has comprehensively reviewed various dimensions of erosion control strategies, highlighting the harmonious interplay between engineering methodologies and the innate mechanisms of plant-based systems.

The synthesis of engineering and botanical prowess, as showcased in erosion control systems employing interlocking elements, underscores the potential of interdisciplinary collaboration in addressing complex environmental challenges. Geotechnical engineering, a cornerstone of erosion control, has demonstrated its efficacy in stabilizing soil and mitigating erosive forces. By systematically analyzing the intricate relationship between soil properties and engineering interventions, practitioners can develop tailored solutions that optimize erosion control efforts while minimizing ecological disruptions.

Biobased interlocking elements have emerged as exemplars of nature-inspired solutions that harness the intrinsic strengths of plant life to protect ecosystems. The symbiotic relationship between vegetation and soil stability is a testament to the evolution of natural systems, offering valuable insights for the design and implementation of erosion control measures. The utilization of native plant species not only enhances erosion resistance but also fosters biodiversity, thereby aligning conservation objectives with sustainable engineering practices.

Within urban contexts, permeable pavements have emerged as pioneering innovations that simultaneously address erosion and runoff concerns. These systems exemplify the integration of hydraulic principles and material science, offering a promising avenue for sustainable urban development. However, our exploration of riprap placements has underscored the need for critical evaluation of conventional practices, prompting consideration of alternative elements that mitigate ecological repercussions while preserving erosion control efficacy.

In the landscape of intellectual property, patents, advancements, and installation guides serve as conduits for the dissemination of knowledge and innovation. As evidenced by ongoing developments in erosion control techniques, the accumulation of intellectual capital contributes to an evolving body of best practices and technological refinements. These resources empower professionals to navigate the complex terrain of erosion control, fostering a culture of continuous improvement and adaptive management. These developments provide optimism in the conservation of our natural resources and the protection of our infrastructure against the detrimental impacts of erosion, particularly in the age of climate variability.

In conclusion, the multifaceted investigation into interlocking elements for erosion control in natural and urban ecosystems traverses a continuum from theory to application, from engineering marvels to ecological mindfulness. The interplay between disciplines, methodologies, and ecosystems that this article elucidates underscores the imperative of adopting a holistic, multidimensional approach to tackle erosion challenges. The path forward necessitates a concerted commitment to interdisciplinary research, ethical engineering, and adaptive implementation to unravel the complexities of erosion, ensuring the sustenance of our intricate ecosystems for generations to come. Moreover, it guarantees the long-term viability of urban green areas while assisting in the control of runoff and erosion within city environments. All the methods reviewed in this study require further advancements in economic efficiency to be more economically viable at all scales (ranging from large-scale projects to small private residences), providing economic benefits for users and appealing to managers and environmental enthusiasts interested in conservation. The geotextiles market, for example, achieved a valuation of $7.10 billion in the year 2022 and is positioned for future expansion, with an estimated compound annual growth rate (CAGR) of 6.6% projected from 2023 to 2030. This anticipated growth is primarily driven by the escalating pace of urbanization and industrialization in developing regions, leading to a surge in civil engineering projects. Moreover, the cost-effectiveness and extended durability of geotextiles, in contrast to alternative materials, coupled with growing concerns regarding soil degradation, are expected to stimulate global demand for this product. Within the United States, the adoption of geotextiles is on the upswing across a diverse range of construction applications, including the construction of drainage systems, harbor infrastructure, road developments, and landfills, all designed to enhance soil stability and mitigate soil erosion. Additionally, the market is experiencing accelerated expansion due to the increasing acceptance of geotextiles, driven by their improved durability and cost-efficient qualities [129].

The results of this review paper highlighted an ongoing requirement to advance towards increasingly creative methods and ecologically conscious materials, taking into account the unique conditions of each location and the characteristics of native plant species. This applies to both natural environments and urban green spaces, aiming to attain the highest level of ecological sustainability in the face of highly fluctuating climate conditions.

4. Conclusion

The future of Incorporating interlocking components and plant species into erosion control systems in urban areas holds great promise for sustainable urban development and environmental conservation. The findings of this review paper indicate a growing demand for innovative ecological and engineering techniques to address erosion issues and enhance soil stability. Some of these techniques and policies include:

1. *Soil Bioengineering Methods:* Soil bioengineering methods, such as the utilization of bio-stabilized soils and soil amendments, are poised to gain prominence. These approaches improve soil structure, enhance water retention, and promote vegetation growth, thereby reducing erosion risks, especially in vegetated interlocking systems.
2. *Advanced Microbial Solutions:* The utilization of microbial communities to enhance soil stability and erosion control is expected to become more sophisticated. Bioengineering has the potential to harness the benefits of soil microorganisms that facilitate vegetation growth and soil cohesion, particularly within hybrid and soft erosion control systems.
3. *Enhanced Research Efforts:* More research is required in the field of advances in sensor technology and data analytics, enabling real-time monitoring of erosion-prone areas. This data-driven approach will enable more precise and adaptive erosion mitigation strategies.
4. *Supportive Government Policies:* Governments and municipalities are likely to introduce incentives and regulations aimed at promoting the use of integrated erosion control systems in urban regions. This may encompass tax incentives for green infrastructure projects and the inclusion of environmentally friendly erosion control measures in building codes.

These techniques will not only shield against soil erosion but also contribute to improved urban resilience, enhanced aesthetics, and overall sustainability.

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Conflict of Interest

The authors declare that they do not have any conflict of interest.

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