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From Electronic Waste to Ecological Restoration: The Study on the Unequal Treatment Model and Landscape Intervention Method of Electronic Waste From a Global Perspective

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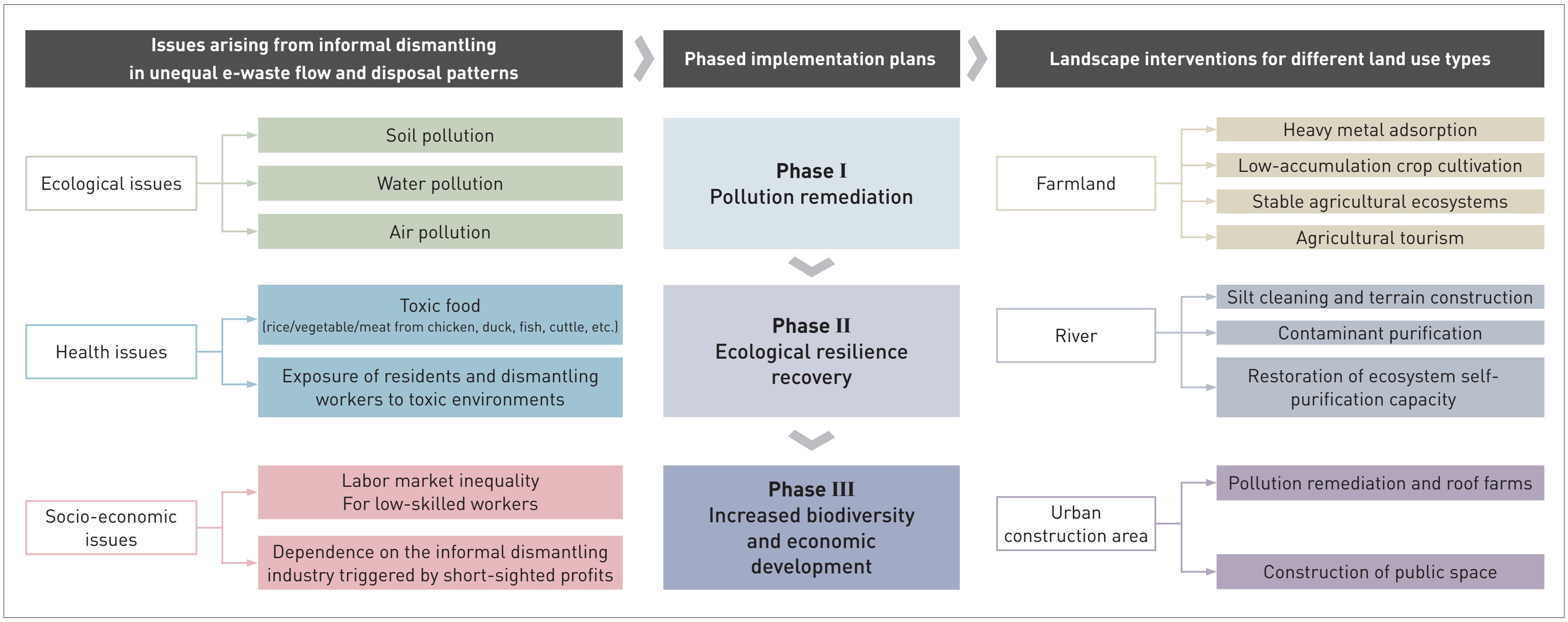
GRAPHICAL ABSTRACT



ABSTRACT

The rapid development of electronic technology has resulted in the annual phase-out of a large amount of waste electrical and electronic equipment, known as “e-waste,” especially in developed countries. In the context of economic globalization, the lack of relevant environmental laws and policies in developing countries and less developed countries, as well as cheap labor, has attracted developed countries to export a large amount of domestic e-waste to these countries. The chemicals produced during the low-tech dismantling process enter the air, soil, and deep groundwater, contaminating drinking water and food, and eventually entering the human body. Due to the inequality of economic and political development, the countries and regions that generate the least e-waste suffer the most. The most affected areas include, but are not limited to, China, India, and Ghana. This paper studies the production, distribution, and movement of e-waste, and its unequal distribution and disposal patterns of e-waste on a global scale. It also analyzes the national and international recycling policies and investigates the consequences of informal dismantling practices on the economy, society, and environment. The conclusion of the paper focuses on Guiyu, China as an example to draw landscape intervention strategies from key landscape issues, specifically for farmland, rivers and urban areas. These strategies are divided into three distinct stages of recovery and development. From the perspective of landscape intervention, this paper attempts to provide research and intervention suggestions for the restoration of ecology, health, and livelihood in global e-waste polluted areas.

KEYWORDS

E-waste; Ecological Health Crisis; Ecological Restoration; Environmental Justice; Landscape Intervention

HIGHLIGHTS

- The global e-waste flow pattern is analyzed under the background of economic globalization and unequal environment distribution
- Proposed phased implementation plans for different conditions of ecology, food, community, and income for e-waste polluted sites
- The intervention measures of e-waste pollution are put forward from the perspective of landscape architecture

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1 Introduction

Today, the rapid growth of electronic waste ("e-waste" hereafter) has become a pressing environmental issue, posing potential threats to human health and profound impacts on ecosystems[1] (Fig. 1). Over the past few decades, scholars have extensively researched the impact of e-waste on the environment and human health. E-waste often contains toxic substances such as lead (Pb), mercury (Hg), cadmium (Cd), and brominated flame retardants (BFRs)[2]. Research by the United Nations Environment Programme indicates that improper disposal of e-waste leads to the release of hazardous chemicals, contaminating soil, water, and the atmosphere[3]. Furthermore, the unequal global e-waste disposal affects the environmental fairness of different regions and social groups. A report by the Basel Action Network reveals the disparities in global e-waste disposal practices, with developing countries often being targeted as dumping grounds for e-waste from developed nations[4].

In the field of ecological restoration, scholars have begun to address the ecological restoration issues in areas affected by e-waste. Studies in *Handbook of Electronic Waste Management*[5] extensively discuss the application of phytoremediation at e-waste contaminated sites, and phytoremediation is considered an attractive method that can be used effectively for the remediation of trace metals and organic contaminants in the field[5]. Peeranart Kiddee et al. provided an overview of the toxic substances present in e-waste, their potential impacts on the environment and human health, and current management strategies being operated in certain countries. Although developed countries have established several tools to manage e-waste, there is still a huge knowledge gap on feasible ecological restoration strategies for developing countries under the global uneven e-waste treatment model.[1]

This study aims to fill this research gap by comprehensively examining the unequal e-waste disposal pattern and landscape intervention methods, thoroughly analyzing the impact of e-waste on ecosystems, and proposing feasible ecological restoration strategies. This research would provide a new perspective for the establishment of a more sustainable e-waste management system for both theory and practice.

1.1 What Is E-waste and E-waste Recycling Industry?

The consumption of electronic and electrical equipment is intricately linked to global economic development, constituting an integral facet of contemporary society and daily life. The widespread availability and usage of these devices have facilitated higher living standards for a significant portion of the world's population[6]. The


Huge quantity of waste includes a mixture of e-waste with other pollutants


E-waste is sorted and disassembled in illegal family workshops


Toxic river water irrigates farmland, threatening food production


Villagers are exposed to toxic water bodies and use them as domestic water


E-waste is deposited near the river and toxic substances seep through the soil and runoff


Traditional disassembly uses river water to clean e-waste, and the sediment of the river is seriously polluted


Outdoor playground in the polluted air and bare soil environment makes the children vulnerable to toxic pollutants


Traditional e-waste incineration process produces toxic gases, and the residents living in such communities pose a serious health threat


E-waste is piled in streets and occupies public spaces, affecting the appearance of the community environment

1

1. Using the photos shot in Guiyu Town, Guangdong Province, China to represent the most common but critical environmental problems caused by the illegal operation of e-waste recycling. Most of illegal workshops at Guiyu were eliminated by the local government since 2015 (taken in October, 2015; source: Division of Landscape Architecture, The University of Hong Kong).

confluence of rapid economic growth, escalating urbanization, increased mobility, and heightened consumer demand has precipitated a surge in the prevalence of electronic and electrical devices[7]. E-waste, the waste of consumed electronic and electrical equipment and its components, includes hazardous and valuable materials. In 2019, a staggering 53.6 million tons of e-waste were generated globally, and projections indicate that this figure will increase to 74.7 million tons by 2030[6].

The imperative for e-waste recycling is underscored by the fact that a mere 25% of e-waste is reclaimed in formal recycling facilities, coupled with the necessity for adequate safeguards for the workforce involved[8][9]. Due to the substantial cost associated with the proper dismantling and disposal of electronics, there is a prevalent practice of shipping e-waste to developing countries for disassembly and recycling[9]. An estimated 80% of e-waste generated in developed nations is exported to other regions, transforming the cross-border trade of e-waste recycling into a profitable industry for developing countries[10]. This highlights the need for a comprehensive and sustainable approach to addressing the escalating challenges posed by the burgeoning e-waste crisis.

1.2 Global E-waste Recycling Policies

The transboundary movement of e-waste is propelled by various factors, including cost-effective labor, a substantial demand for raw materials and the allure for smaller operators in developing nations, lacking adequate pollution control tools and technology to recover valuable materials from e-waste[10]. In response, as of October 2019, approximately 78 countries worldwide have implemented policies, laws or regulations aimed at dealing with e-waste problems[11]. As a notable global initiative addressing this issue, the *Basel Convention* of 1989, which came into effect in 1992, places the responsibility on exporting nations to ensure that hazardous wastes are managed in an environmentally sustainable manner within the receiving countries. Of the 164 signatories, all have endorsed the convention, with the exceptions of Afghanistan, Haiti, and the USA[12].

Efforts at the national, regional, and global levels have led to the establishment of policies, laws or regulations in each country to control the proliferation of e-waste. Despite these measures, the predicament still persists due to shortcomings in execution and enforcement, as well as the vulnerabilities in the legislation[11]. The challenges to e-waste management underscore the need for enhanced international cooperation, stringent enforcement mechanisms, and continuous efforts to address the gaps in the existing legal frameworks for a more effective and sustainable management of e-waste on a global scale.

1.3 Global E-waste Unequal Treatment Model Under the Background of Economic Globalization

The management of e-waste presents a complex and uncertain challenge, with diverse destinations and environmental impact across regions[6]. The global economy significantly drives the export of e-waste to Asia[13]. Advanced nations like the USA, major contributors to e-waste production, export a substantial economic and environmental burden through the inequitable and environmentally hazardous trade[13], posing formidable risks to more vulnerable communities with toxic substance exposure and environmental degradation[14].

In affluent nations with well-developed recycling infrastructure, discarded products sometimes undergo refurbishment and are often exported as second-hand goods to lower- or middle-income nations. However, a significant amount of e-waste is illicitly exported or concealed as reuse or counterfeit scrap metal, constituting approximately 7% ~ 20% of total e-waste production in cross-border transport[6]. In less developed countries, the underdeveloped or nonexistent e-waste management infrastructure necessitates the reliance on informal sectors, leading to subpar disposal conditions and severe health consequences for workers and children in proximity to e-waste management sites[6].

Nations most affected by e-waste include China, India, and Ghana[15]. China has banned the import of foreign waste, but countries in Southeast Asia, Africa, and South America, with weak infrastructure and limited health awareness, continue to bear the burden of the e-waste dismantling industry. Africa has a growing demand for information technology, but is limited in manufacturing capacity. While there are many functional electronic items donated in good faith, middlemen often fill containers with non-functional waste, exacerbating the e-waste burden for African importers[16]. Table 1 shows the global disparities in e-waste management, resulting in unequal global e-waste treatment patterns[6]. These complexities emphasize the urgent need for comprehensive international cooperation, strengthened regulations, and sustainable management practices to address the multifaceted challenges posed by the global e-waste issue.

2 Considerable Economic Benefits Brought by the E-waste Recycling Industry

E-waste encompasses valuable and recyclable components, including precious metals and plastics, making e-waste recycling an economically attractive venture. The estimated cost of extracting and purifying copper (Cu) and gold (Au) from e-waste is significantly below the global market prices for these metals on commodity exchange[17].

China has emerged as a leader in e-waste recycling, with 70% of the global e-waste recycled—equivalent to 28 million tons annually, including 5.6 million tons of copper[10]. This amount is significant, constituting 19% of China's existing copper reserves and over tenfold the copper it imported in 2009[10]. Notably, the gold reclaimed from e-waste in Guiyu, Guangdong Province, amounts to 5% of China's annual gold production and impacts the global gold price[14].

Beyond environmental benefits, e-waste recycling has played a crucial role in the industrial development of rural China, acting as a pivotal revenue source for local governments and residents. Additionally, it has created employment opportunities for local non-skilled individuals and migrants, contributing to the economic growth of these regions[10].

Conversely, a survey of e-waste laborers in Ghana revealed people's dissatisfaction with working conditions[18]. Despite discontent, the e-waste industry remains a vital source of income and financial support for families and the allure of rapid financial gains continues to attract informal workers, highlighting the complex dynamics at play in balancing economic opportunities with the challenges posed by the conditions of e-waste labor[18].

3 Adverse Effects of E-waste Dismantling Process on Human Health

3.1 Traditional Recycling Mode of E-waste

The term "recycling" may not accurately describe the prevalent e-waste disposal methods, as landfill and incineration are the most common methods[19]. Referring to e-waste recycling, particularly in less developed countries that are primary importers, it entails manual dismantling, cleaning with hazardous solvents, and incineration[20]. While this procedure effectively retrieves valuable components, it falls short in mitigating the related hazards, and inadequate recycling operations can lead to additional hazards.

The majority of e-waste ultimately ends up in landfills, where substantial volumes are directly disposed of without any fundamental pretreatment, leading to landfill leakage[21][22]. The release of noxious substances will further result in groundwater contamination and inflict severe harm on ecosystems[23]. Another significant approach is incineration, which is commonly utilized for the disposal of the remaining e-waste once all the valuable materials have been recovered[14].

Table 1: E-waste disposal policies in different regions of the world in 2019

Region	E-waste status			Legislation	E-waste management system
	Generated	To be collected and properly recycled	Number of countries with national e-waste legislation, policy or regulation in place		
Africa	2.9 million tons, 2.5 kg per capita	0.03 million tons (counting for 0.9 %)	13	Most African countries still lack specific legislation on e-waste management	In most African countries, e-waste management is led by informal collectors or recyclers; no organized recycling systems or licensing requirements for sorting and dismantling e-waste; government control is minimal and inefficient
Americas	13.1 million tons, 13.3 kg per capita	1.2 million tons (counting for 9.4 %)	10	Across the Americas, the lack of regulatory harmonization is evident, with differences in approach, jurisdictional level, definition, stakeholder engagement, role allocation, and e-waste category	Regulatory pressures elevate the significance of structured collection systems, alongside the growth in individual and collective compliance initiatives
Asia	24.9 million tons, 5.6 kg per capita	2.9 million tons (counting for 11.7 %)	17	Specific legislation has been implemented in India, parts of Southeast Asia, and East Asian countries such as China, Japan, and Republic of Korea, while legislation in West and Central Asia has lagged behind	It covers a wide range of activities from highly advanced countries such as Republic of Korea and Japan to co-existence of informal activities with advanced recycling systems in China to predominantly informal sector activities in Southeast Asia
Europe	12.0 million tons, 16.2 kg per capita	5.1 million tons (counting for 42.5 %)	37	In Europe, most e-waste management follows the WEEE (Waste from Electrical and Electronic Equipment) Directive, which is implemented in the EU and Norway, and several other countries have similar laws that set targets for the collection, recycling, reuse and recovery of e-waste	The EU has a well-developed e-waste management infrastructure, while meeting higher collection targets remains a challenge; formal recycling rates in Northern and Western Europe are already among the highest in the world, while e-waste management infrastructures in Eastern Europe and the Balkans are still developing
Oceania	0.7 million tons, 16.1 kg per capita	0.06 million tons (counting for 8.8 %)	1	Australia's National TV and Computer Recycling Program, implemented through the Product Management Act 2011, provides industry-funded recycling services for residents and small businesses, with a target of 80% of TV and computers to be recycled by 2027	Australia has made significant progress with its national TV and computer recycling program; Victoria has introduced an e-waste ban, while New Zealand and Pacific Island countries are still exploring effective e-waste management solutions

NOTE

The information presented in this table is sourced from Ref. [7].

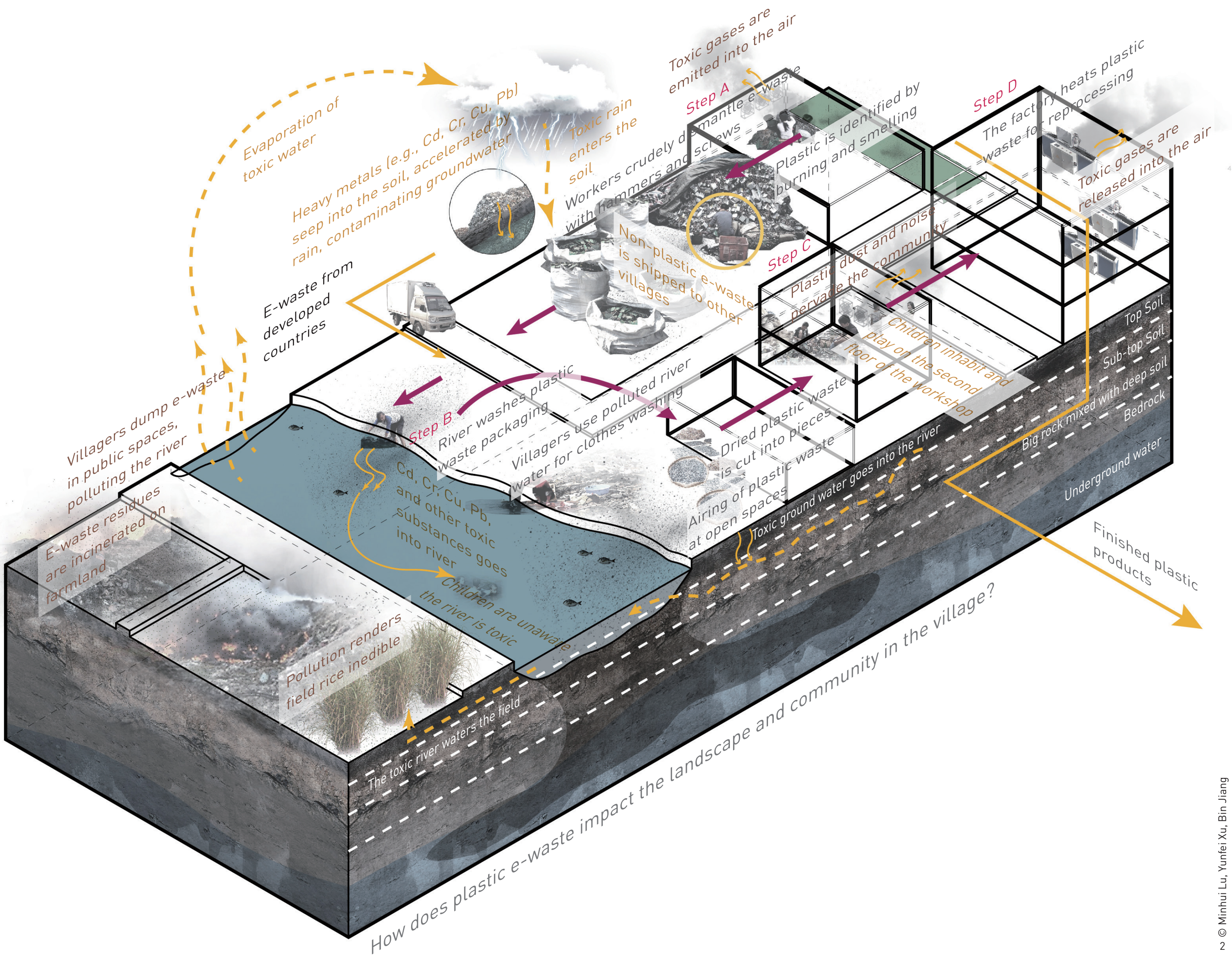
3.2 The Movement of Hazardous Substances in Communities and Landscapes

This study uses plastics in e-waste components as an example to show how contaminants flow through communities and landscapes (Fig. 2). E-waste dumps are often stored in backyards[24] and public spaces without any protective measures[14]. After completing demolition, a substantial volume of materials without further recycling value would be disposed of or openly incinerated near rivers[14]. Runoff transports heavy metals and various chemicals into soil and water, leading to groundwater contamination[25]. Furthermore, farmland is irrigated with contaminated water, yielding food that is unsafe for consumption. Plastic parts are melted and regenerated into plastic particles, but the process will produce a large amount of smoke, aggravating air pollution. Metals and chemicals entering the air would return to the land via rain.

3.3 The Threats of E-waste Disassembly to Human Health

The release of numerous hazardous pollutants during the e-waste disposal process poses a significant menace to both environmental well-being and human health. E-waste disassembly and disposal workers are not the sole individuals exposed to pollutants; the public is also impacted through environmental exposures[14]. Due to air, water, and soil pollution, more and more people are suffering from the illegal dismantling of e-waste. Heavy metals and organic compounds generated during the process can enter the human body through ingestion, inhalation, and skin contact, causing a variety of damage or interference to the intracranial, respiratory, reproductive, nervous, and endocrine systems[26].

Considering the distinctive manner in which children engage with their surroundings and their dynamic behaviors, they may be exposed to higher doses of toxic substances than adults[27]. The



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2. Take the dismantling process of the plastic part of e-waste as an example to display the flow of toxic substances in the landscape and community.

employment of children in the e-waste recycling industry makes them more vulnerable[8].

4 The Socio-economic Disparity Caused by Traditional Disassembly Methods

The unequal treatment of e-waste has exacerbated socio-economic disparity. Firstly, the rise of e-waste disposal businesses has resulted in labor market inequality. Typically, the related jobs involve low-skilled yet high-risk tasks, and are often undertaken by socially marginalized or low-income groups, intensifying their economic challenges[28].

Secondly, the processing of e-waste contributes to environmental inequality. The economically disadvantaged communities that working with e-wastes face exacerbated environmental problems for lacking the capacity to resist the impact of environmental pollution, leading to intensified socio-economic disparities[28]. Additionally, these regions accepting the disposals may be reliant more on this industry, losing economic diversification[28]. Any disruptions to this industry, such as regulatory changes or market fluctuations, could have a more significant impact on the economy of these areas.

Implementing equitable practices in managing e-waste faces various challenges in technology, economy, and society. Technologically, there is a deficiency in technical expertise and infrastructure. economically, the financial resources available are often lacking; while socially, there is an absence of robust community engagement[29]. To tackle these issues effectively, it necessitates global collaboration, financial incentives to safeguard workers, and strategies that reduce negative effects on both environmental and human health[30].

5 Design Strategies—Taking Guiyu as an Example

5.1 Study Area

The globally unequal disposal treatment of e-waste has caused some areas to become the "terminal stations" for e-waste. Some regions may suffer from the negative impact due to shouldering excessive responsibilities for e-waste disposal, while others may benefit from the processing and recycling of e-waste. This unequal treatment is not just an issue of environmental justice but also involves global social responsibility and principles of sustainable development.

In response, landscape intervention measures become a crucial means. By implementing appropriate landscape design, plant restoration, and soil remediation strategies in areas affected by e-waste, ecosystem recovery and community sustainability can be promoted.

Guiyu, the study site for this research, covering an area of 52.4 km^2, is known as the "World's E-waste Terminal" and a glaring example of disparity and unregulated practices in the global trade of e-waste[31]. Since the mid-1990s, Guiyu has been recycling over a million tons of e-waste annually, with over 150,000 tons of plastics and over 200,000 tons of heavy metals recovered. At the peak, up to 80% of households in Guiyu were involved in this industry, making recycling the mainstay of the local economy[32].

The land use types of Guiyu Town mainly include farmland, rivers, and urban construction areas. A study published in 2016 measured the concentrations of multiple organic pollutants in 23 farmland soil samples and 10 river sediment samples in Guiyu indicates that the total concentration of PAHs (Polycyclic Aromatic Hydrocarbons) in soil was 56 ~ 567 ng/g, while in sediments, the total PAH concentration was 181 ~ 3,034 ng/g. This suggests that soil contamination levels are relatively low, whereas sediment contamination levels are higher[33], which might cause carcinogenic risks to the groundwater system, threatening the health of the locals and the environment. By focusing on the Guiyu case, this study attempts to demonstrate the landscape intervention measures for the restoration of e-waste dismantling site.

5.2 Phased Implementation Plans at Different Levels of Ecology, Food, Community, and Income

As a result of the prolonged build-up of pollution, even if Guiyu has initiated or intends to regulate e-waste dismantling procedures and to manage pollution sources in the future, the site will continue to bear the burden of existing residual pollution. For this reason, the process of restoration must unfold incrementally, progressively bolstering ecological resilience, and it should be structured with varying objectives for each phase (Fig. 3).

In the first stage, the main objective is contamination remediation and ensuring the availability of healthy food to sustain daily life and safeguard basic health. The second stage aims to rejuvenate the ecological resilience of the site. During the third phase, the site will undergo transformation, lead to the creation of a new landscape and a more robust industrial structure that will facilitate healthy and sustainable development in the future. E-waste recycling sites in different zones will build up well-established business networks over time and should keep evolving. After all, it will become the main source of income for the locals and support their lives.

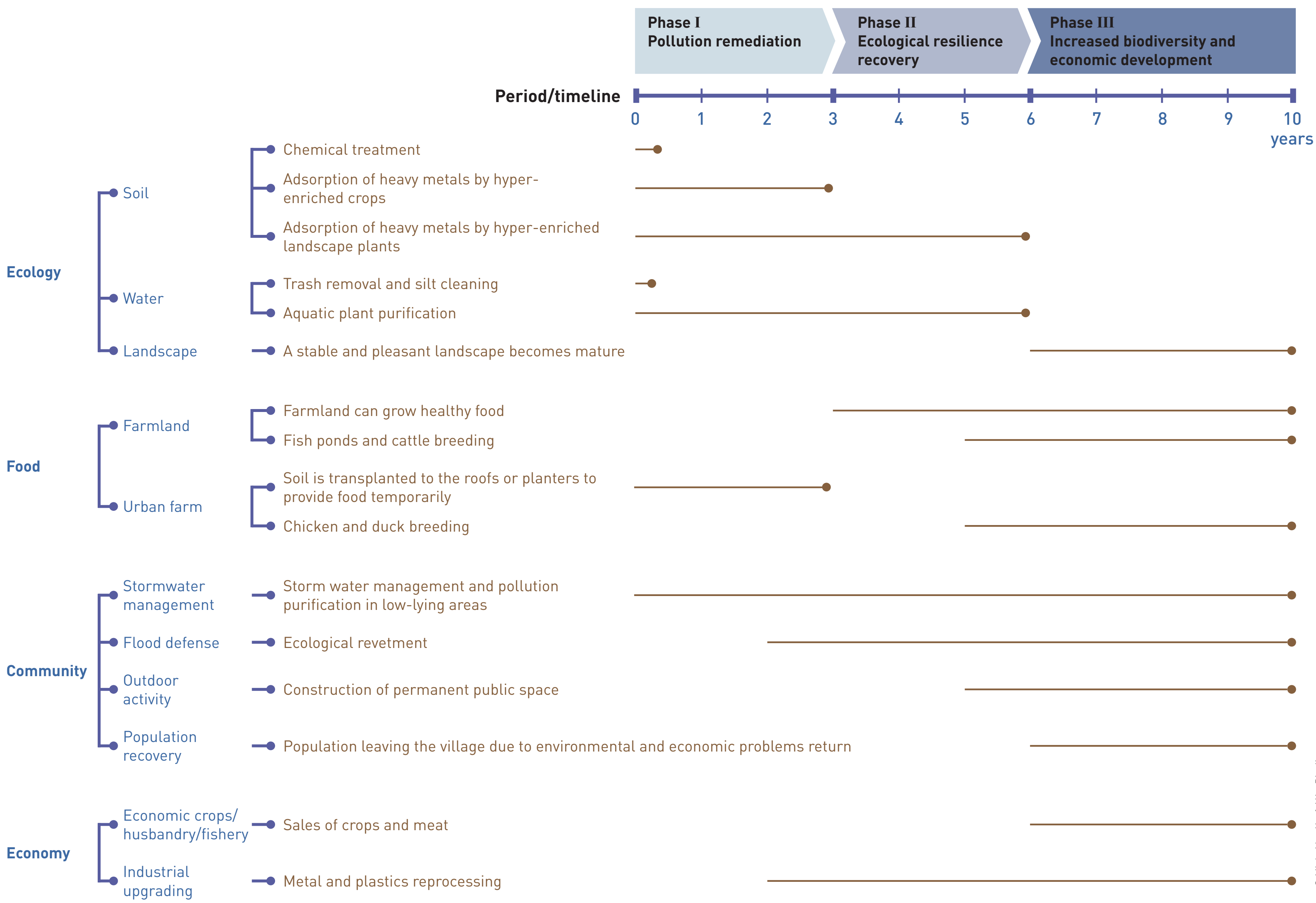
5.2.1 Phase I: Pollution Remediation

The first stage takes the first three years. Some of the less polluted farmland soil can be repaired first, while cleaning up the remaining waste in the river. Some of the restored soil will be transplanted into roofs or planting ponds to temporarily provide edible food in the form of rooftop farms, and some green infrastructure construction will be initiated in the countryside for sewage purification and in urban construction areas for stormwater management.

5.2.2 Phase II: Ecological Resilience Recovery

In the second stage, from the third to the sixth year, most of the remaining farmland and rivers are repaired by the planting of specific hyper-accumulators that absorb pollutants such as heavy metals. After that, healthy food can be produced on the farmland, and the treated rainwater can be incorporated into the domestic water supply for every household. Because the most direct stacking site of e-waste is located in urban public spaces and family workshops, and the pollution spreads to rivers and farmland with runoff, the accumulation of pollution in urban construction areas over the years may be more serious than that in farmland, and the soil repair in these areas will take a longer period of time. Some temporary public spaces isolated from the polluted soil can be designed and built first to meet the needs of daily life.

3. The three phases of ecological and livelihood restoration are combined into four perspectives: ecology, food, community, and economy.



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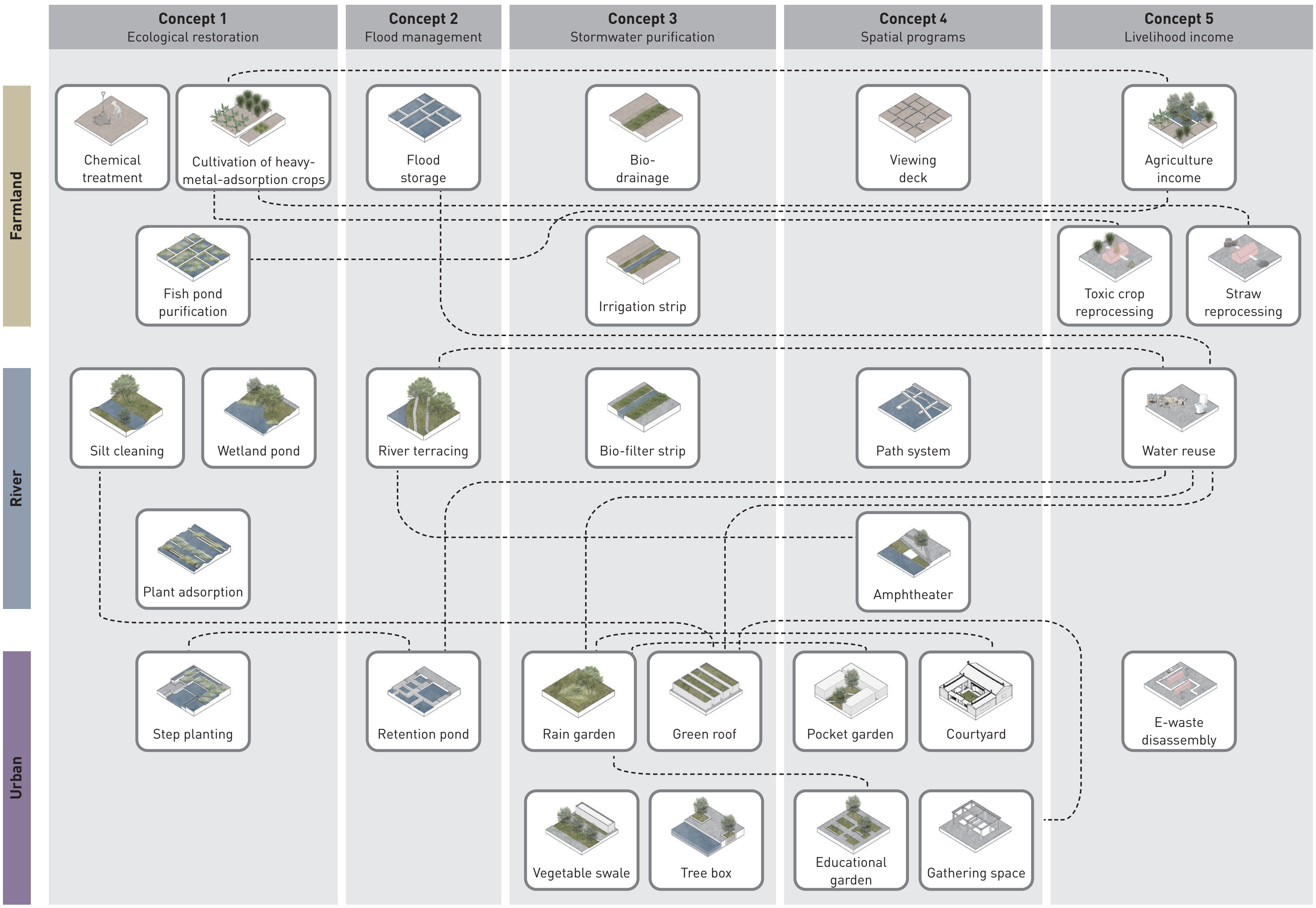
5.2.3 Phase III: Increased Biodiversity and Economic Development

The third stage, from the sixth to the tenth year, the ecological restoration has been completed, and the environment of the site has turned into a new landscape. Residents can also begin to increase their income through the development of agriculture, animal husbandry, and fishing. Other materials recovered from e-waste can be used in building public facilities after restoration. Residents who were once displaced due to environmental issues might also be relocated back. Simultaneously, the metal and plastic processing sector of e-waste is growing in maturity and could emerge as a key economic driver for the area.

6 Design Intervention for the Three Land-use Types of the Study Area

Depending on where the e-waste is stacked and the space it will indirectly impact, the conceptualized design strategies integrate the three land use types of the site: farmland, river, and urban construction area. From the perspective of landscape intervention, these three land use types can be combined with five concepts: ecological restoration, flood management, stormwater purification, spatial programs, and livelihood income (Fig. 4). These five concepts are integrated to form a comprehensive system

4. Landscape intervention strategies for farmlands, rivers, and urban construction areas of the study site. The dashed lines indicate the connections between the interventions.



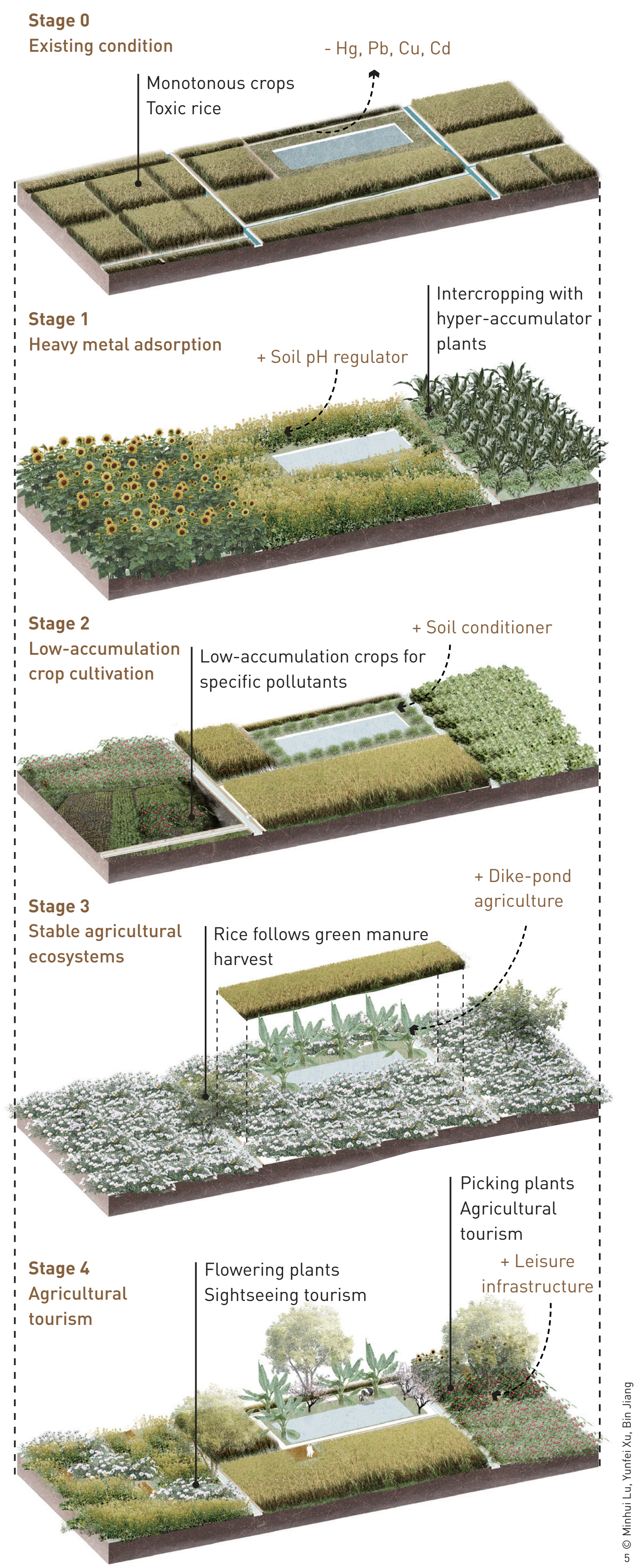
aimed at addressing the environmental and social issues stemming from the global unequal treatment of e-waste. Soil remediation and water purification intersect, utilizing plant-based and microbial remediation to not only enhance soil quality but also alleviate water pollution. Rainwater management synergizes with soil remediation, reducing runoff, contributing to soil erosion mitigation and promoting soil restoration. The redesign of public spaces enhances water purification, as well as urban green spaces and cultural landscapes. Simultaneously, livelihood income, brought by e-waste management projects, fosters local community engagement in the maintenance and improvement of public spaces. These five concepts collectively harness the interrelationships and synergies of the land use system to achieve comprehensive management of e-waste disposal.

In terms of soil remediation, agricultural areas comprising rice fields and fish ponds employ soil amendments such as calcareous materials to improve the soil's pH condition[34] and rotating hyper-accumulators to lower pollution levels[35]. Additionally, straw can be repurposed into biochar materials to facilitate soil remediation[36]. Contaminated fish ponds are treated with aquatic plants, and dike-pond agriculture is developed for sustainable resource circulation[37][38]. Residents engage in rooftop farming during soil restoration. Water purification focuses on eliminating pollution sources into rivers, including e-waste, domestic sewage, and garbage. Main channels and secondary tributaries undergo purification through sediment removal, wetland ponds, and the adsorption by aquatic plants[39]. Stormwater management involves soft revetments in low-lying areas and the repurposing of rainwater through green infrastructure in urban development areas. Public spaces incorporate plants with adsorption capacity for heavy metals[40], with tailored spatial designs for various land use types. Combining the income from formal e-waste dismantling industry with the economic benefits derived from the cultivation, harvesting, and incineration of hyper-accumulator plants to reclaim heavy metals[35] can aid in providing livelihood income during ecological restoration.

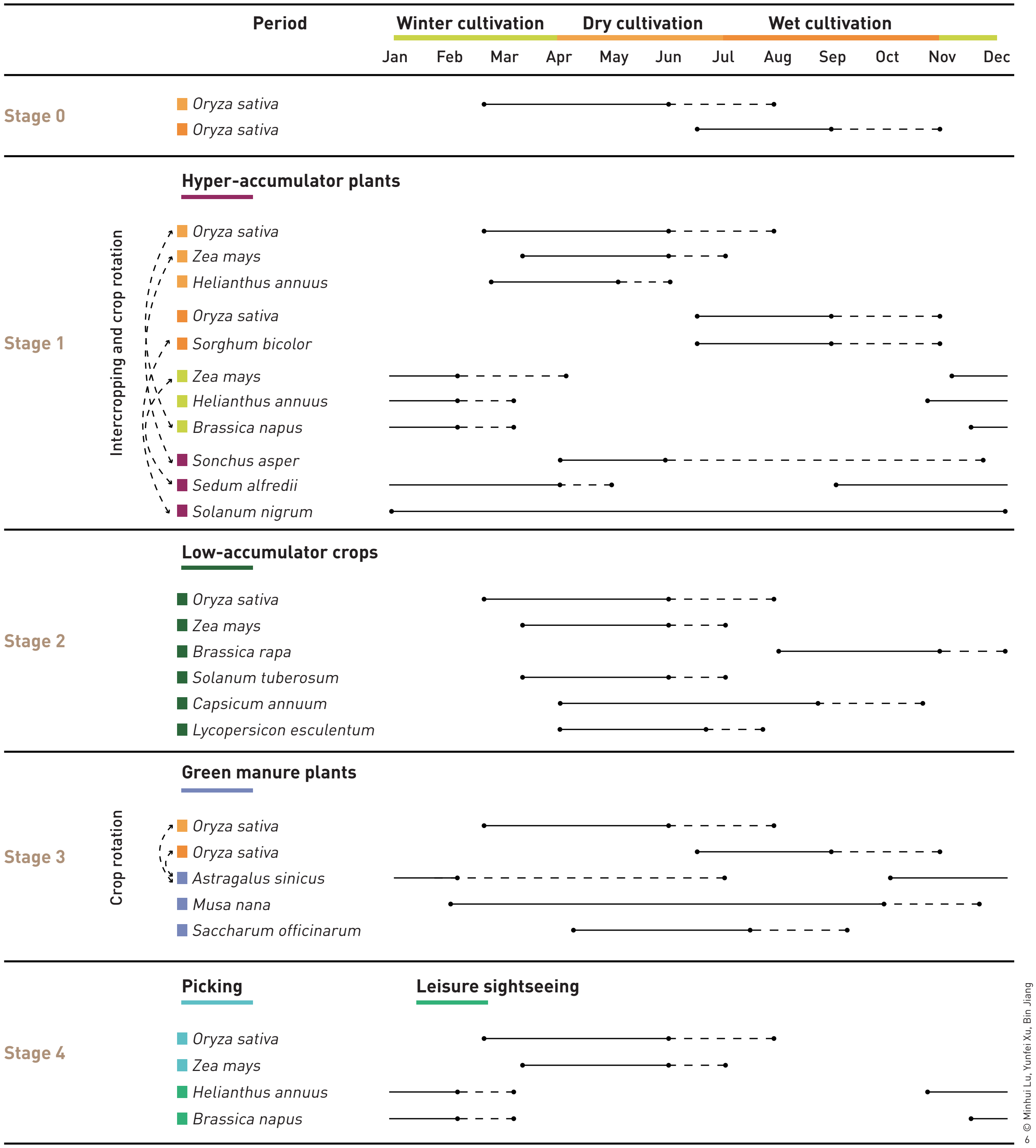
6.1 Design Intervention for Farmland

The farmland soil pollution spans a wide area, presenting a complex situation. The restoration of farmland can be divided into four steps (Fig. 5), and each step has a specific plant species selection (Fig. 6).

The first step involves the adsorption and treatment of existing pollutants. The primary task is to improve the soil's pH environment. Studies have shown that the bioavailability of heavy metals in soil is negatively correlated with soil pH. Increasing pH helps reduce the toxicity of heavy metals in the soil and promotes plant growth.[34]



5. The phased intervention strategies for farmland.



6. Plant selection for different restoration stages in farmland. The arrows indicate the most beneficial planting patterns between different plants, the solid lines indicate the growth periods of plants, and the dashed lines shows the harvest or flowering period of the plant.

After that, specific hyper-accumulators are selected to absorb heavy metals. Subsequent treatments include harvesting the aboveground parts of the plants to extract heavy metals or ferment plant residues into ethanol, creating economic benefits. Despite the relatively long restoration period, this step is environmental friendly and cost-effective[34] (Fig. 7).

During the second step, when most heavy metals have been eliminated, the introduction of soil amendments such as straw aims to decrease the uptake of heavy metals by crops. In the process, cultivating crops with lower adsorption of heavy metals that are suitable for the soil conditions will help local residents partially sustain the food sources[34].

In the third step, once the soil meets the required standards for planting, a crop rotation system involving green manure is

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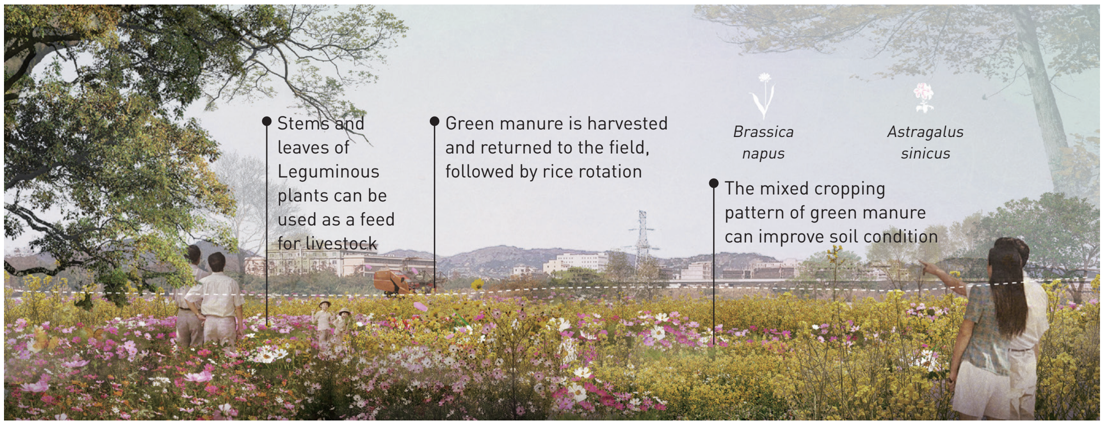

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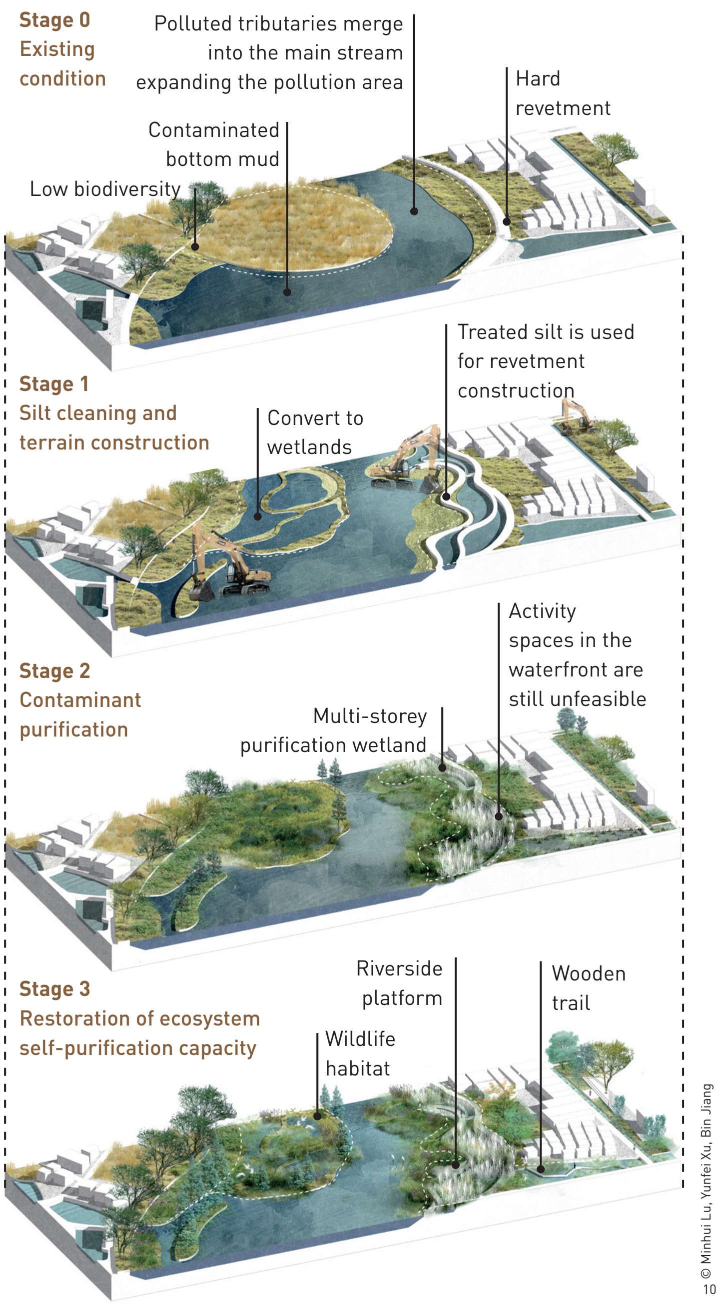
7. Removal of organic pollutants from farmland by hyper-accumulator plants.
8. Plant green manure to restore soil vitality in farmland after pollution remediation.
9. Balanced development of farmland ecology and tourism.

introduced, along with the development of dike-pond agriculture. This encourages beneficial material cycles between crops, gradually restoring soil vitality. Furthermore, this step promotes the development of fisheries and animal husbandry (Fig. 8).

Lastly, the incorporating leisure infrastructure facilitates the development of agricultural tourism, including sightseeing and harvesting. This involves the introduction of crop varieties suitable for local cultivation, with short growth cycles and aesthetic appeal. The integration of agricultural production, tourism, education, and experiential activities within the farmland landscape seamlessly blends it into the urban ecological environment, creating significant tourism opportunities for the local community (Fig. 9).

6.2 Design Intervention for River

The river restoration process can be divided into three steps to mitigate pollution and enhance biodiversity (Fig. 10). The first step involves the dredging and the construction of natural embankments. Dredged sediment can be purified[41] and used for rooftop agriculture and embankment restoration. Subsequently, a variety of wetland purification methods are employed for



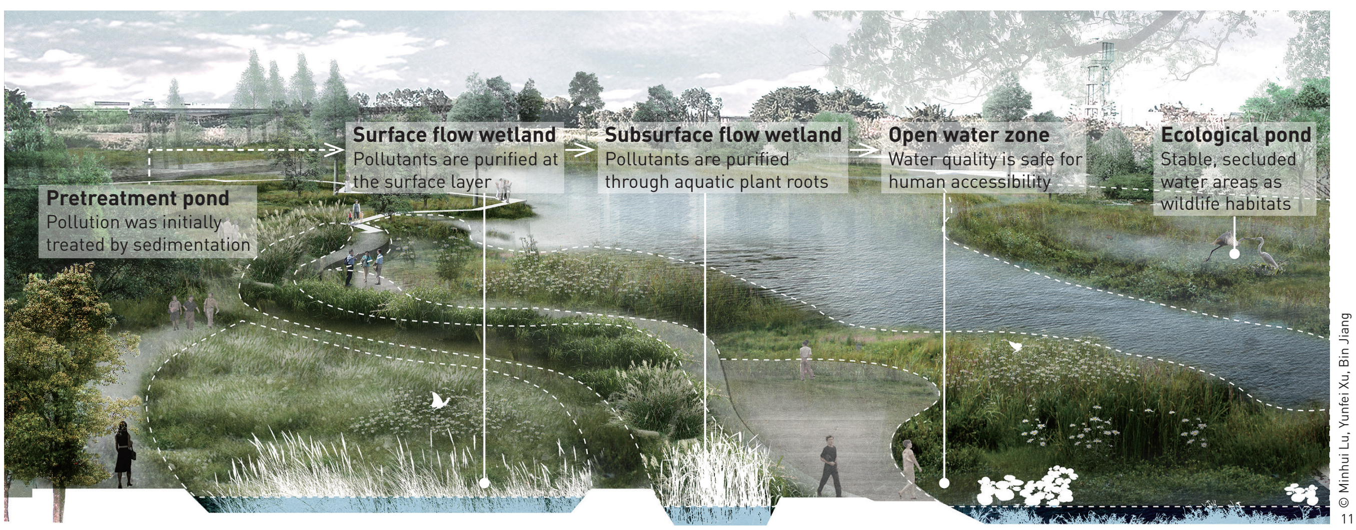
remediation. Gradually, the biodiversity of the river can be improved and the ecosystem can be stabilized, allowing people to interact with the water and get engaged in various activities around the riverfront.

Urban wastewater initially goes through pretreatment tanks, consisting of a grid, a sand settling tank, a settling tank, and a stabilization tank to reduce the suspended matters in sewage[42]. After the pretreatment, the wastewater enters the surface flow constructed wetland, where sewage is purified by biofilms on the stems of aquatic plants. Then, the pre-purified water enters the subsurface flow wetland, and the pollutants are removed by the biofilm growing on the surface of the substrate, the abundant plant roots, and the interception of the substrate. The purified water eventually flows into the main river, ensuring the stable water quality of the river[42] (Fig. 11).

The selection of aquatic plants is of paramount importance, especially in environments with high concentrations of various pollutants. The selected plants must adapt well to local ecological conditions, possess strong soil adaptability, and can effectively remove contaminants from the surrounding environment. According to the local soil and climate conditions, as well as the varying water depths and degrees of pollution in different areas, appropriate submergent plants, floating plants, emerging aquatic plants, as well as aquatic trees should be chosen[43] (Table 2).

6.3 Design Intervention for Urban Construction Areas

In urban construction areas, existing urban green spaces have been abandoned and polluted, and most roads are covered with hard surfaces, while rivers remain untreated. Runoff carries the major source of pollution, causing significant contamination in both the river systems and farmlands. The current systems make runoff swiftly



10. The phased intervention strategies for river.
11. A multi-system revetment purification mode for river.

Table 2: Aquatic plant selection list

Type	Latin name	Absorbed chemicals	Suitable water depth	Plant traits and planting requirements
Submerged plants	*Ceratophyllum demersum*	Cu, Zn, Pb	0.3 ~ 6 m	Open water Growth has high water quality requirements, and can only be used as the strengthened stable plant in the constructed wetland system
	Potamogeton distinctus	Cu, Zn, Pb		
	Myriophyllum verticillatum	Cu, Zn, Cd, Pb		
Floating plants	*Lemna minor*	Mn, Fe, Zn	0.15 ~ 5 m	Open water Strong vitality, good adaptability to the environment, developed roots; large biomass and rapid growth
	Eichhornia crassipes	PAHs		
	Leersia hexandra	Cr, Ni, Cu, Zn		
Deep-rooted emergent plants	*Iris tectorum*	Cu, Cd, Pb	0 ~ 1.5 m	Pretreatment pond/subsurface flow wetland/cascade wetland Suitable for planting in the subsurface flow constructed wetland
	Typha orientalis	Mn		
	Lythrum salicaria	Zn, Cd, Hg		
Shallow-rooted emergent plants	*Phragmites australis*	Cd, Pb	0 ~ 1.5 m	Surface flow wetland/cascade wetland The root system is shallow and generally grows in soil, which is suitable for the surface flow constructed wetland
	Canna indica	Cd, Pb		
	Sagittaria trifolia var. *sinensis*	Pb		
Aquatic trees	*Metasequoia glyptostroboides*	Cu, Cd, Pb	Higher than normal water level	Island Generally, plants that are found in the local or natural wetlands within the study area can be selected
	Taxodium distichum	Mn, Cu	Higher than normal water level	
	Glyptostrobus pensilis	Cu, Cd, Pb	Higher than normal water level	

NOTE
The information presented in this table is sourced from Ref. [43].

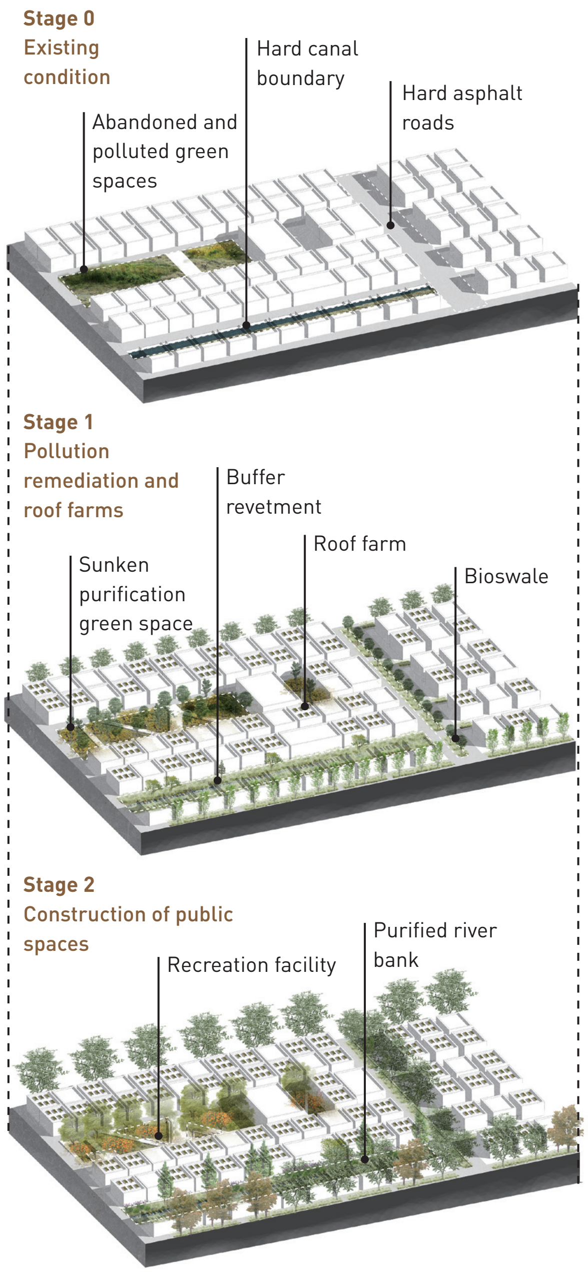
flow over the ground without adequate filtration and purification. Therefore, it is crucial to establish multiple green buffer zones along streets and waterfront areas to purify runoff (Fig. 12).

The primary green infrastructure suitable for the site includes rain gardens, eco-friendly tree boxes, grassed eco-terraces, pervious pavements, and riparian buffers[44] (Table 3). Additionally, hyper-accumulator plants will be employed to absorb pollutants. During this process, rooftop farms can efficiently utilize the vertical spaces of buildings to grow vegetables. Finally, residents will have the opportunity to experience the restored land by themselves in the public space.

Sunken green spaces not only filter pollutants and temporarily store rainwater during peak downpours, but also provide residents with gathering and recreational places. During heavy rainfall seasons, these sunken green areas can serve as temporary reservoirs, within which the wetland vegetation can purify the contaminants flowing over the ground. Ecological grassed terraces also offer a diverse range of activity spaces for local residents, fostering social interaction and community engagement (Fig. 13).

7 Conclusions

A major challenge in this research is mitigating the enduring exposure risk of pollutants from e-waste recycling activities



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12

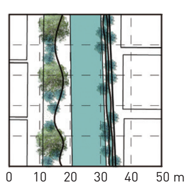
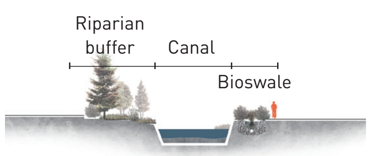
12. The phased intervention strategies for urban construction area.

to communities and landscapes. The e-waste problem has been growing in recent years. Even the illegal demolition activities have been banned, certain hazardous elements persist in deep and invisible environment and have the potential to accumulate within various organisms, including plants and animals. Community members may suffer from the prolonged impact from lingering chemicals in soil, water, and food resources. As e-waste recycling practice continues to improve across countries and regions, it is of utmost importance to address historical pollution and ensure a safer means of earning a livelihood through e-waste recycling.

Another key challenge of this study lies in balancing the health problems of informal workers and relevant residents against the potential income from e-waste dismantling industry. Many workers in informal e-waste recycling prioritize the immediate provision for their families over the potential long-term health consequences of e-waste exposure. So the design intervention should be both beneficial and sustainable. How to design and provide communities with ways to generate economic benefits from other formal sources of income also needs to be considered.

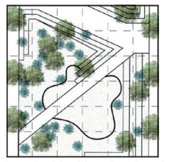
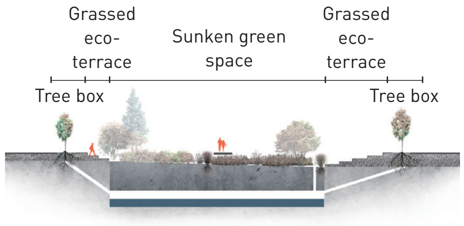
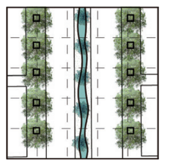
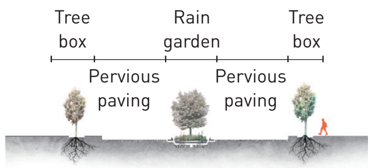
From the perspective of spatial interventions for the land use types of farmland, river, and urban construction area, this article provides design interventions for ecological restoration, health recovery, and livelihood improvement in e-waste polluted areas around the world. This not only mitigates the negative environmental impacts of e-waste, but also provides a healthier and a better living environment for local communities. This study enhances our understanding of the interconnections between global e-waste flow, unequal emissions, and landscape interventions, contributing to comprehensive solutions for more just and sustainable e-waste management.

Table 3: Green infrastructure types in urban construction areas

Spatial Type	Plan	Section	Green infrastructure type	Function	Optional plant species
Canal			Riparian buffer	At a width of 10 ~ 30 m, 50% ~ 80% of rainwater pollutants can be filtered	*Canna Indica, Lythrum Salicaria, Metasequoia Glyptostroboides, Nerium Oleander, Salix Babylonica, Vinca major*
			Bioswale	Strong biological purification	

(Continued)

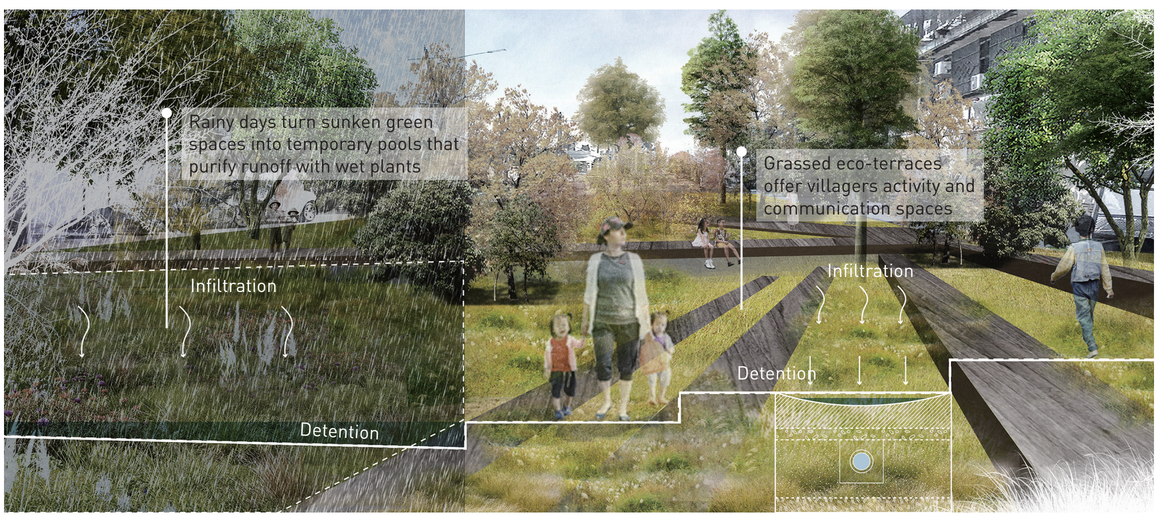
Table 3: Green infrastructure types in urban construction areas (Continued)

Spatial Type	Plan	Section	Green infrastructure type	Function	Optional plant species
Sunken rain garden			Tree box	Planting soil stores natural water and absorbs rainwater for plant growth	*Ficus concinna, Iris Tectorum, Scirpus Validus,Typha Orientalis*
			Filter strip	Filter large particles of sediment in the water and slow the water flow	
			Rain garden	Absorb rainwater from the building and purify it through the combined action of plant roots, soil and microorganisms	
Road			Tree box	Filter media and plant roots adsorb and decompose pollutants in street runoff	*Canna indica, Cosmos Bipinnatus, Salix Matsudana, Typha Orientalis*
			Rain garden	Absorb and purify street runoff	
			Pervious Paving	Filter and preliminarily purify rainwater	

NOTE

The information presented in this table is sourced from Ref. [40].

13. Sunken green spaces for rainwater and runoff purification can serve as community gathering places.



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13

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Competing interests | The authors declare that they have no competing interests.

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从电子垃圾到生态恢复：全球视角下的电子垃圾不平等处理模式与景观干预方法研究

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摘要

电子技术的飞速发展导致了每年大量电子垃圾（废弃电气和电子设备）的产生，在发达国家尤其如此。在经济全球化的背景下，发展中国家和欠发达国家由于缺乏相关环境法律和政策的保护且劳动力成本较低，导致发达国家将数量庞大的电子垃圾出口至这些国家。在低技拆解这些电子垃圾的过程中，产生的有害化学物质进入空气、土壤和深层地下水，污染饮用水和食物，并最终进入人体。由于经济和政策发展不均衡，产生电子垃圾最少的国家和地区（例如中国、印度、加纳等）反而遭受最大的损失。本文研究了全球范围内电子垃圾的生产、分布和流动情况，及其不平等的分布和处理模式；随后分析了不同国家和国际电子垃圾回收政策，并讨论了非正规拆解行为对经济、社会和环境造成的影响；最后，以中国贵屿为例，重点关注农田、河流和城市用地三种用地类型，从关键景观问题中总结出景观干预策略和方法，并将其实施划分为三个不同的恢复和发展阶段。本文旨在从景观干预的角度，为全球电子垃圾污染地区的生态、健康和生计恢复提供研究和干预建议。

关键词

电子垃圾；生态健康危机；生态修复；环境正义；景观设计干预

文章亮点

- 从经济全球化和环境分布不均的背景出发，分析全球电子垃圾的流动模式
- 针对电子垃圾污染地的生态、食品、社区、收入等不同层面提出分阶段实施方案
- 从景观设计学角度提出电子垃圾污染的干预措施

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