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Toward Sustainable Brownfield Redevelopment Using Life-Cycle Thinking

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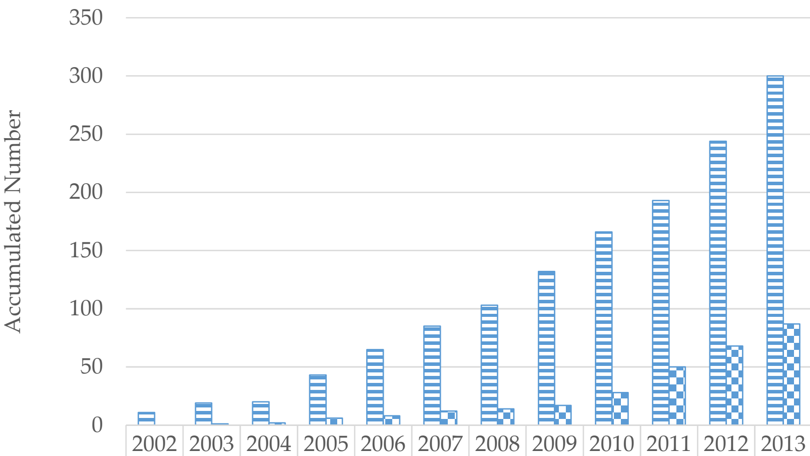
Abstract: The redevelopment of brownfields has become an important issue, as the number of contaminated sites has been increasing. However, a comprehensive regulatory framework is lacking that includes urban planning and a sustainability plan at the national level to support brownfield redevelopment in Taiwan. Few studies have explored sustainable management objectives to reduce the environmental impact of increasing economic value of the proliferating redeveloped brownfields. This study proposes a feasible definition for "brownfield" in Taiwan and analyzes the remediation goals to enable their inclusion in future land-use categories for urban planning. In order to rank the various options for brownfield development by sustainability, this study evaluates the external costs and benefits based on the environmental impact. Finally, the brownfield sustainability index (BSI) was developed to determine the feasibility of sustainable redevelopment relevant to the different land reuse scenarios. For the selected study site, the option of green land with solar energy (ground P-Si panels) was determined to be the best choice compared with the commercial, residential, and industrial scenarios. This study provides a framework for planning brownfield assessment strategies to address the current soil and groundwater remediation and land use policy issues in Taiwan.

Keywords: brownfield sustainability index; life cycle; external costs; urban planning; solar energy

1. Introduction

In developed countries, brownfields are usually associated with high crime levels, population decline, and the downturn of economic activity in cities. Until the 2000s, there was no general definition of the term "brownfield" [1–6]. The United States Environmental Protection Administration (U.S. EPA) defines brownfields as "industrial and commercial sites which were abandoned, idled or unused, with the presence of environment pollutants or the possibility of existence of pollutants" [7]. The U.S. EPA proposed the Brownfields Revitalization and Environmental Restoration Act in 2001, which changed the way contaminated lands were managed. To provide a general guideline for managing brownfield sites, the U.S. EPA established statutory provisions, regulatory requirements, and policies [8]. However, strategies are yet to be developed for restoring a large number of potentially contaminated sites based on thorough investigation and efficient management approaches for reuse, such as the life-cycle perspective. Therefore, useful tools need to be established for the regeneration of potentially contaminated lands, and sustainable management strategies need to be developed further and incorporated into land and environmental regulations.

In Taiwan, underused industrial lands have existed since the 1980s. The owners of such lands have usually focused on land speculation rather than engaging in any industrial activities [9]. There was little incentive for the Taiwan Environmental Protection Administration (TWEPA) to prioritize the redevelopment of these contaminated sites, as it was simply easier to acquire and convert green land. Moreover, a large number of new potentially contaminated sites required the attention of the TWEPA. In Taiwan, low efficiency of management of new potentially contaminated sites is the lack of a comprehensive regulatory framework for urban planning and no brownfield reuse policies. If management of potentially contaminated sites does not consider urban planning, a large amount of time and money would be lost in investigating pollution conditions while not contributing much to the urban development. The number of potentially contaminated sites from abandoned factories has increased in Taiwan. Moreover, the presence of environmental pollutants on contaminated sites poses complex resulted in too much money and time on remediation and intractable problems for land redevelopment [10,11]. The delisting of contaminated sites has been delayed in Taiwan, and the delisting of only 29% of contaminated control sites (control sites and remediation sites) alludes to the difficulty of redeveloping contaminated sites in Taiwan (Figure 1). Under the current regulations, the TWEPA has made a significant effort to manage potential pollution from lands, such as from abandoned factories, by way of Articles 8 and 9 of the Soil and Groundwater Pollution Remediation Act (SGPRA). However, the administration of Articles 8 and 9 does not provide a clear method for the reuse of potentially contaminated sites in terms of the current regulations. TWEPA has been using the preliminary assessment (Hazard Ranking System (HRS)) to identify controlled sites in terms of Article 12 of the SGPRA [12]. However, this system has limited scope for the reuse/development of the "remediation site" using the remediation goals based on the risk assessment. Moreover, TWEPA assumes that these control sites have to be cleaned up to pass the regulation standards; therefore, if the contaminated soil and groundwater do not meet the regulation standards, the current regulations forbid any reuse of the control sites. Consequently, the person or entity potentially responsible for the pollution is required to draft a pollution control plan or remediation plan, with the aim to reduce the concentration of the pollutants to meet the regulation standards. However, there is no legal definition and comprehensive reuse procedure for "brownfields". As a result, remarkable resources have been spent on investigating and assessing pollution from potentially contaminated sites, but there has been no mention of developing a strategy for the redevelopment of brownfields in Taiwan. In contrast, the U.S. EPA has incorporated risk assessment to streamline the site assessment and cleanup of brownfields by combining pollutant characteristics, environmental transport mechanisms, and future land use [13]. In addition, the U.S. EPA established the Small Business Liability Relief and Brownfields Revitalization Act in 2002 to lay down a precise definition of "brownfield" and to develop the principle of potentially responsible stakeholders [14].



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Listed	11	19	20	43	65	85	103	132	166	193	244	300
Delisted	0	1	2	6	8	12	14	17	28	50	68	87

Figure 1. Accumulated number of contaminated sites declared and delisted by the Taiwan EPA from 2002 to 2013. (Other statistic data of listed remediation sites updated to 2015: https://sgw.epa.gov.tw/public/En/Default.aspx?Item=RemediationSites).

As there was no practical and economical way to restore all the contaminated sites to their original condition, the legal term "brownfield" was coined in an effort to remove the stigma associated with contaminated sites for marketing purposes and to present an urban image to such sites [15–17]. Therefore, as a sustainable strategy, appropriate policies, regulations, and assessment tools need to be designed for the reuse of brownfields [3,5,18–20]. Although the government could analyze the driving forces of market transactions based on the social and economic aspects of brownfield reuse, the criteria for defining "successful redevelopment" have rarely been studied [21–24]. Based on such criteria, the government could determine the sustainable management options for successful brownfield redevelopment that it desires. Most of the existing literature on brownfields is focused on the redevelopment process and the potential profit from the redevelopment [25]. In the past, the classification and evaluation of brownfields have been done usually according to the following four approaches for decision-making: (1) evaluation based on health and environmental risks, using, for example, the Hazard Ranking System developed by the U.S. EPA; (2) evaluation based on a cost–benefit analysis, for example, the A-B-C model and the external benefits of economic growth to evaluate brownfields based on the net monetary profit from development [26–28]; (3) evaluation based on the score of selected indicators covering social, environmental, and economic aspects, which could vary from the national to the local scale [29–31]; and (4) evaluation based on specific policy purposes, i.e., the renewable energy potential of brownfield sites. However, the brownfield regeneration decision-making models that have been developed in the past, such as the multi-attribute decision-making method, the risk analysis method, the cost–benefit analysis method, and the expert selection system were developed to evaluate the efficiency of the redevelopment of contaminated land [32–36]. Few studies have explored how to set up sustainable management objectives to reduce environmental impacts based on increasing economic value of the proliferating redeveloped brownfields. In the past, research has only assessed the external costs and environmental benefits to determine the best options for environmental policy [37–39]. However, a comparison of the net environmental benefits with the external costs of no action and the different scenarios has emerged as a good methodology to integrate into the life-cycle assessment of the long-term implementation of multiple management strategies [40,41].

The integration of economic benefits and environmental impacts is an important process for building sustainable principles in the redevelopment of brownfields. Although a comprehensive approach to rank the sustainable options for brownfields has been discussed, environmental, economic, and social indicators are usually evaluated qualitatively for brownfield management. Redevelopment of brownfields focusing on sustainable management should consider the environmental benefits of pursuing economic benefits by life-cycle thinking. Therefore, the authors have developed a brownfield reuse procedure for assessing the sustainable redevelopment of brownfield sites to suit the current legal framework of TWEPA. Moreover, this study defines a brownfield sustainability index (BSI) that evaluates the ratio of net external benefits and net economic benefits. In this index, life-cycle analysis for environmental impacts, including carbon emissions and water consumption, is evaluated for the remediation, construction, and reuse stages of potentially contaminated land.

2. Materials and Methods

2.1. Establishing the Management Procedure for Brownfield Redevelopment

Reusing brownfield sites is usually regarded as part of the urban planning for a more sustainable city. Therefore, the authors propose a feasible definition of "brownfield" in Taiwan as "potentially contaminated sites under Article 8 and 9 of SGPRA, which were abandoned and whose use is prohibited for urban and farmland purposes." This research developed a brownfield reuse framework that can be incorporated into the current remediation and urban planning regulations (Figure 2). In accordance with the current regulation under Article 12 of SGPRA, the authorities should order the cleanup of "remediation sites" if the HRS scores exceeded 20. HRS is used to establish the "double threshold system" and distinguish between "control sites" and "remediation sites", based on the environmental risk from the current characteristics of a site and the transportation potential of contaminants. A "control site" refers to a site where the contamination exceeds the regulation standards, whereas, a "remediation site" refers to a site where the contamination exceeds the HRS score or remediation goals, for which specific geological conditions can be set. However, this double threshold system is a special management strategy before implementing of the evaluating remediation goals in Taiwan. As a result, few remediation sites have been allowed to have flexible remediation goals, which could exist in specific geological conditions. Besides, current regulation standards consider only concentration to judge onsite safety for different contaminations but not multiple receptors. In contrast, remediation goals regarding urban planning consider more types of exposure pathways of on-site and off-site receptors. In order to protect all receptors from changing land use due to brownfield redevelopment, re-analyses of remediation goals are required. In this study, flexible remediation goals are advocated for urban planning when the pollutant concentrations exceed the regulation standards, but are still considered safe in terms of risk assessment, i.e., the cancer risk for humans is lower than 10^{-6} and the hazard quotient of non-cancer for humans is lower than 1. Then, the brownfield sustainability index (BSI) can be further evaluated based on the safety of all receptors. In addition, the remediation goals relevant to urban planning have more flexibility than the regulation standard because of the receptor-specific considerations of different land-use types. Therefore, a comprehensive brownfield redevelopment strategy could link the remediation goals with future land planning before a contaminated site is managed as a "double threshold system". As a result, this study proposes that such sites be defined as brownfields, including "control sites" and "abandoned factories", if their land use types will be changed during urban planning before being claimed as "remediation sites". The less contaminated sites, such as "abandoned factories", could be eligible to use flexible remediation goals in urban planning before the "double threshold system". However, remediation sites could require immediate remediation and any use of such sites could be forbidden based on the determination of remediation goals relevant to specific geological conditions. The authors recommend that the same management strategy of brownfield redevelopment should be applied to control sites and remediation sites if the remediation goals of the contaminated site were achieved. Finally, integrated sustainability assessment and management should be applied to rank the sustainability potential of the sites.

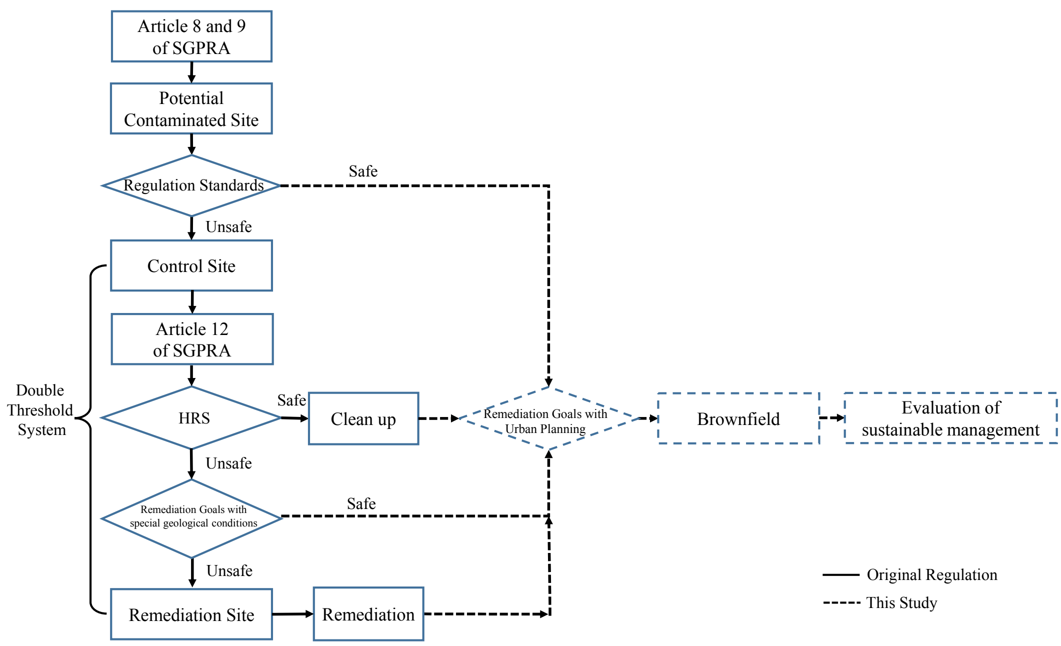


Figure 2. The management procedure incorporated into the current regulations for brownfield redevelopment.

2.2. Sustainable Assessment Indicators and Schematic Diagram of Brownfield Redevelopment

To assess the feasibility of the sustainable management of brownfields, indicators need to be developed to evaluate the impact on social, environmental, and economic aspects in order to comply with the desired sustainability goals. In determining how to incorporate sustainable development into urban planning, previous studies have noted that carbon emissions and water consumption were the main environmental concerns [42]. Therefore, the main objective of this study was the evaluation of a quantitative method that involves life-cycle thinking in order to determine the best sustainable reuse scenarios for the redevelopment of brownfields. This study examined a 25-year period of brownfield redevelopment, from the remediation phase to the reuse phase, based on an investigation of urban planning in Taiwan [43]. As a result, the authors developed schematics of the life cycle of brownfield redevelopment, including the remediation, construction, and reuse phases (Figure 3). The assessment categories of the external costs and the benefits to the environment, as well as the economic costs and benefits are shown in Table 1. To set up a useful brownfield sustainability index, the authors established a conceptual diagram, including the influential factors, the calculations for each factor, and the indicators (Figure 4). Using the life-cycle assessment of the environmental impacts of each phase, we analyzed the external costs of carbon and water emissions for the redevelopment and cleanup of contaminated sites. The driving factors contributing to the pollution conditions of sites determine the remediation goals and remediation technology; therefore, the authors calculated the cost of cleanup, remediation, and the impact costs from water and carbon emissions as external costs. In addition, the authors analyzed the carbon-emission mitigation benefits if renewable energy were sourced from the brownfields. Finally, the net external benefits were calculated as mitigation benefits minus external costs. Additionally, the authors collated a local database of building materials and construction types in order to assess the redevelopment costs, business value, and external costs of the reuse scenarios relevant to this study. In the economic cost benefit analysis, we analyzed land value and redevelopment costs from the remediation phase to the redevelopment phase for redevelopment stakeholders. Relevant to the socio-economic benefits, we considered additional income from employment in the socio-economic benefits. The details of the equations used to calculate the net external benefits and net economic benefits from the indicators of the brownfield sustainability assessment are shown in Section 2.3.

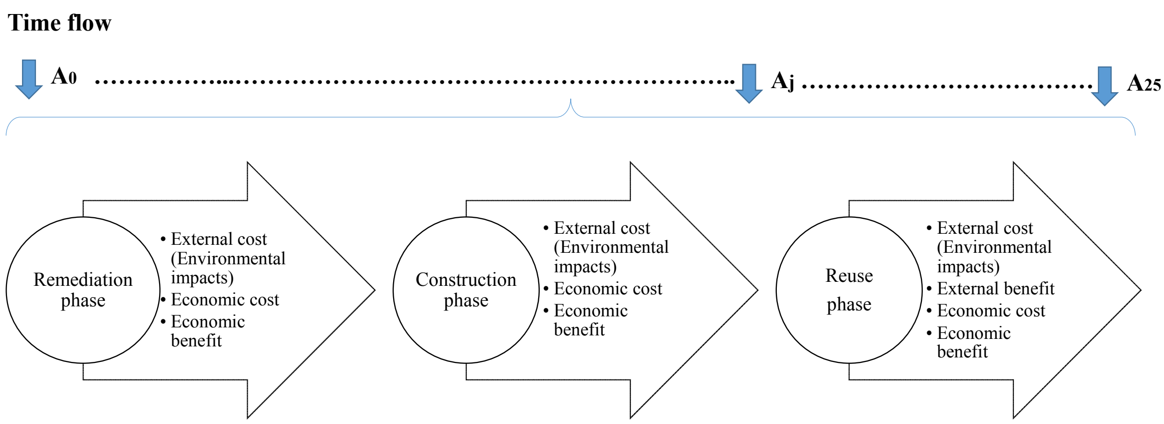


Figure 3. The schematics of brownfield redevelopment relevant to life-cycle thinking.

Table 1. The indicators and factors of brownfield sustainability assessment in this study.

Categories	Remediation Phase	Construction Phase	Reuse Phase
External Cost	Cleanup cost Remediation cost External cost from carbon and water emissions	External cost from carbon and water emissions from resource materials of new building Demolition cost	External cost from carbon and water emissions from human lifestyle
External Benefit	-	-	Mitigation benefit of renewable energy
Economic Cost	Land value (including stigma damage)	Building demolition cost	Redevelopment cost
Economic Benefit	-	-	Increased land value Business value Renewable energy subsidy
Social Benefit	Added employment income from remediation projects	Added employment income from construction projects	Added employment income from reuse projects

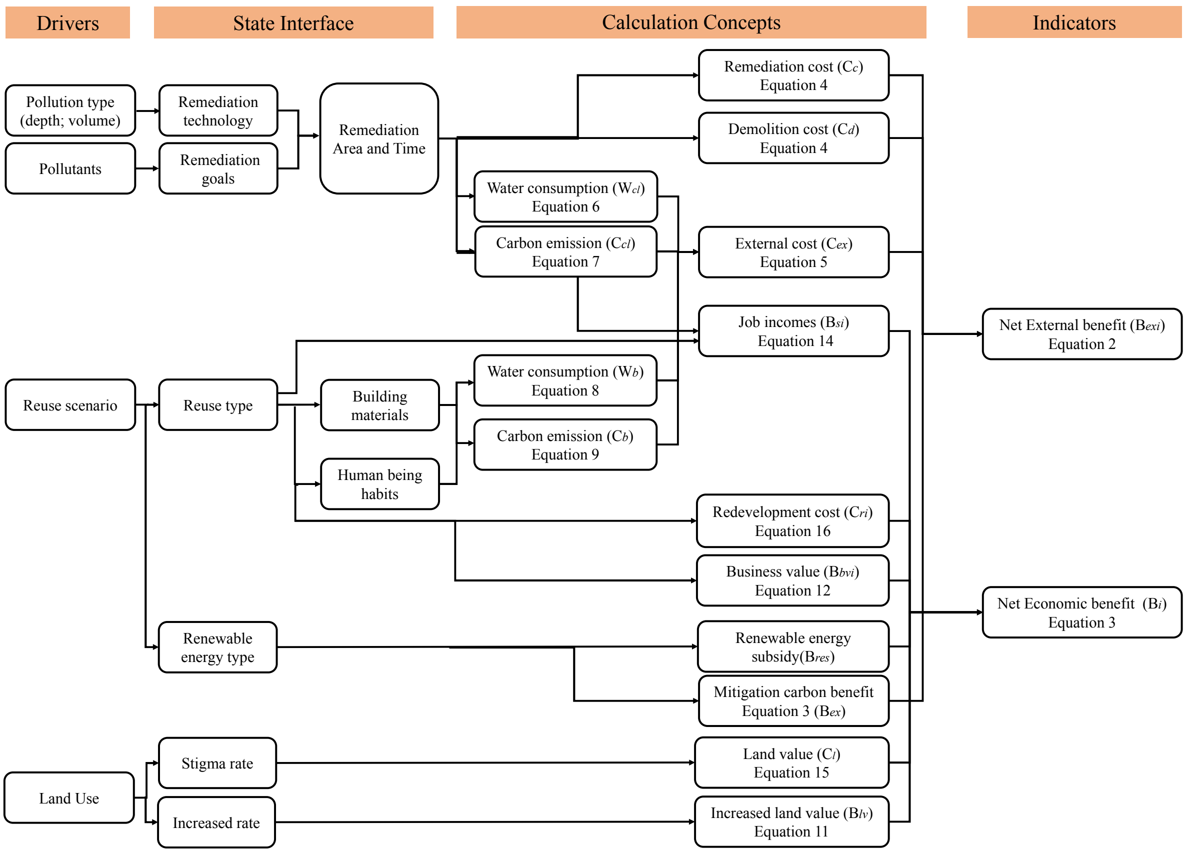


Figure 4. Conceptual diagram of the sequence of each process for the brownfield sustainability index.

2.3. *Establishment of the Brownfield Sustainability Index (BSI)*

This study considered the net present value (NPV) to determine the brownfield sustainability index. To determine the sustainability of brownfield redevelopment, reuse scenarios should not only have lower external costs but should also have higher economic benefits. Therefore, the authors calculated the net external benefits per net economic benefit in the brownfield sustainability index (BSI). In addition, the external costs and benefits, and the economic costs and benefits were combined and a commercial real estate discount rate of 6% was used as the ratio of the present value and net benefit benchmark index. Finally, the highest BSI value was determined to be the best choice. In this study, the brownfield sustainability index (BSI) was calculated by using the following formula:

$$\text{BSI} = B_{exi}\,(t)\;/B_i\,(t) \tag{1}$$

where t is the total "time for brownfield redevelopment"; i is the type of reuse phase, including residential, commercial, industrial, and green land; B_{exi} (t) is the net external benefits of i type; and $B_i(t)$ is the net economic benefits value of i type.

(a) Net external benefits

To analyze further the external costs and benefits in this study, the assumptions relating to the environmental impacts had to be considered. The water consumption and carbon emission factors were evaluated by using remediation technology based on the volume of soil and groundwater remediated. Additionally, site information, including the type of soil and contamination, the depth and area of the contaminated soil, and the density of the soil was taken into account to determine the best remediation technology and remediation time. In addition, the water consumption and carbon emission factors were evaluated by using material reuse and consumption data, as well as by looking at the lifestyle and behavior of human beings in the brownfield redevelopment scenarios. Therefore, the data on the structural types and construction materials in the redevelopment scenarios, including for residential, commercial, and industrial use, as well as renewable energy, were collected to analyze the environmental impacts of the resources. Moreover, the authors estimated the environmental impacts of brownfield redevelopment from the choice of reuse scenarios based on human behavior. The external cost per volume of water treatment (C_w) and that of carbon emissions per power plant (C_{ca}) were evaluated by taking into account local reports in Taiwan [44]. The renewable energy plan was found to be the best choice for improving external benefits by mitigating carbon emissions. This research calculated the external benefits of solar energy based on the primary strategies of brownfield redevelopment in Taiwan [45]. This can be calculated by the following equations:

$$B_{exi}\,(t) = B_{ex}\,(t) - [C_c\,(t) + C_{exi}\,(t)] \tag{2}$$

$$B_{ex}\,(t) = \sum_{t=A_j}^{A_{25}} \left[B_{ex}/\,(1+r)^t\right] \tag{3}$$

$$C_c\,(t) = \sum_{t=0}^{A_j} \left[C_c + C_d/\,(1+r)^t\right] \tag{4}$$

$$C_{exi}\,(t) = W_{cl} \times C_w + C_{cl} \times C_{ca} + Wb_i \times C_w + Cb_i \times C_{ca} \tag{5}$$

$$\mathrm{W}_{cl} = \sum_{t=0}^{A_j} [(W_r \times V)/\,(1+r)^t] \tag{6}$$

$$C_{cl} = \sum_{t=0}^{A_j} [(C_r \times CEC_e + C_{co} \times CEC_\alpha \times A)/\,(1+r)^t] \tag{7}$$

$$Wb_i = \sum_{t=A_j}^{A_{25}} [W_{re} \times A/\,(1+r)^t] \tag{8}$$

$$Cb_i = \sum_{t=A_j}^{A_{25}} [(C_{ri} \times CEC_e + \sum_{t=A_j}^{A_{25}} C_{re} \times CEC_{re})/\,(1+r)^t] \tag{9}$$

where A_j is the total time for remediation phase; r is the commercial real estate discount rate in Taiwan; $B_{ex}(t)$ is the total external benefits from carbon mitigation because of renewable energy use; $C_c(t)$ is the

the sum of cleanup costs and remediation costs; C_d is the the sum of demolition costs; $C_{exi}(t)$ is the external costs from water and carbon emissions of i type; W_{cl} is the total water consumption in the remediation phase; W_r is the water consumption per cleanup volume in remediation and construction phases; V is the the volume of cleanup and remediation; C_{cl} is the total carbon emissions in remediation phase; C_r is the electricity and fuel use in the remediation and construction phases; CEC_e is the carbon emission coefficient per electricity and fuel use; C_{co} is the electricity and fuel use for manufacturing materials for new buildings based on life-cycle analysis; CEC_α is the carbon emission coefficient of selected structural materials; Wb_i is the total water consumption of i type; W_{re} is the annual water use per unit floor area of i type; A is the the floor area or site area; Cb_i is the total carbon emissions of i type; C_{ri} is the annual electricity and fuel use per population of i type; C_{re} is the annual electricity and fuel use from renewable energy; CEC_{re} is the carbon emissions from the selected renewable energy type; C_w is the external cost per volume of water treatment in Taiwan; and C_{ca} is the external cost per carbon emission in the power plant in Taiwan.

(b) Net economic benefits

As regards the economic costs and benefits, the land value factors were calculated by using a stigma rate and the increased value in the different brownfield redevelopment scenarios [46]. The business value factors were calculated based on the residential rent and operation incomes of the commercial and industrial scenarios. The redevelopment costs were evaluated by using planning and design costs, advertising costs, sales charges, management fees, taxes, and other costs, and the interest on capital and profits. To improve the economic growth relevant to the framework of sustainable urban development, this research also assessed the economic benefits from added job opportunities. Subsequently, the authors calculated the annual remuneration of employees in each county from the remediation phase to the reuse scenarios. Net economic benefits were calculated by using the following equations:

$$B_i\,(\mathrm{t}) = [B_{lvi}\,(t) + B_{bvi}\,(t) + B_{res}\,(t) + B_{si}\,(t)] - [C_l\,(t) + C_{ri}\,(t)] \tag{10}$$

$$B_{lvi}\,(t) = \sum_{t=A_j}^{A_{25}} \left[B_{lvi}/\,(1+r)^t\right] \tag{11}$$

$$B_{bvi}\,(t) = \sum_{t=A_j}^{A_{25}} \left[B_{bvi}/\,(1+r)^t\right] \tag{12}$$

$$B_{res}\,(t) = \sum_{t=A_j}^{A_{25}} \left[B_{res}/\,(1+r)^t\right] \tag{13}$$

$$B_{si}\,(t) = \sum_{t=o}^{A_{25}} \left[B_{si}/\,(1+r)^t\right] \tag{14}$$

$$C_l\,(t) = \sum_{t=0}^{A_j} \left[C_l \times SR/\,(1+r)^t\right] \tag{15}$$

$$C_{ri} = \sum_{t=A_j}^{A_{25}} \left[C_{ri}/\,(1+r)^t\right] \tag{16}$$

where $B_{lvi}(t)$ is the total increased land value of i type; $B_{bvi}(t)$ is the total business value of i type; $B_{res}(t)$ is the total renewable energy subsidy; B_{si} is the total job incomes of i type; $C_l(t)$ is the total land value; SR is the stigma rate of contaminated site in Taiwan; and C_{ri} is the total redevelopment cost of i type.

3. Results

The study site, an abandoned chemical factory previously engaged in the manufacture of printed circuit boards (PCBs), was investigated because the copper pollution of the soil exceeded the regulation standard. The land area proposed for redevelopment amounted to 1905 m^2, with urban planning by the local government. Copper is classified as a group D chemical in the Integrated Risk Information System (IRIS) database, which indicates there are no data in terms of carcinogenicity relevant to humans of copper compounds [47]. The Agency for Toxic Substances and Disease Registry (ATSDR) develops toxicological profiles, considering the oral minimal risk levels (MRLs) for copper based on numerous regulations and guidelines [48]. In addition, the International Agency for Research on Cancer (IARC) defined copper as group 3, which implies that more research is required to determine whether it is carcinogenic or safe to human. In this study, screening levels were employed to set remediation goals with site-specific and chemical-specific information including exposure assumptions and toxicity principles, such as reference dose for copper [49]. According to the U.S. EPA guidelines, the maximum exposure dose of each pathway for different receptors was assumed for future land-use in order to analyze the remediation goals; the concentration of screening level corresponds to the cancer risk of 10^{-6} and the hazard quotient of non-cancer of 1 [50]. The analyzed context consisted of residential and green land, and considered the habits of adults and children, as well as the industrial/commercial land characteristics relevant to the occupational places of workers. Therefore, site-specific parameters, such as exposure relevant to lifestyle were replaced by information from the local database to reduce the assessment bias. In Taiwan, contaminated sites have to follow a single regulation standard to implement remedial actions. In the study area, to comply with regulations, copper levels had to be 400 mg/kg. This is extremely strict, with no flexibility in the permitted dosages for brownfield redevelopment. Therefore, the authors estimated the remediation goals of the different land uses to confirm the allowable concentration for redeveloping the brownfield site (Table 2). Relevant to the methodology of the remediation goals in this research, the target concentrations would be easier to meet if the brownfield sites were redeveloped as green space, or commercial or residential land. As a result, the study area had already acquired potential eligibility for brownfield redevelopment because the remediation goals could reduce the risk impact and minimize the remediation costs. In particular, if the study site could be changed to green land, the remediation goal (84,206.12 mg/kg) would be less stringent than that for other land uses. Additionally, the authors recommend that remediation goals replace the methodology of preliminary assessment (HRS) and regulation standards in the current regulations in Taiwan. In this way, the original schematic of the double threshold system of the SGPRA could be streamlined.

Table 2. Comparison between remediation goals and regulation standards of the study site.

Industrial Category	Pollutant	Regulation Standard (mg/kg)	Remediation Goals (mg/kg)		
			Residential Land	Industrial/ Commercial Land	Green Land
Electronic Components Manufacturing	Cu	400	11,261.29	72,024.99	84,206.12

This study further assessed the net external benefits (B_{exi}) and net economic benefits (B_i) in order to evaluate each phase of the four reuse scenarios (Figure 5). The economic benefits of residential, industrial, and commercial land were positive for three phases of brownfield redevelopment, indicating that such redevelopment implied growth in the economic category. Green land had the lowest economic benefits of all the phases of brownfield redevelopment, but it also obtained the best external benefits by mitigating carbon emissions. In contrast, commercial land obtained the highest economic benefits (1.83×10^{10} NTD) in comparison with residential and green land. The main reasons for the higher net economic benefit of commercial land are the higher contribution of business value per unit floor area (B_{bv}) and the greater land value (B_{lv}) compared with other land in Taiwan. However, the results of this study indicated negative external benefits for residential, industrial, and commercial land, particularly in the reuse phase. The authors further calculated the time and area available for the remediation and reuse phases for brownfield redevelopment according to the flexible remediation goals of different land types. Green land had the shortest remediation time and the highest area in which to develop solar energy. In contrast, negative external benefits associated with industrial land were attributed to the environmental impacts, such as the high annual water use per unit floor area (W_{re}) and the annual electricity or fuel use per population (C_r). Consequently, the worst choice for the study area was the industrial land scenario, although the net economic benefits were positive.

Figure 5. The economic benefits (B_i) and external benefits (B_{exi}) for each phase of the four scenarios.

To assess the sustainability of brownfield redevelopment, we calculated the brownfield sustainability index (BSI), as shown in Figure 6. The BSI was negative in all instances, except for green land. Therefore, converting to green land was the best choice because of the positive BSI (BSI = 0.13), attributable to the positive values of the net external benefit (B_{exi} = 5.22 $\times$ 10^6) and net economic benefit (B_i = 3.89 $\times$ 10^7). Converting to residential land was the second best choice (BSI = −0.01) because there were fewer environmental impacts that translated to negative external benefits (B_{exi} = −7.69 $\times$ 10^6).

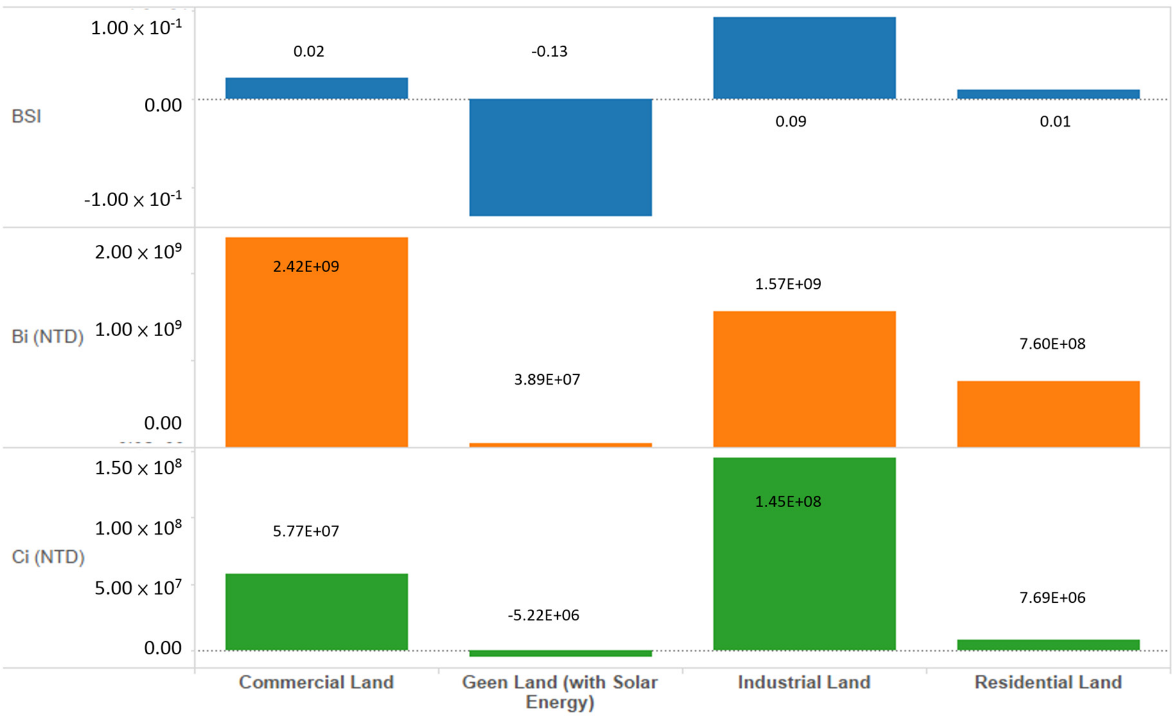


Figure 6. The brownfield sustainability index (BSI), net external benefits (B_{exi}), and net economic benefits (B_i) for the four scenarios.

4. Discussion

As regards the environmental impacts during the construction phase, the authors calculated only the carbon emissions using the floor area, based on three structural types, namely, reinforced concrete, steel reinforced concrete, and steel construction. Moreover, the water consumption and carbon emissions of different reuse land categories were the main causes of negative external benefits in the reuse phase. In addition, the data collected from consulting companies on the water use and carbon emissions in the remediation stage were determined based on the selected technologies. With the data on the usage of water, fuels, and electricity per ton of soil treated, the authors could obtain the total carbon emissions and water usage based on the formulae in the remediation phase. Consequently, the causes of different environmental impacts in the four reuse scenarios were determined from the variations of factors, such as the carbon emission coefficient (CEC_e, CEC_α, and CEC_{re}) and the annual water use (W_{cl}, Wb_i, W_r, and W_{re}).

In the economic cost–benefit analysis, the comparison of net economic benefits between industrial land and commercial land revealed higher operational costs for the industrial category than for the commercial category. This research analyzed the increased rate of present value of land in Taiwan as the main economic benefit of the four land use types. In addition, residential land in the reuse phase used only quantitative rent value to represent economic benefit. However, residential land in Taiwan has qualitative value from social factors and human comfort. Therefore, the uncertainty regarding home value suggests that additional data are required on the human benefits of residential land in order to complete the database for the brownfield sustainability index for further research, as well as data on, for example, ecological value. In addition, this research could include assessing innovative and sustainable methods of planning to reduce the above-mentioned impacts in the future.

5. Conclusions

The Taiwan EPA expends a remarkable amount of resources on the cleaning up of potentially contaminated sites during urban development. From the perspective of sustainable urban planning, the inadequate land use policy, including the reuse of brownfields, is attributable partly to the indicators of environmental and social impacts usually being qualitative, rather than quantitative. Therefore, a brownfield sustainability index, incorporating an urban plan, is an important strategy for brownfield redevelopment. To avoid land speculation under the guise of a cost–benefit analysis, this study uses environmental impacts and life-cycle thinking to explore the net external benefits per net economic benefits for the sustainable redevelopment of brownfields. This flexible method uses the remediation goals of different land reuse types to combine urban planning and contaminated site management. Furthermore, the authors recommend that the remediation of contaminated land be combined with urban sustainable development and green remediation to preserve soil fertility. This study developed a conceptual model to assess brownfield sustainability, namely, the brownfield sustainability index (BSI), which includes four environmental categories describing the net external benefits and six economic categories according to the net economic benefits (Figure 4). Although the conceptual model in this study did not measure equally the environmental, economic, and social sectors for brownfield redevelopment, the authors used quantitative analysis in the BSI to reduce and overcome uncertainty. In the future, the BSI will consider also ecological value to identify additional social and environmental costs and benefits from redeveloping contaminated sites in Taiwan.

This research developed a balanced approach to assist public and private stakeholders to choose between brownfield redevelopment options by using quantitative evaluation mechanisms. If the government facilitated sustainable development in the planning of brownfields, this tool could be employed to pre-screen the most appropriate land use patterns. In this study, the authors demonstrated that the value of solar energy could make the redevelopment of brownfields as green space the most competitive option in Taiwan.

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Abbreviations

The following abbreviations are used in this manuscript:

BSI	Brownfield sustainability index
NPL	National priorities list
GAO	General accounting office
SGPRA	Soil and groundwater pollution remediation action
TWEPA	Taiwan EPA
HRS	Hazard ranking system
NPV	Net present value
IRIS	Integrated risk information system
LCT	Life-cycle thinking

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