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REVIEW

Ecological revetments for enhanced interception of nonpoint source pollutants: a review

Pengcheng Wang, Jiaqi Ding, Yan He, Difang Wang, Chengjin Cao, and Minsheng Huang

Abstract: The riparian zone is a transitional zone between aquatic and terrestrial ecosystems and is also the only passage for surface runoff to enter a river. The role of the riparian zone as a means for intercepting nonpoint source (NPS) pollution has been receiving growing attention and, in recent years, various ecological revetments have been developed to strengthen the interception of runoff pollutants. This research reviews the current development of ecological revetments in terms of NPS pollution control with a focus on the key functions and optimization methods of vegetation allocation and substrate configuration. Future research on improving the ecological revetments for enhanced NPS pollution control are also highlighted. This review is intended to provide a technical reference for the optimization and implementation of ecological revetment projects, and possible pathways for the effective control of NPS pollution.

Key words: riparian zone, ecological revetment, nonpoint source pollution, vegetation, substrate.

Résumé : La zone riveraine consiste en une zone de transition entre des écosystèmes aquatiques et terrestres qui constitue aussi le seul passage permettant aux eaux de ruissellement de se jeter dans une rivière. Le rôle de la zone riveraine comme moyen d'intercepter la pollution de sources non ponctuelles (SNP) a été l'objet d'une attention croissante, et au cours des dernières années, plusieurs types de revêtements écologiques ont été développés afin d'intercepter plus efficacement les polluants de ruissellement. Cette recherche fait la synthèse du développement actuel de revêtements écologiques en matière de contrôle de la pollution de SNP en se concentrant sur les fonctions clés et les méthodes d'optimisation d'allocation de la végétation et de configuration des substrats. Les recherches futures sur l'amélioration des revêtements écologiques en vue d'un meilleur contrôle de la pollution de SNP sont aussi soulignées. Cette synthèse vise à fournir une référence technique pour l'optimisation et la mise en œuvre de projets de revêtements écologiques, de même que des pistes possibles pour contrôler efficacement la pollution de SNP. [Traduit par la Rédaction]

Mots-clés : zone riveraine, revêtement écologique, pollution de sources non ponctuelles, végétation, substrat.

1. Introduction

1.1. Definition

The riparian zone (Fig. 1) is a transitional zone between aquatic and terrestrial ecosystems and is also a channel for energy, substance, and biological information in river ecosystems (Gregory et al. 2010). Riparian zones have an important impact on the input of nonpoint source (NPS) pollution to rivers (Ou et al. 2016). Ecological revetment is a modern new slope protection technology with ecological and environmental protection functions, which integrates hydraulic engineering, environment science, biology, and ecology with landscape science (Shi et al. 2009; Wu et al. 2017). Compared with traditional hard revetment, ecological revetment takes ecological and environmental effects into consideration, in addition to preventing floods and securing shores (Rong et al. 2018).

1.2. History

In the past, the reconstruction of riparian zones mainly focused on flood control capacity of riverbanks. The hard revetments, such as cast-in-place concrete and precast concrete block, were often used to reinforce the bank slope. Due to the disconnection of aquatic and terrestrial ecosystems, hard revetments cannot meet the demand of ecological functioning and thus impact the sustainability of river ecosystems.

Seifert (1983) first proposed the "Near Natural Torrent Control" concept in 1983, which refers to treatment plans that enhance the flood resistance of riverbanks while maintaining as much natural landscape as possible. It could be seen as the origin of ecological revetment. In the 1990s, some scholars further proposed the concept of ecological revetment, which referred to the combination of plants and civil engineering materials to alleviate the instability and erosion of riparian slopes (Liang et al. 2014).

In China, natural materials such as stones, bamboo, and wicker were used to reinforce riverbanks in the 28th century BC (Xia and Yan 2004). Subsequently, the concept of "Eco-Hydraulic Engineering" was proposed, which defined ecological revetment as a water conservancy project centered on river ecosystems and river dynamics. Ecological revetment was considered not only to meet people's demand for water, but also to maintain the integrity of the aquatic ecosystem (Tian et al. 2016).

1.3. Interception of NPS pollution by ecological revetment

Ecological revetment is considered to be an important means to intercept and reduce NPS pollution entering water bodies (Liu et al. 2013; Wu et al. 2018) and is one of the effective measures for improving surface runoff and groundwater quality (Mi et al. 2015).

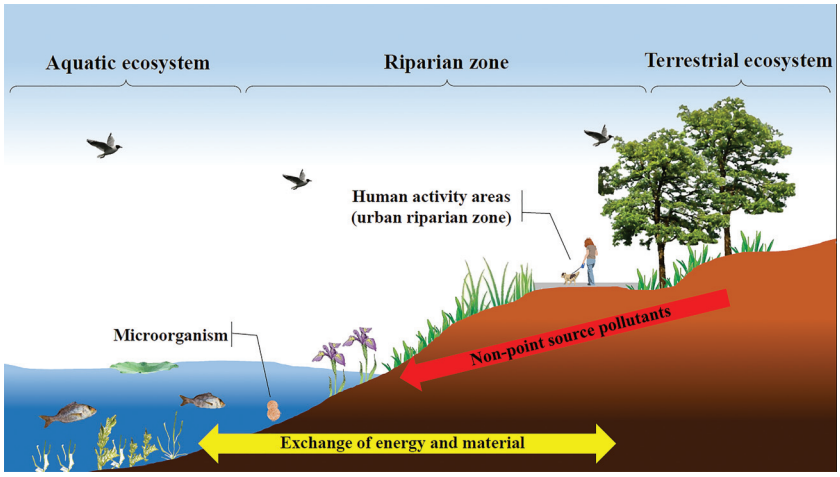
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P. Wang, J. Ding, Y. He, D. Wang, C. Cao, and M. Huang. Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, Institute of Eco-Chongming, East China Normal University, Shanghai 200062, China.

Corresponding author: Yan He (email: yhe@des.ecnu.edu.cn).

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Fig. 1. Common riparian ecosystem (human activity areas are generally unique to urban riparian zones).



The removal rate of NPS pollutants via ecological revetments can be up to 55.0%~87.0% (Nava-López et al. 2016; Xu et al. 2013) and is two- to four-fold greater than that of hard revetments (Wu et al. 2017). Various pollutants can be trapped in different areas of riverbanks by sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and various microbial processes (Chen et al. 2017). In theory, most of the nitrogen and phosphorus loads can be controlled if the ecological riparian zone is wide enough (Aguiar et al. 2015). However, the width of the riparian zone is relatively limited especially for urban riparian zones. Therefore, the optimization of vegetation allocation and substrate configuration are attracting more attention for enhancing NPS pollution control by riparian zones (He et al. 2020). Based on the current research status of ecological bank protection, we provide technical references for the optimal implementation of ecological revetment projects and discuss possible ways for the effective control of NPS pollution.

2. Vegetation configuration of ecological revetments

Vegetation is an important part of ecological revetment projects (Weissteiner et al. 2014; Mander et al. 2017; Fortier et al. 2010). Plants can help to reinforce riverbanks by their roots (Chen et al. 2015). Furthermore, plant roots can absorb or uptake NPS pollutants directly and act as a reaction medium for the biochemical degradation process of various NPS pollutants (Fig. 2) such as nutrients, heavy metals, antibiotics, and endocrine-disrupting chemicals (EDCs) (Boz and Gumiero 2016; Ledesma et al. 2016; Momm et al. 2014).

The distribution of riparian plants is hierarchical, and submerged, emergent, and terrestrial plants are distributed from the center of the river to the riverbank (Xu 2008). Riparian plants have a high demand for water and nutrients and are tolerant to waterlogging (Stromberg and Merritt 2016). It is equally important to implement reasonable vegetation optimization for long-term NPS pollution control in riparian zones considering plants act as a medium for purification reactions by enhancing a variety of removal processes and directly utilizing nitrogen, phosphorous, and other nutrients.

2.1. Interception of NPS pollution by vegetation

As the main biological component of riparian zones, plants can intercept NPS pollution through various pathways. Related research has focused on the adsorption and enrichment of nutrients such as nitrogen and phosphorus by riparian vegetation. However, the scope of NPS pollution has increased to include emerging pollutants such as heavy metals, antibiotics, and EDCs. Some submerged plants and emergent plants have been found to have strong enrichment abilities, whereas information regarding anchors and shrubs is scarce in the published literature. The absorption and enrichment performances of commonly used plants in ecological revetments are summarized in Table 1. Most research has focused on NPS pollutants such as nitrogen, phosphorus, and heavy metals (Bai et al. 2016; Zeng et al. 2010). The enrichment by heavy metals is mainly centered on Cu^{2+}, Zn^{+}, Pb^{2+}, Cr^{6+}, V^{5+}, As^{3+}, and Hg^{2+} (Phillips et al. 2015; Amari et al. 2017; Bonanno et al. 2017). However, studies dedicated to vegetation enrichment of antibiotics and EDCs are rare (Tasho and Cho 2016).

2.2. Vegetation configuration of ecological revetments

As a transition, riparian zones tend to be characterized by both upland and aquatic ecosystems and are usually divided into four areas, namely submerged plant, water level change, slope protection, and landscape area (Yu et al. 2012). The vegetation configuration of ecological revetment is mainly based on the planting area (summarized in Fig. 3). Sedges and rushes often dominate the herbaceous (or nonwoody) species and willows in the woody plant category. To achieve the effective interception of NPS pollution, vegetation configuration should follow the principles of integrity, hierarchy, ecology, diversity, and sustainable development (Bai 2015). In particular, growth characteristics and interspecies competition should be given special attention. For example, fast-growing species should be proportioned and managed to reduce conflict with slower-growing species. A higher percentage of slower-growing species may be required to succeed in the development of plant associations. Pioneer species should be spaced in the plant succession scheme without causing undesirable competition with desirable plants.

3. Substrate configuration of ecological revetments

As important components of ecological revetments, substrates should meet the requirements of structural stability, ecological compatibility, and effective interception of NPS pollution. Ecological stone cages, turf reinforcement mats, vegetation ecological concrete, ecological fish tank bricks, and ecological bags are common ecological substrates used in ecological revetments (Wang et al. 2017).

3.1. Ecological stone cage

Ecological stone cages originated from the Italian stone cages of the 16th century, which were wicker baskets filled with mud to strengthen the embankment. China's Dujiangyan water conservancy project also used bamboo cages filled with pebbles to consolidate the dam. Newly developed ecological stone cages are a

Fig. 2. Interception and purification of runoff pollution by vegetation roots.

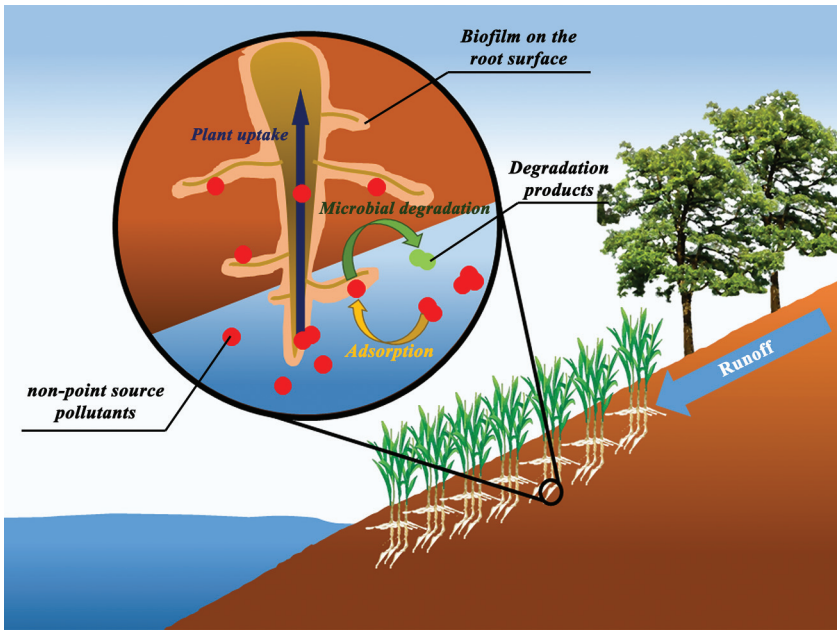


Table 1. Enrichment and adsorption of nonpoint source pollutants of common riparian vegetation.

		Enrichment and adsorption			
Type	Latin name	Nitrogen and phosphorus	Heavy metals	Antibiotics	Endocrine-disrupting chemicals
Submerged plants	*Myriophyllum verticillatum Linn.*	√	√	√	√
	Potamogeton crispus Linn.	√	√	—	√
	Hydrilla verticillata (Linn. f.) Royle	√	√	√	√
	Vallisneria natans (Lour.) Hara	√	√	√	—
Emerged plants	*Arundo donax Linn.* var. *versiocolor Stokes*	√	√	√	—
	Typha angustifolia Linn.	√	√	—	—
	Canna indica Linn.	√	√	√	—
	Scirpus validus Vahl	√	√	—	√
Small arbors and shrubs	*Photinia serrulata Lindl.*	√	√	—	—
	Ligustrum lucidum Ait.	√	√	—	—
	Hibiscus syriacus Linn.	√	√	—	—
	Cercis chinensis Bunge	√	√	—	—
Arbors and landscape plants	*Salix babylonica Linn.*	√	√	—	—
	Magnolia grandiflora Linn.	√	√	—	—
	Taxodium ascendens Brongn	√	√	—	—
	Ginkgo biloba Linn.	√	√	—	—
	Linum perenne Linn.	√	—	—	—
	Achillea millefolium L.	√	—	—	—
	Zephyranthes candida (Lindl.) Herb.	√	—	—	—
	Festuca elata Keng ex E. Alexeev	√	√	—	√

Note: A √ indicates that the plant has a certain ability to absorb and enrich contaminants and — indicates unknown.

combination of steel wire and filling stones and are referred to as Gabions or Renault stone cages (Fig. 4). The ecological stone cage is characterized by integrity, ecology, erosion resistance, corrosion resistance, and good water permeability. This type of revetment is commonly applied to steep sloped banks or bank slopes with high flow velocity that are predisposed to soil erosion. Ecological stone cages are effective at trapping contaminants because they do not block the channel of material exchange between aquatic and terrestrial ecosystems, they maintain the original ecological balance, and the gap filled with soil between the stones provides a good point of attachment for plant roots. Some studies found that different fillers in ecological gabions could affect their ability to remove contaminants. For example, Lin et al. (2012) compared the removal of NPS pollution by three different fillers (pebble, granite block, waste building block) and found that pebbles demonstrated the highest NH_4^+-N removal rate (up to 65.26%) of these fillers. Therefore, the development of high-efficiency fillers such as aged refuse, air-entrained concrete, and iron-containing material, as well as investigations of filler–contaminant relationships in selective adsorption processes are needed (He et al. 2020).

3.2. Turf reinforcement mat

The turf reinforcement mat was first developed by the Mark Phil Group (Yuan et al. 2015). The turf reinforcement mat is made of hexagonal twisted aluminum–zinc alloy wire mesh as the main structure, combined with a polypropylene geotextile pad, which reinforces the structural strength of the ordinary mic pad (Feng et al. 2014) (Fig. 5). The turf reinforcement mat is characterized by high strength, good coherence, minor wear and tear, and strong

Fig. 3. Area division and vegetation configuration of ecological revetment.

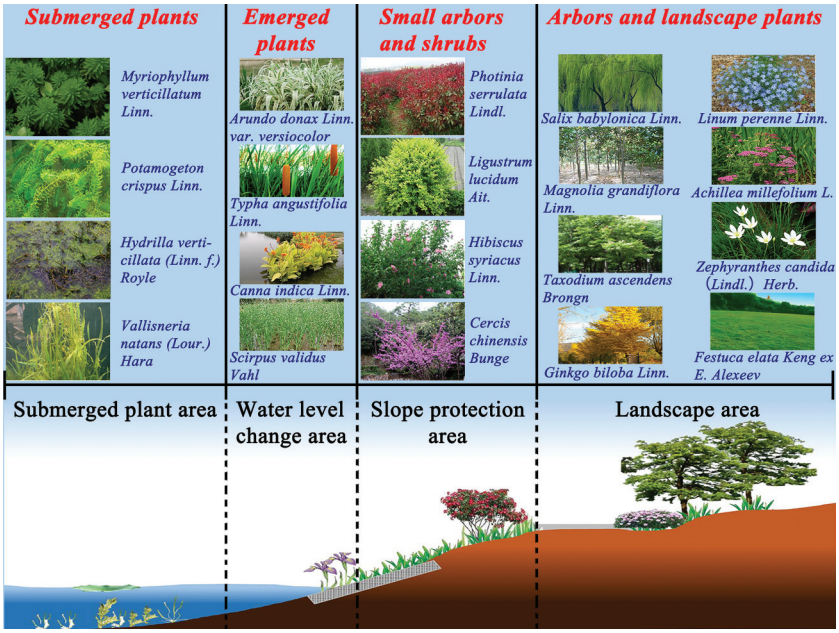


Fig. 4. Ecological stone cage.

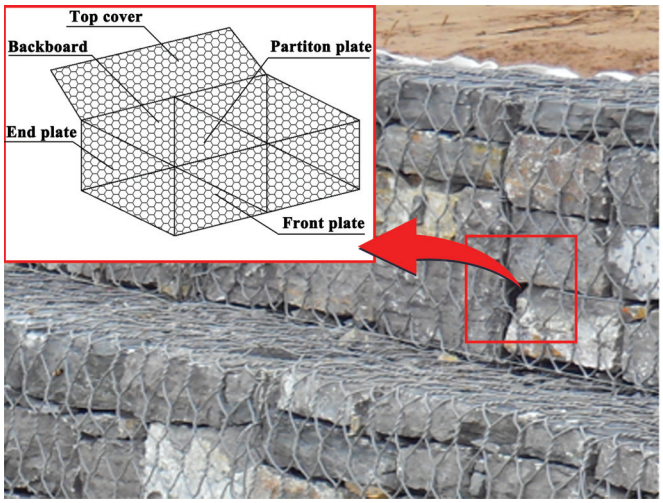
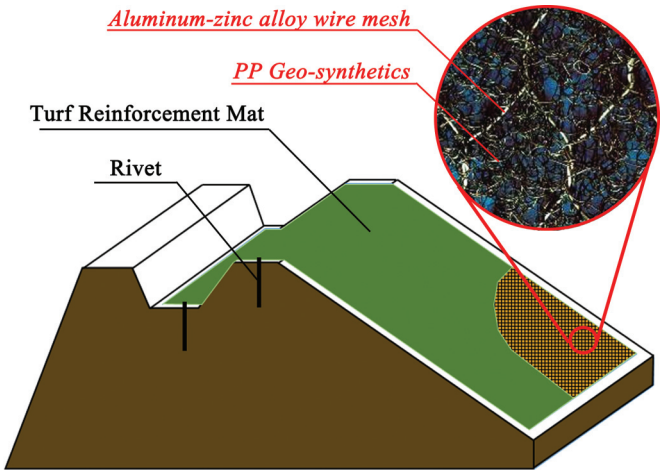


Fig. 5. Turf reinforcement mat.



anti-scouring performance. Compared with other substrates, it costs less and can be applied to both flat and steep slopes. Additionally, some findings indicate that the net structure of the turf reinforcement mat provides space for plant roots and microorganisms, which is key for pollution retention and water purification (Xu et al. 2012; Pan et al. 2013; Li et al. 2015).

3.3. Vegetation ecological concrete

The concept of vegetation ecological concrete (eco-concrete) was first put forward in Japan and then put into use in Europe and North America at the end of the 20th century. Vegetation ecological concrete contains light porous rock, long-term slow-release fertilizer and water-retaining material (Ido and Shimrit 2015). The porosity of the vegetation eco-concrete layer helps improve the water permeability of ecological revetments and provides space for the growth of plant roots and microorganism (Fig. 6). Compared with other ecological revetments, vegetation eco-concrete is expensive, and its ability to remove NPS pollutants is limited (Jiang et al. 2012). To decrease the costs of vegetation eco-concrete and increase the removal of NPS pollution, some inexpensive industrial by-product materials, e.g., blast furnace slag, rice husks, and sawdust, have been introduced into the preparation of vegetation eco-concrete (Kim et al. 2016; Liu et al. 2018).

3.4. Ecological fish tank brick

The ecological fish tank brick is a new river revetment component proposed in developed countries in the early 21st century. Ecological fish tank bricks are characterized by a cavity structure that helps to form turbulence in different velocity regions to increase dissolved oxygen levels and promote the growth of aquatic organisms including fish (Wang et al. 2007) (Fig. 7). Due to the rigid structure of the ecological fish tank brick, it is applicable to waterfront sections and some special locations that experience serious water erosion and frequent water level fluctuations and that have high stability requirements. It is suggested that the practical application of ecological fish tank bricks should consider the natural type of fish growth in the water. Ecological fish tank bricks with narrow channels are suitable for turbulent water and small-sized fish such as squid, but in watersheds where large and medium-sized fish such as grass carp grow, ecological fish tank bricks with wider migration channels should be used (Wang

Fig. 6. Vegetation ecological concrete.

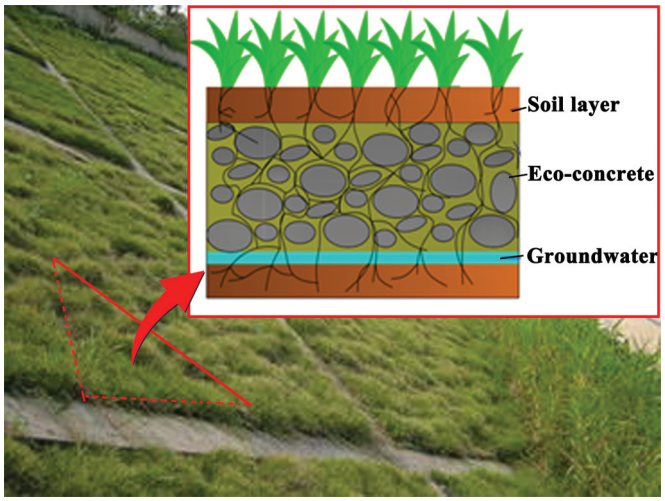
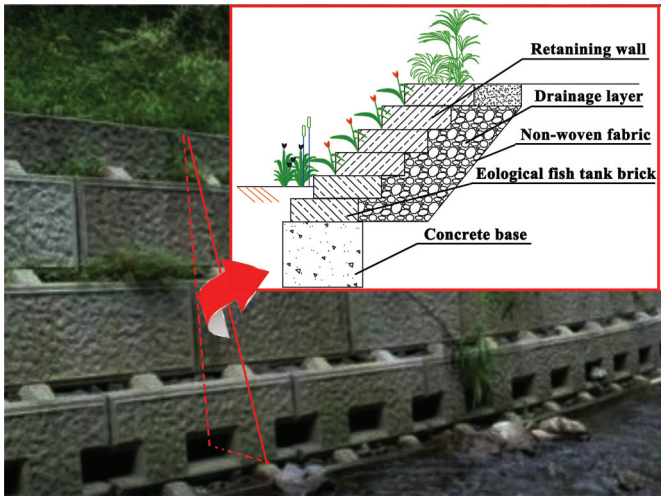


Fig. 7. Ecological fish tank brick.

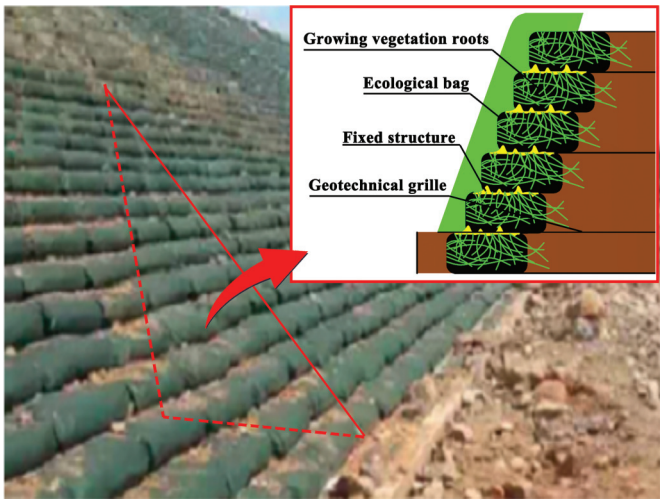


et al. 2007; Ge 2010). However, future research should give priority to sustainable maintenance (e.g., cleaning up of silt in fish tank bricks) for long-term NPS pollution control as well as the problem of poor adaptability of ecological fish tanks to water level changes.

3.5. Ecological bag

The ecological bag originated in Japan in the 1990s. This ecological revetment adjusts exposed rock slopes using cotton mesh ecological bags. The ecological bag is made of nylon fiber net and nonwoven fabric into which grass seeds, fertilizer, and water retaining agents are packed (Yu et al. 2016). Soil cannot pass through the ecological bag, thereby providing a permanent habitat for plants (Fig. 8). The ecological bag is characterized by strong water permeability, ultraviolet light corrosion resistance, nontoxicity, simple construction, low cost, and high efficiency. Ecological bags are mostly applied to the protection of steep riverbanks, especially urban vertical riverbanks (Li et al. 2017; Chen et al. 2013). In recent years, the emergence of new ecological bags with microbial inoculants has improved the removal rate of organic matter and nitrogen nutrients (Q. Li et al. 2018). Research on the integration of microbial technology and ecological bags deserves further attention.

Fig. 8. Ecological bags.



In addition, the development of new ecological matrix materials has proven to be effective in intercepting NPS pollutants (Table 2). Generally, these new ecological matrix materials are characterized by having a porous structure that can provide an effective growth space for plant roots, microorganisms, and animals, thereby achieving improved adsorption of NPS pollutants. Moreover, carbonization and (or) addition of acid additives (such as fly ash) and low-alkali cement are commonly used to reduce the adverse effects of the pore fluid alkalinity of ecological concrete on plants (L. Li et al. 2018; Wang et al. 2015). Further work is needed to develop new filling materials that have good removal performances, low costs, and easy operation (Guo et al. 2014).

4. Conclusions and prospects

Ecological revetments have considerable potential for NPS pollution control. Vegetation allocation and substrate materials configuration are two critical factors of ecological revetments for enhancing the ability to intercept NPS pollutants. For vegetation configurations, different types of vegetation have different control effects on NPS pollutants. Current research is mainly focused on aquatic plants and results confirm their ability to help purify NPS pollution, while information available on terrestrial plants such as shrubs and trees remains scarce. Additionally, the ability

Table 2. Purification of pollutants in ecological revetment with different substrates combination.

		Contaminant interception				
Substrates combination	Types of revetment	TN (%)	TP (%)	COD (%)	NH_4^+-N (%)	Reference
Pebble	Ecological stone cage	—	—	—	65.3	Lin et al. 2012
Crushed stone + ordinary portland cement	Vegetation ecological concrete	23.2	68.9	35.4	52.5	Kim et al. 2016
Sparse mud block		48.0	51.6	35.0	37.0	Bian et al. 2014
Aged refuse + zeolite + gravel	Ecological revetment	70.0	—	—	95.0	Wang et al. 2017
New cementitious materials + fly ash + zeolite	Ecological revetment	—	15.53 mg/g (adsorption)	—	—	Ding et al. 2015
Pebbles + gravels + sandstones + zeolite	The media sieve revetment	81.0	—	76.5	95.0	Xue et al. 2008

Note: TN, total nitrogen; TP, total phosphorus; COD, chemical oxygen demand.

of plants to enrich emerging NPS pollutants such as antibiotics and endocrine disruptors remains unclear. Therefore, a comprehensive evaluation of NPS pollution retention capacity of various plants deserves attention in future research.

Although substrates are closely related to the interception of NPS pollution by ecological revetments, the costs of existing substrates are a major obstacle to the construction of ecological revetments. As such, it is necessary to develop new and cost-effective waste materials such as iron scraps, slags, and aged refuse to replace more expensive options. However, the leaching toxicity of these matrix materials, especially the substrates based on waste byproducts, needs to be systematically evaluated. In addition, to enhance the ability to intercept NPS pollution and to achieve the removal of multiple pollutants, new methods that include the addition of slow-release carbon sources and microbial inner electrochemical materials should be further explored.

Future research should strive to improve ecological revetments by increasing its capabilities of intercepting NPS pollution and sustaining NPS pollution removal. To achieve long-term control of NPS pollutants by ecological revetments, suitable vegetation harvesting strategies (to deal with decay of fallen leaves) and self-adsorption–bioregeneration synergistic processes of substrates needs to be developed. In summary, to maximize the interception of NPS pollution by ecological revetments, systematic evaluation of plants and substrates, key pathways to pollution control, and degradation mechanisms, as well as maintenance strategies, are all important considerations for future research.

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