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Green and sustainable remediation (GSR) evaluation: framework, standards, and tool. A case study in Taiwan

Wen-Yen Huang[1] · Weiteng Hung[2] · Chi Thanh Vu[1] · Wei-Ting Chen[1] · Jhih-Wei Lai[1] · Chitsan Lin[1]

Abstract Taiwan has a large number of poorly managed contaminated sites in need of remediation. This study proposes a framework, a set of standards, and a spreadsheet-based evaluation tool for implementing green and sustainable principles into remediation projects and evaluating the projects from this perspective. We performed a case study to understand how the framework would be applied. For the case study, we used a spreadsheet-based evaluation tool (SEFA) and performed field scale cultivation tests on a site contaminated with total petroleum hydrocarbons (TPHs). The site was divided into two lots: one treated by chemical oxidation and the other by bioremediation. We evaluated five core elements of green and sustainable remediation (GSR): energy, air, water resources, materials and wastes, and land and ecosystem. The proposed evaluation tool and field scale cultivation test were found to efficiently assess the effectiveness of the two remediation alternatives. The framework and related tools proposed herein can potentially be used to support decisions about the remediation of contaminated sites taking into account engineering management, cost effectiveness, and social reconciliation.

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✉ Chitsan Lin
  ctlin@webmail.nkmu.edu.tw

[1] Department of Marine Environmental Engineering, National Kaohsiung Marine University, 142 Haijhuan Rd., Nanzih District, Kaohsiung City 81157, Taiwan, Republic of China

[2] National Cheng Kung University, Department of Resources Engineering, 1 University Road, Tainan City 70101, Taiwan, Republic of China

Introduction

Soil remediation is the reduction or removal of unwanted contaminants from the soil. During that process, the remediation activities themselves may also become an additional source of contamination (Yasutaka et al. 2016). Since the mid-1990s, with the significant increase in remediation sites, the scientific community has paid an increasing amount of attention to those additional threats introduced by remediation efforts, increasing the need for better evaluation and management of such remediation projects (Bardos et al. 2016).

The Sustainable Remediation Forum (SURF) has played an important role in connecting different stakeholders, disseminating knowledge, and building and developing a framework and set of criteria for evaluating remediation activities (Bardos et al. 2016). Although the original SURF was started in the USA in 2006, it has taken off more in Europe where there has been an increase in the number of SURFs and SURF evaluation activities throughout the continent (Bardos et al. 2016). These SURFS have produced publications covering guidance recommendations (NICOLE 2011), evaluation frameworks (CL:AIRE 2010, Holland et al. 2011), evaluation standards (ASTM 2013a, 2013b, ISO 2014), and evaluation tools (Lemming et al. 2010, Perini & Rosasco 2013, Beames et al. 2014, Volchko et al. 2014, Rosén et al. 2015). To keep up with the pace of these developments, there is continual need for case studies evaluating recommended remediation efforts and the accuracy of newly introduced tools of evaluation. Such case studies can facilitate refinement of the methods as well as expand their application, make possible greater understanding and wider adoption of these methods, and of course, encourage the further development of sustainable remediation methods (Bardos et al. 2016).

Although Taiwan is densely populated with limited land use, it has 2517 controlled hazardous sites, including 2295 farmlands, 79 gas stations, and 143 abandoned or operating factories (TaiwanEPA 2012). While many soil remediation

projects have been undertaken there in the past 20 years (TaiwanEPA 2012), little attention has been paid to evaluating the results of these projects. There remains the possibility that these remediation activities, themselves, may have had a negative impact on human health and the surrounding environment. Concern over insufficient remediation or inappropriate remediation activity has inevitably given rise to the need for better evaluation of these efforts for which suitable frameworks, standards, and tools related to the assessment of soil remediation activities are required (TaiwanEPA 2013c). Different evaluation tools have been developed to evaluate remediation activities and use such approaches as cost-benefit analysis (monetization) (Söderqvist et al. 2015), CO_2 calculation (Praamstra 2009), and spreadsheet-based methods (Rosén et al. 2015, Yasutaka et al. 2016) that vary in the indicators they use (environmental, social, or economic), weighting systems they use (qualitative, quantitative, and semiquantitative), and how their results are displayed (excel sheets, tables, or graphs). The combination of tools used depends largely on the contaminants, the nature of the contaminated site, requirements of local agencies, and the professional judgment of remediation practitioners (Beames et al. 2014, Bardos et al. 2016).

In 2012, the US Environmental Protection Agency (USEPA) introduced what is known as the Methodology for Understanding and Reducing a Project's Environmental Footprint (USEPA 2012). This methodology included a quantitative evaluation tool called spreadsheets for environmental footprint analysis (SEFA). The tool was created using the framework "green and sustainable remediation (GSR)" developed by the Interstate Regulatory Council (ITRC 2011) which incorporated the USEPA's concept of green remediation. "Sustainable remediation" concerns itself with the evaluation of the social, economic, and environmental impacts of remediation efforts (ISO 2014; Bardos et al. 2011). "Green remediation," however, represented by Interstate Regulatory Council's GSR framework, concerns itself with the evaluation of five core elements: (1) energy, (2) air, (3) water resources, (4) materials and wastes, and (5) land and ecosystem. The spreadsheets used in SEFA are designed to cover the five core elements of GSR and quantify energy consumption and carbon footprint produced by remediation efforts. These five core GSR elements should be incorporated in the development of best management practices when remediating contaminated sites, as they would help ensure the overall success of the remediation efforts.

This case study tested the use of GSR-based SEFA and field scale cultivation test to evaluate the results of two different remediation efforts (chemical oxidation and bioremediation) on one site contaminated with total petroleum hydrocarbons (TPHs) divided into two study lots. The results of this case study may contribute to our understanding of how the GSR framework, a set of standards and related tools, may be applied to domestic remediation projects.

Evaluation framework

Related acts

This part of discussion is specific to Taiwanese laws and regulations. In Taiwan, when developing a framework for evaluating remediation activities, it is important to first consider what domestic environmental laws define as land needing remediation and what standards they set for remediation efforts before, during, and after remediation. For example, these laws are used to sets standards for determining whether immediate remediation or monitored natural attenuation (MNA) options are needed (Declercq et al. 2012). Some may also legislate which technologies or combination of technologies is required for the remediation of certain types of sites (Woll et al. 2003, Simon 2010). Any framework that does not take in the environmental laws of a country would be careless.

Table 1 lists the various legislative environmental acts introduced in Taiwan (TaiwanEPA 2012, 2013a). These legislative documents generally cover air (greenhouse gas emission, air pollution control and quality), water (drinking water, surface water, and groundwater), soil, and materials and waste (especially the concentration of toxic chemicals) because remediation activities themselves can produce greenhouse emissions, wastewater, and many types of wastes originating from both from onsite and offsite sources (TaiwanEPA 2013a). Because laws are most often based on previous scientific findings and conclusions, it is important for an evaluation framework to include what might be legislated in the future.

Plans for soil remediation need to take into account not only the impact of remediation but also the laws designed to reduce the negative impact of remediation activities on the people and their recreational activities in the surrounding areas (Woll et al. 2003, Rosén et al. 2015), as well as laws enacted to reduce noise and toxic gasses that might affect neighboring areas (Bardos et al., 2001). From a green point of view, future laws may be enacted to minimize materials and waste and ensure that standards of resource recycling or reuse and waste disposal be followed (Lemming et al. 2009, Lemming et al. 2010, Prior 2016). They may also call for educating people involved in the process about possible environmentally unfriendly behaviors (Abbot 2005).

Evaluation framework for GSR

Figure 1 depicts the proposed framework for evaluating green and sustainable remediation (GSR). The framework is divided into two stages: site assessment, which occurs before remediation, and site verification, which occurs during and after the remediation.

Table 1 Taiwan's Acts related to remediation

No.	Acts	Date issued
1	Basic Environment Act/Constitution Level	December 11, 2002
2	Air Pollution Control Act	May 23, 1975 (amended on December 19, 2012)
3	Clean Environment Greening Promote and Landscape Esthetics Act (Draft)	September 12, 2013
4	Drinking Water Management Act	November 10, 1972 (amended on January 27, 2006)
5	Environmental Agents Control Act	November 10, 1997 (amended on January 27, 2006)
6	Environmental Impact Assessment Act	December 30, 1994 (amended on January 08, 2003)
7	Greenhouse Gas Reduction Act (Draft)	July 01, 2015
8	Indoor Air Quality Act	November 23, 2011
9	Marine Pollution Control Act	November 01, 2000 (amended on June 04, 2014)
10	Noise Control Act	May 13, 1983 (amended on December 3, 2008)
11	Public Nuisance Dispute Mediation Act	February 01, 1992 (amended on June 17, 2009)
12	Resource Recycling Act	July 03, 2002 (amended on January 21, 2009)
13	Resource Recycling Reuse Act (Draft)	July 25, 2013
14	Soil and Groundwater Pollution Remediation Act	February 02, 2000 (amended on February 03, 2010)
15	Sustainable Development Basic Act (Draft)	December 30, 2010 (amended on February 21, 2012)
16	The Environmental Education Act	June 05, 2001
17	Toxic Chemical Substances Control Act	November 26, 1986 (amended on December 11, 2013)
18	Waste Disposal Act	July 26th, 1974 (amended on May 29, 2013)
19	Water Pollution Control Act	July 11, 1974 (amended on February 04, 2015)

Site assessment

In this framework (Fig. 1), we first determine whether possibly contaminated land (or brownfield) should be designated a remediation site (in need of urgent remediation) or a control site (in need of monitoring while it naturally recovers or a site whose remediation could be postponed until a later date). This designation can be based on such preliminary data as the concentration of the contaminants, site location, or its future use (Woll et al. 2003, Maurice et al. 2007, Declercq et al. 2012). When a site is designated a control site, any plans for routine monitoring or ongoing monitoring results should be announced to the public to ensure public awareness of the site and prevent unintentional trespassing (Declercq et al. 2012, Prior 2016). If the site is designated a remediation site, then the framework calls for determining whether evaluators can use the "triad approach" to manage decision making. Developed by USEPA, the triad approach helps resolve "decision uncertainty" taking into consideration the site's contamination history (systematic planning), the results of real-time field analytical methods, and input from all stakeholders including experts and overseeing boards (dynamic decision making) (Woll et al. 2003, Ellerbusch et al. 2004, Mack et al. 2004). The use of the triad approach makes possible

more rapid, efficient, and cost-effective assessment and remediation activities (Ellerbusch et al. 2004, Maurice et al. 2007). When using the triad approach to determine which remediation measures are to be taken, the remediation team must take into consideration all the materials, equipment, resources (human and non-human), and stakeholders' involvement (Mack et al. 2003, Mack et al. 2004). When doing this, conceptual site models (CSMs) for the site are generated to estimate the amount of contaminants, distribution, fate, possibility of exposure possibility, and probable mitigation measures (ITRC 2003, Woll et al. 2003). All possibilities are taken into consideration to produce the soundest remediation plan with the aim of cutting remediation costs and reduce the uncertainties involved (Mack et al. 2003, Mack et al. 2004). If the CSMs are incomplete, then input variables are reviewed and adjusted until the models can be completed (Woll et al. 2003, Mack et al. 2004).

Once the triad approach had been used to comprehensively characterize the site and suggest possible remediation models, then any legal restrictions on remediation activities and land use must be taken into consideration. For example, if the land will be used for cultivation purposes in the future, then the plans must not include any remediation activities that would negatively impact soil fertility and bioactivity. Additionally,
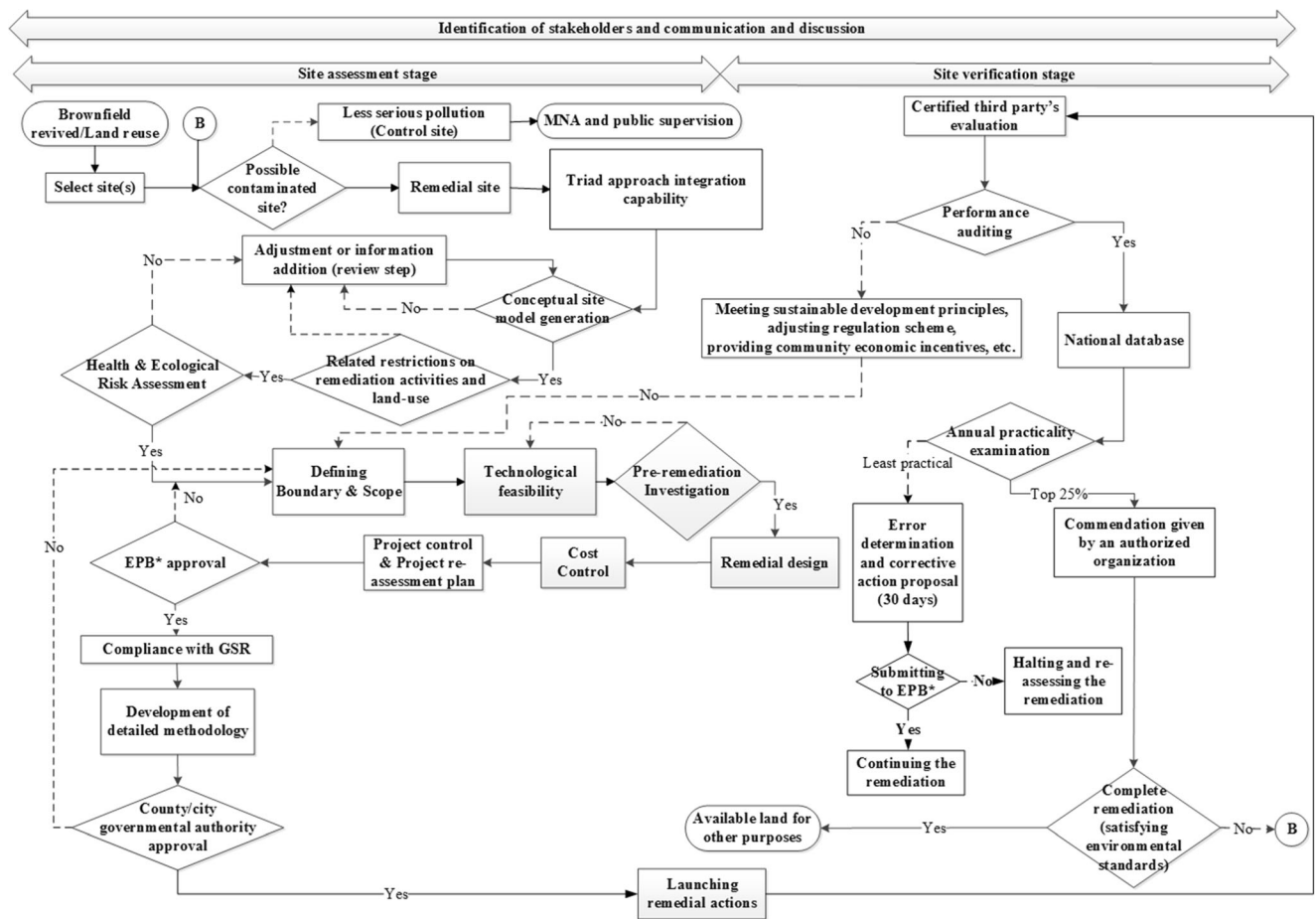
Fig. 1 Evaluation framework for green and sustainable remediation, *In Taiwan, there are only two levels of environmental management. While central-scale Taiwan Environmental Protection Agency (Taiwan EPA) is responsible for composing acts and distributes funding for remediation projects in all the administrative areas, the local-scale Environmental

Protection Bureaus (EPB) implements the remediation-related acts and supervises the remediation works. Due to the large number of local-scale remediation projects, the role of local-scale EPBs is very important and is emphasized in this study

health and ecological risk are assessed to ensure that the remediation activities have a low impact on the health of the workers or people in the neighborhood and a minimal impact on the ecosystem (Geckeler et al. 2010, Simon 2010, 2011, Söderqvist et al. 2015), as any negative impact in these areas would result in significantly higher remediation costs (Schirmer et al. 2012). If the results of these assessments do not meet the set standards, the possible remediation activities are reviewed and changed or adjusted, and then land use readiness and health and ecological risk are reassessed.

To further assess the site, the boundary and scope of the remediation are defined. To do this, the remediation team must consider the manufacture of materials and the equipment needed for remediation effort as well as the transport of soil and the disposal of waste together with the energy necessary to carry them out on site (Yasutaka et al. 2016). Then, technological feasibility is assessed to determine whether the technology is available (Mack et al. 2003, Woll et al. 2003) and a pre-remediation investigation is performed to determine if the use of these technologies is appropriate (Woll et al. 2003). For

example, if a site is found to lack space, then sizeable ex situ technologies would be inappropriate or if the feasible technologies were unavailable in Taiwan, then the options should be discarded because greater costs might incur.

Once the variables and goals are understood, the remediation activity is designed detailing the technologies needed in performing the remediation. The design should be completely accepted by different stakeholders, including administrative bodies, academic institutions, remediation practitioners, local citizens, and property owners as well as related industries and non-governmental organizations (NGOs), etc. (Woll et al. 2003, Beames et al. 2014). Defining which parties should be involved in the remediation design may largely depend on the specific characteristics of the remediation site, the availability of instructive documents provided by the government, and partly on the professional judgment of the remediation practitioners (Woll et al. 2003, Cundy et al. 2013, Prior 2016).

Cost control follows. Whole-life-cost-related issues starting from the initial setup all the way through to the last stage are estimated carefully, taking into account any casualties that may

occur during or after the remediation (Kaufman et al. 2005). A limit, however, should be set for the total budget spent on the remediation activities (Woll et al. 2003). Cost control is followed by project control and project reassessment plans. Here, instructions and human resources for the control and reassessment of the project are clarified and may be adjusted and updated gradually even during the remediation in response to casualties and unforeseen difficulties (Woll et al. 2003).

Once the design is conceived and its details are worked out, it needs approval by the Environmental Protection Bureau (EPB), a local branch of the Taiwan's EPA. If not approved, boundary and scope may need to be redefined. If the plan complies with GSR principles*, the remediation planners can begin to develop a detailed methodology, which includes the operational steps, the standard of operation (SOP) for the device, the detailed location of the remediation activities, human resources, responses to casualty, data collection, the frequency of report, etc. Further, the methodology should include frequent monitoring of the contamination state of the site during and after the remediation (Mack et al. 2003, Mack et al. 2004, Maurice et al. 2007), with the results of that monitoring used to evaluate the GSR performance. Before any remediation actions can be launched, the final step, county or city government approval of the plan and methodology by the highest governmental body in a specific city or county, must be granted. Similar to the EPB approval step, a review of boundary and scope is required if no approval is granted.

Site verification

The second stage of this proposed framework is site verification, which involves evaluating the remediation process and its conformity to the relevant laws during and after the remediation. This requires a certified third party able to guarantee an independent and objective evaluation. This third party is responsible for evaluating the remediation activities ensuring that they are in accordance with GSR standards. If they are, records of remediation are entered into the national database. If not, then the boundary and scope needs to be reviewed and adjusted. Issues such as green and sustainable development principles, Taiwanese regulation scheme, and community economic incentives should be reconsidered at this time. The EPB examines the practicality of the GSR projects annually. The teams in charge of the least practical projects need to determine their errors and propose corrective actions within 30 days. If the EPB finds no improved practicality, then remediation must be halted and reassessed with remediation teams bearing the brunt of all reassessment costs. The top 25 % most practical GSR projects, on the other hand, will receive the commendation given by an authorized organization. Eventually, when the remediation is complete and related environmental standards are satisfied, the land is returned for reuse or redevelopment. When environmental standards are not satisfied, then decisions shall be made as whether continuing

remediation is necessary or only MNA is needed (site assessment stage).

Scheme of site assessment stage

The initial site assessment stage is most important for setting the GSR framework standards as it establishes the standards or criteria for evaluation to be used during the site verification stage.

Figure 2 shows which standards were applied during the site assessment stage for the proposed remediation. Two guidelines were used to determine whether the possibly contaminated site is a needing-immediate-remediation site or a control site. They were chosen for lack of better alternatives. The first set we used was American Society for Testing and Materials (ASTM) WK23495—Guide for Green and Sustainable Site Assessment and Cleanup (proposed standard), though at the time of this study, these guidelines were merely proposals and had yet become official. The second set we used was ASTM E1984-03—Standard Guide for Process of Sustainable Brownfields Redevelopment. It was withdrawn in 2012 and to date has not been replaced. These two documents, when they are made available again, should introduce in-depth strategies for the integration of the principles of GSR into a remediation plan starting from the very first step. Until then, for the purpose of this study, they remain helpful and are by no means a disappointing option. At least, they can provide a glimpse into the kinds of GSR principles that can be incorporated into the specific remediation. Once a site is selected for remediation, two other general guidelines are used to direct what kind of assessment the site requires. They were ASTM E1527-05—Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process and ASTM E1903-11—Standard Practice for Environmental Site Assessments: Phase II Environmental Site Assessment Process. Both documents provide criteria and outline the steps needed to assess a remediation site.

Once assessment begins, the site needs to be studied in detail. For this, the triad approach is used. The detailed guidelines for applying the triad approach to assess a site and cleanup can be found in USEPA (2013). Models of various remediation approaches are created. Their creation can be guided by ASTM E1689-95 (2014)—Standard Guide for Developing Conceptual Site Models for Contaminated Sites. The ASTM E1689-95 (2014) is an instructive document detailing with every aspect of building conceptual site models for the contaminated sites and cannot be overlooked.

During the assessment of engineering and legal restrictions on remediation activities, two sets of guidelines are particularly relevant. One is ASTM E2091-11—Standard Guide for Use of Activity and Use Limitations, including Institutional and Engineering Controls and the other is ASTM E2435-05
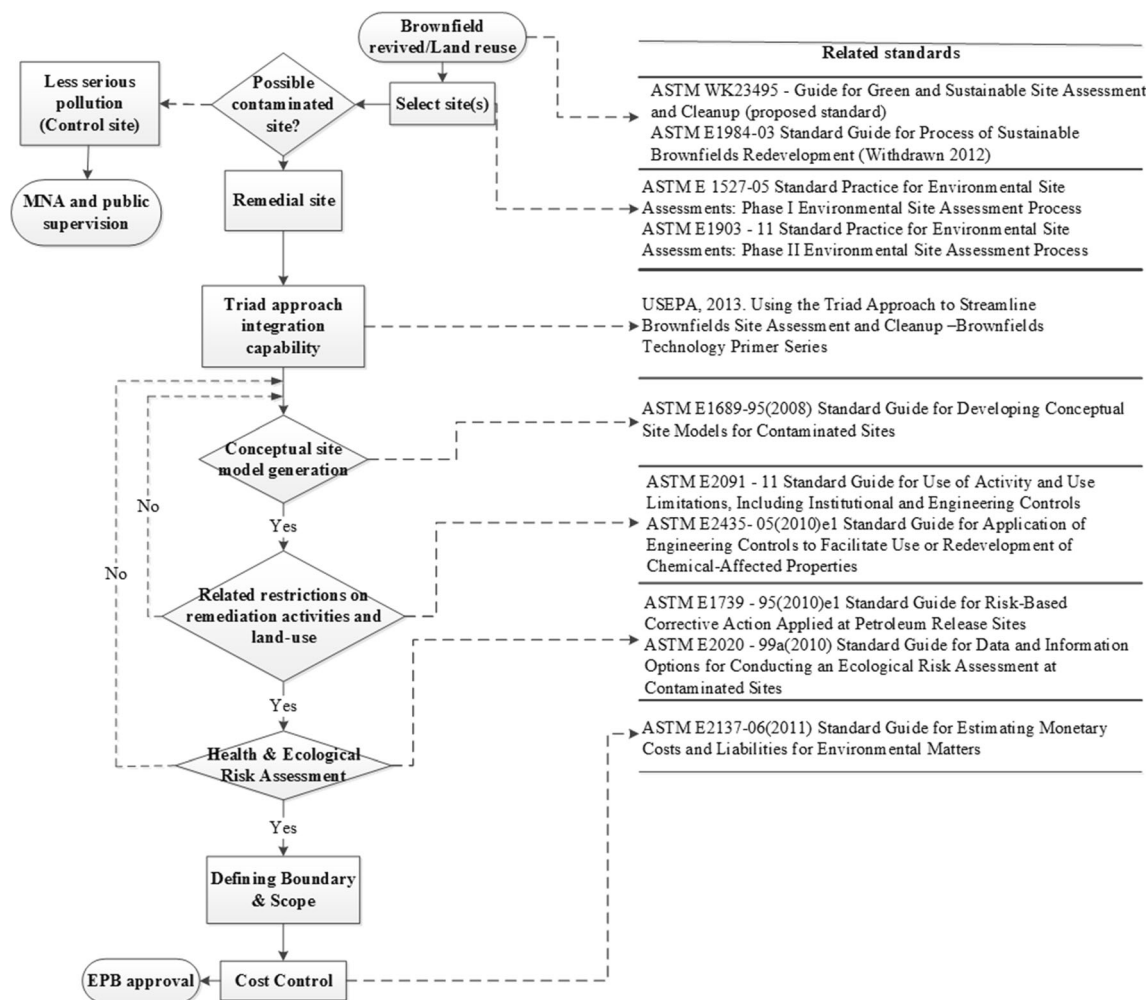
Fig. 2 Site assessment stage scheme

(2015)—Standard Guide for Application of Engineering Controls to Facilitate Use or Redevelopment of Chemical-Affected Properties. Both address a broad range of restrictions ranging from engineering restrictions to institution-related restrictions. Because they may alter the design of remediation projects, these restrictions should never be considered redundant when considering the use of possible remediation activities.

For health and ecological risk assessment, two other guidelines are useful. One is ASTM E1739-95 (2015)—Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites and the other is ASTM E2020-99a (2010)—Standard Guide for Data and Information Options for Conducting an Ecological Risk Assessment at Contaminated Sites. Both provide instructions and standards for assessment of issues relative to human health and the threats to the ecosystem. Any risks stemming from the remediation toward human health and the ecosystem can increase the costs and give rise to social issues (Woll et al. 2003, Söderqvist et al. 2015).

Therefore, any possible risk in these two areas should be identified and plans should be made to reduce that risk. If plans are not consistent with the standards or guideline in these documents, then a return to the model generation is needed and the whole remediation plan may need adjustment.

Finally, assessment of remediation activity requires cost control. Costs can be estimated following ASTM E2137-06 (2011)—Standard Guide for Estimating Monetary Costs and Liabilities for Environmental Matters. This standard guide will clarify cost-related issues involved in environmental matters. The document also provides formulas and tools needed for cost estimation.

Case study

We performed a case study using GSR-based SEFA and field scale cultivation test to evaluate the results of chemical oxidation

and bioremediation on one TPH-contaminated site divided into two different study lots.

Site description

The study site selected was an abandoned gas station where total petroleum hydrocarbon (TPH)-contaminated soil (classified as sandy loam) was dug up for treatment. Most of the soil was excavated from around leaking underground storage tanks. The site, located in northern Kaohsiung City, Taiwan, had an area of about 200 m^2. The initial TPH concentration was approximately 3000 mg/kg dry soil, three times higher than the standard limit—1000 mg/kg dry soil (TaiwanEPA 2014).

TPHs are a mixture of hydrocarbons found in petroleum products and include the toxic compounds benzene, toluene, ethylbenzene, hexane, naphthalene, xylenes, etc. (Chiu et al. 2013). The negative impacts of TPHs on human health and the ecosystem have been well documented (Park & Park 2010, Pinedo et al. 2014, Zhou et al. 2014). In Taiwan, many sites have been found to have enough TPH soil and groundwater contamination to require urgent remediation (TaiwanEPA 2013b).

The results of our "technological feasibility" analysis suggested five possible remediation activities: incineration, low temperature thermal desorption, soil washing, chemical oxidation, and bioremediation. However, the first two technologies were rejected due to possible high costs (Kulkarni et al. 2008) as well as possible fire and explosive hazards. The third option, soil washing, was also rejected because it would produce a large amount of wastewater needing additional treatment (Trellu et al. 2016), which would increase the total cost of remediation. The last two technologies, chemical oxidation and bioremediation, were finally selected because they were deemed either to be less harmful to the environment or more easily controlled.

Spreadsheets for environmental footprint analysis (SEFA)

Overview of SEFA

In this study, SEFA was used to evaluate the footprint of two remediation activities: chemical oxidation and bioremediation. SEFA is a quantitative evaluation tool that characterizes the environmental footprint (water and energy use, air emissions) produced by the remediation activities (USEPA 2012). A clear understanding of this environmental footprint can facilitate the decisions that need to be made about the remediation approach, choice of remediation activities, and the remediation processes (Woll et al. 2003, USEPA 2012). SEFA makes possible the good management of the environmental footprint which can also help reduce remediation costs (Woll et al. 2003).

Although SEFA is by no means a detailed life cycle assessment (LCA)* (USEPA 2012), this spreadsheet-based evaluation tool responds quickly to data input, has an easily read display,

and is user friendly. It produces sufficiently detailed and trustworthy results. Furthermore, the tool can be easily accessed via https://clu-in.org/greenremediation/methodology/. The aims of the SEFA when evaluating the five core elements of the environmental footprint are as follows:

1. Energy. It encourages the use of alternative fuels and clean and renewable energy and minimizes the total energy consumption for the remediation project.
2. Air. It aims to reduce air pollution and greenhouse gas emissions.
3. Water resources. It aims to reduce the consumption of water and decrease the negative impact of remediation activities on natural water resources.
4. Materials and wastes. It aims to make possible the better management of raw materials and the reduction of waste.
5. Land and ecosystem. It aims to protect the ecosystem by helping provide an evaluation that can be used to choose remediation activities least harmful to the land and the ecosystem.

Table 2 shows the steps taken to perform a SEFA analysis starting with the first step, setting up remediation goals, objectives, and scope; followed by the evaluation of the five core elements subdivided into measureable parameters; and ending with the last step which reports on sustainability and potential costs. The values for these parameters are mathematically obtained through basic calculations, estimated according to technical information, or obtained based on the recorded data of previous projects (USEPA 2012).

Field-scale cultivation test

While SEFA states clearly that land and ecosystem is an important consideration when evaluating remediation activities, it does not clearly define how that is measured. To measure soil fertility, we used methods recommended by the American Society for Testing and Materials (ASTM) and the International Seed Testing Association (ISTA), which include the measurement of pH values (ASTM D4972-13), electrical conductivity (ASTM E1004-9), ash content (ASTM D2974-14), carbon-to-nitrogen ratio (ATSM D5291-10), and percentage of germinated seeds (ISTA Orange and Blue) (Table 6). Bioactivity is an important consideration (Conte et al. 2001, Fava and Piccolo 2002, Conte et al. 2005). To evaluate this, the study site was divided into two lots (100 square meters each). The background soil for both lots was categorized as sandy with a small amount of silt (less than 20 %). The study lots were refilled with their respective remediated soils to a depth of about 25 to 30 cm. We also planted the same maize seeds (Taiwanese hybrid yellow sweet type) on both lots each containing 15 rows and 32 lines of maize and the distance between two consecutive stalks was approx. 30 cm. The lots

Table 2 Seven steps of SEFA analysis (USEPA 2012)

Step 1	Setup remediation goals, objectives, and scopes
Step 2	Collect data and information related to feasible remediation technologies
Step 3	Quantify amount of raw materials required and waste generated onsite and offsite, including the manufacture and transportation of materials and the generation, transportation, remediation and disposal of waste
Step 4	Quantify the amount of water required for the remediation and the amount from reuse or recycling sources. Types of water may cover tap water, surface water, groundwater, stormwater, or reused and recycled water from the remediation
Step 5	Quantify the amount of energy consumption and air emissions. Energy can come from various sources such as biomass, sun, wind, geothermal, etc. Air emissions include carbon dioxide emissions, NOx, SOx, HAPs, GHGs, etc.
Step 6	Qualitatively describe the affected ecosystem services both positively and negatively by the remediation action
Step 7	Report remediation evaluation, including aspects of sustainability (energy and water consumption, materials used, waste generated, air emissions, soil fertility, etc.) and potential costs incurred.

were irrigated with the same amount of water at the same times. We measured plant growth once a week (Fig. 3) and ear size after 10 weeks (Table 7) and noted any anomalies. We assumed that the greener of the two remediation activities would produce more fertile land that would produce healthier crops.

Results and discussion

Characteristics of the two remediation activities

The contaminated land was divided into two lots, one remediated with chemical oxidation and the other by bioremediation. Chemical oxidation employed hydrogen peroxide (H_2O_2) vapor sprinkled onto overturned contaminated soil using an excavator (backhoe). It was assumed that hydrogen peroxide would facilitate oxidative capacity by inducing the production of hydroxyl radical (·OH), a very powerful oxidative species (Cheng et al. 2016). During this process, the soil was continuously overturned to ensure that the hydrogen peroxide sprinkled on the surface could reach all contaminated soil particles. Bioremediation, which involved aerobic food waste composting, was simultaneously carried out on the other lot of land. Food waste and contaminated soil were commingled together with a consistent air supply during the treatment. It was thought that food waste would provide nutrients supporting the growth of naturally available TPH-degrading bacteria leading to their decontamination of the soil (Chen et al. 2015). The durations of the treatment technologies were 5 weeks each. Both remediation processes met the Taiwan Environmental Protection Agency's remediation standards for that type of contaminated land (1000 mg/kg dry soil) (TaiwanEPA 2014).

Tables 3 and 4 show what data were input into the SEFA to characterize transportation, equipment, materials, and water

usage needed to perform the chemical oxidation and bioremediation, respectively. The entry of these data factors is important to SEFA results. With regard to transportation, although both required the same number of trips (ten), types of cars and fuel types, chemical oxidation required longer transportation distances, though the distance only marginally affected energy consumption. With regard to the onsite equipment needed, the two methods of remediation required different devices, leading to large differences in energy and water consumption as well as air emissions. While the number of hours needed to run that chemical oxidation equipment was greater than that needed for bioremediation, bioremediation required more equipment. The energy needed remained unknown at this point. The materials used for both remediation technologies were rounded 50 t of hydrogen peroxide (for chemical oxidation) and food waste (for bioremediation) (1 t materials/1 t TPHs). However, due to the need to dilute the chemical agent (3:1), chemical oxidation required almost 130 more tons of tap water than bioremediation.

SEFA evaluation of the two remediation processes

One core element of SEFA is materials and waste. As can been seen in Table 5, the sustainability results produced by our SEFA analysis, both remediation technologies required the use of unrefined materials (hydrogen peroxide and food waste). The unrefined materials are those that are used onsite originating from offsite sources and have not been through any significant processing or refinement (USEPA 2012). Although hydrogen peroxide requires some processing, that processing is not complicated enough for it to be considered a refined substance (Seo et al. 2016). Still, chemical oxidation required the use of 50 t of hydrogen peroxide, which would clearly make it "less green" compared to 50 t of food waste, based on the perspective that use of recycled or reused

Fig. 3 Field scale tests of remediated-soil bioactivity. **a** Comparison of corn growth (after 10 weeks), **b** comparison of corn root systems, and **c** comparison of growing height of corns
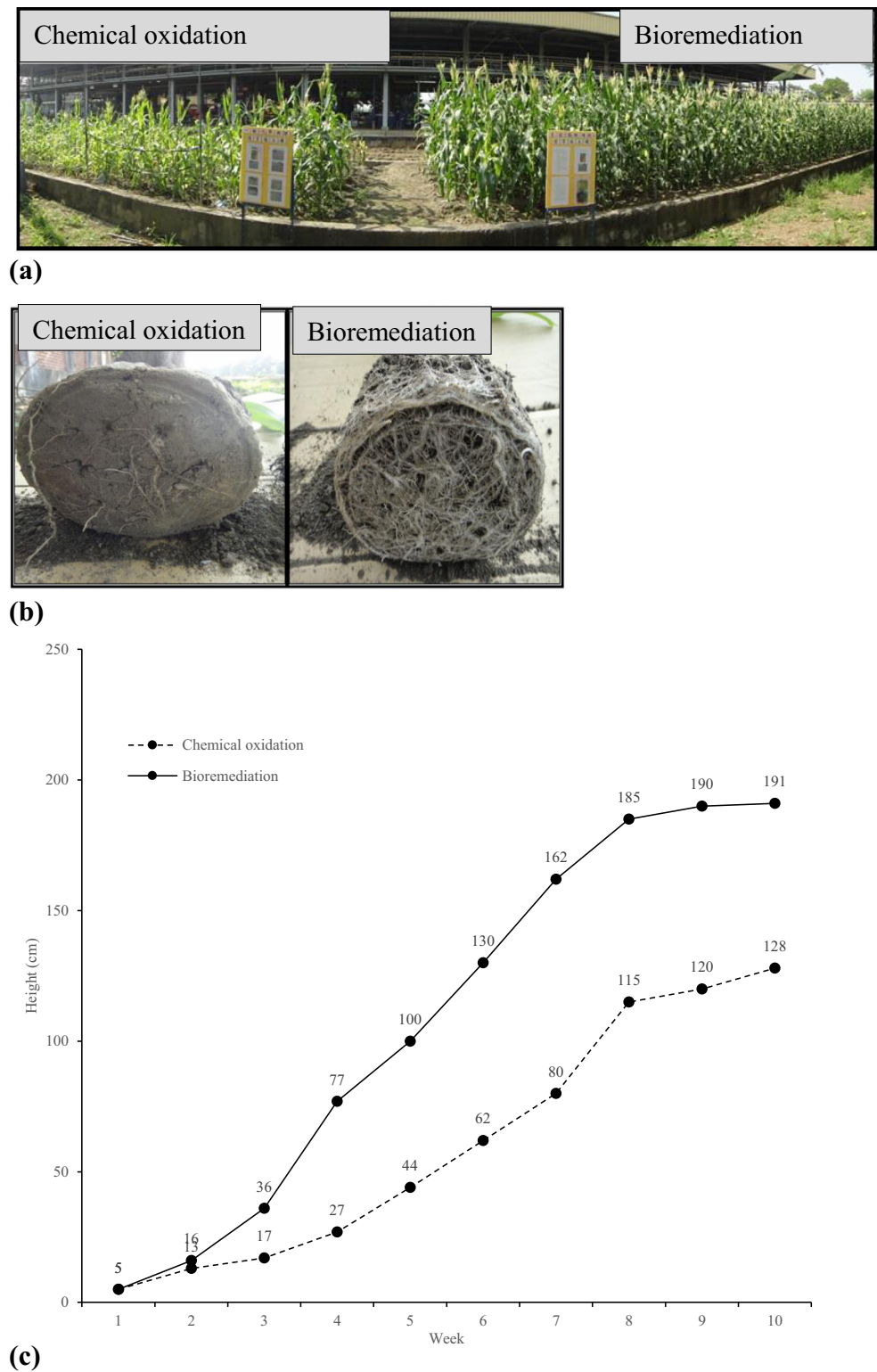
material is given higher priority in green technologies (USEPA 2012). Neither remediation process produced any hazardous waste. The definition of hazardous waste includes remediated product (USEPA 2012), so we were left to consider non-hazardous waste alone. Chemical oxidation produced

50 t of non-hazardous waste (clean soil), while bioremediation produced 80 t (50 t clean soil and 30 t compost material). Recycling or reusing is an important green value and encouraged by SEFA. For bioremediation, the potential for waste recycling was 100 %, since mature compost and soil remain

Table 3 Input information for chemical oxidation

Target contaminant	TPHs (50 t)				
Personnel transportation	Trips	Roundtrip distance (km)	Vehicle type	Fuel type	
	10	6.4	Car	Gasoline	
Onsite equipment	Equipment type	Load factor (%)	Operational hours	Roundtrip distance (km)	Fuel Type
	Excavator—medium (175 HP)	80	96	5.76	Diesel
	Water truck (400 HP)	65	96	5.76	Diesel
	Dump truck (400 HP)	65	30	5.76	Diesel
Materials	H_2O_2 (50 t)				
Water use	Tap water (150 t)				

bioactive and can be further used for cultivation purposes. For chemical oxidation, that potential was only 25 %, since the kind of soil left over could only be used for construction or non-cultivation purposes.

Another core element of SEFA is water usage. The only kind of water used in the remediation of both lots was tap water. Therefore, the process that used less tap water in this case would be considered the greener of the two processes. Chemical oxidation required seven times more water consumption than bioremediation, clearly making it the less green alternative. Energy consumption is another core element. Both remediation activities required the use of the same kind of energy (diesel fuel) on site. Bioremediation additionally needed electricity to operate some of its equipment to process the soil off site. Regardless, chemical oxidation used more total energy (564.04 MWh) than bioremediation did (54.69 MWh) due to the longer hours needed in chemical oxidation to dig and turn over the soil. Thus, from this perspective, chemical oxidation was also less green.

The air emissions covered by SEFA are nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter less than 10 μm in size (PM10), hazardous air pollutants (HAPs) such as benzene, etc., and greenhouse gasses (GHGs). The first three less

Table 4 Input information for bioremediation

Target contaminant	TPHs (50 t)				
Personnel transportation	Trips	Roundtrip distance (km)	Vehicle type	Fuel type	
	10	5.76	Car	Gasoline	
Onsite equipment	Equipment type	Load factor (%)	Operational hours	Roundtrip distance (km)	Fuel type
	Loader—small (75HP)	80	34	5.76	Diesel
	Water truck (400HP)	65	34	5.76	Diesel
	Dump truck (400HP)	65	15	5.76	Diesel
	Equipment type	Load factor (%)	Activated hours	Percentage of actual operational hours	Energy consumption (kWh)
	Dewatering extruder (20HP)	65	8	65	14.92
	Crusher (50HP)	65	8	65	37.3
	Compost turner (25HP)	70	16	70	18.65
Materials	H_2O_2 (50 t)				
Water use	Tap water (20.85 t)				

Table 5 Sustainability matrix output of SEFA

Core elements		Unit of measure	Chemical oxidation			Bioremediation		
			Excavation	H_2O_2	Total	Excavation	Composting	Total
Materials and waste	Unrefined materials used onsite	Tons	0	50	50	0	50	50
	Percent of unrefined materials from recycled or waste material	%	0	0	0	0	100	100
	Onsite non-hazardous waste generated	Tons	0	50	50	0	80	80
	Percent of total potential onsite waste that is recycled or reused	%	0	25	25	0	100	100
Water	Tap water use	Liters	1,892,705.90	136,274.82	2,028,980.72	1,892,705.90	18,927.06	1,911,632.96
Energy	Total energy consumption (onsite and offsite)	MWh	17.53	546.51	564.04	17.53	37.16	54.69
	Onsite grid electricity consumption	MWh	0	0	0	0	0.716	0.716
Air	Onsite NOx, SOx, and PM10 emissions	kg	28.22	195.51	215.57	28.22	59.93	88.16
	Onsite HAP emissions	kg	0.0009	0.0054	0.0064	0.0009	0.0018	0.0027
	Total NOx, SOx, and PM10 emissions	kg	38.72	667.45	706.18	38.72	71.72	110.44
	Total NOx emissions	kg	30.23	321.35	351.58	30.23	60.70	90.93
	Total SOx emissions	kg	4.27	314.25	318.52	4.27	9.69	13.96
	Total PM10 emissions	kg	4.22	31.85	36.08	4.22	1.32	5.55
	Total HAP emissions	kg	0.02	0.86	0.88	0.02	0.13	0.16
	Total greenhouse gas emissions	Tons CO2e	5.667	112.747	118.414	5.667	9.973	15.64

hazardous categories are grouped by SEFA to streamline footprint presentation. The HAPs are listed in the Clean Air Act Amendments of 1990 and subsequent modifications (USEPA 2012) and greenhouse gasses (GHGs) are listed in Jones (2013). Both onsite emissions associated with remediation activities and offsite emissions associated with electricity generation, material manufacturing, transportation, etc. are included in the calculations of air emissions for SEFA (USEPA 2012). Most air emissions associated with bioremediation were onsite NOx, SOx, and PM10 emissions from the burning of fuel (diesel) and the evaporation of the gasses residing inside the soil, with NOx dominating. Most air emissions associated with chemical oxidation were NOx, SOx, and PM10 produced offsite during the manufacturing of hydrogen peroxide, mostly originating from the energy used in factory production. HAP emissions, which were not significant, were largely due to the transportation of materials and equipment. Comparing air emissions of the two remediation activities, the biggest difference was found in total NOx, SOx, and PM10 emissions. Chemical oxidation released much more of these than bioremediation did (706.18 vs. 110.44 kgs, respectively). The least difference was found in onsite HAP emissions (chemical oxidation 0.0064 kg; bioremediation 0.0027 kg). Greenhouse gas emissions were measured in

terms of CO2e (global warming potential). Chemical oxidation emitted much more CO2e than bioremediation (118.414 vs. 15.64 t, respectively).

In summary, the results of our SEFA analysis revealed that bioremediation was the greener alternative, as it consumed less water and energy and did not produce nearly the same quantity of air emissions as chemical oxidation. Water use in bioremediation mostly occurred during the excavation stage, not the composting stage.

Land and ecosystem evaluation of the two remediation processes

Although there are five core elements that need to be evaluated for a remediation project, the SEFA spreadsheet only includes four (USEPA 2012). The last element, land and ecosystems, should be qualitatively evaluated independently using field scale tests to determine soil fertility and bioactivity (Conte et al. 2001, Fava and Piccolo 2002, Conte et al. 2005) of the two lots treated with different treatment technologies. We found that the lot treated with bioremediation appeared to be more productive than the one treated with chemical oxidation after 10 weeks (Fig. 3a). We also examined the root of the plants after 10 weeks and found the

Table 6 Comparison of the fertility of chemically oxidized and bioremediated soils

	Chemical oxidation	Bioremediation	Optimal range (obtained from Taiwan COA)	Method of analysis
pH	*8.7*	*7.6*	*5.5~7.5*	ASTM D4972-13 Standard Test Method for pH of Soils
Electrical conductivity (mS/m)	0.2	0.8	0.5~1.2	ASTM E1004-09 Standard Test Method for Determining Electrical Conductivity Using the Electromagnetic (Eddy-Current) Method
Ash content (%)	*90*	*79*	–	ASTM D2974-14 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils
Carbon-to-nitrogen ratio	*19*	*17*	*<20*	ASTM D5291-10 (2015) Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants
Percentage of germination (%)	70	95	>80 %	ISTA Orange and Blue

root system of the plants planted in bioremediated soil to better developed and more porous than those of the chemically oxidized soil (Fig. 3b). The root systems in the bioremediated soil created better conditions for microorganism to grow and for the uptake of nutrients. Figure 3c shows plant growth over the 10-week study period. Starting the second week, we were able to observe a significant difference in growth rate between the two lots. Both grew to 5 cm the first week. However, by the second week, plants from the bioremediated soil grew to 16 cm and plants from the chemically oxidized soil grew to 13 cm. By the tenth week, plants in the first lot were 191 cm high on average and those in the second were 128 cm.

We measured soil fertility following ASTM and ISTA recommendations (Table 6). The optimal ranges were obtained from the Taiwan Council of Agriculture Soil (Taiwan COA; http://eng.coa.gov.tw/list.php?catid=8799). The fertility of the bioremediated soil proved to be better than the chemically oxidized soil with a pH of 7.6 falling into the optimization range 5.5 to 7.5 vs. 8.7, an EC of 0.8 falling into the optimal range 0.5 to 1.2 vs. 0.2, and an ash percentage of 79 vs. 90. There was no optimization range given for this criterion. Both remediation processes created good C/N ratio (both below 20). The percentage of seeds that underwent germination was higher in the bioremediated soil (95 vs. 70 %), with optimal value set at above 80 %.

Table 7 compares the quality of the maize ears (30 for each field). As can be seen, the quality of ears produced by the chemically oxidized soil was inferior to those produced by

Table 7 Comparison of harvested maize ear quality

	Chemical oxidation		Bioremediation	
Number of maize ears measured	30		30	
Average height (cm)	20.1	12.6	23.4	16
Average width (cm)	4.4	3.9	5.4	4.9
Average weight (g)	114.4	92.6	222.7	189.5

the bioremediated soil. The chemically oxidized soil produced ears with and without stalks that were lower in average height, width, and weight. Particularly, the ears of maize from plants in the bioremediated soil were heavier (with stalks 222.7 vs. 111.4 g; without stalks 189.5 vs. 92.6 g). The ears from the bioremediated soil were also bigger and had a richer color of yellow.

In summary, the results of our fertility and bioactivity tests found the contaminated soil that had undergone bioremediation to be more fertile and more bioactive than the soil that had undergone chemical oxidation, making it the greener of the two methods.

Conclusions

In this study, a two-stage framework for evaluating site remediation activities in Taiwan was proposed. Within that framework could be found detailed procedures for planning, choosing, and integrating green and sustainable principles into a remediation project. The USEPA's triad approach was used to reduce the cost and time needed to construct conceptual site models of different proposed treatment alternatives. The framework also included procedures for cost control, project management, and assessment.

In our case study, the effects of chemical oxidation and bioremediation on TPH-contaminated soil were evaluated based on the five core elements of GSR: energy, air, water resources, materials and wastes, and land and ecosystem. For this evaluation, SEFA was used to evaluate the first four core elements and field scale cultivation test to evaluate the fifth core element, land and ecosystem, in this case the, fertility and bioactivity of the remediated soil. Both SEFA and the cultivation test found bioremediation to be greener and more preferable to chemical oxidation for the remediation of this contaminated site.

To the best of our knowledge, this is the first time this framework, set of standards, and evaluation tool for soil remediation projects have been thoroughly studied in Taiwan. Hopefully, the framework and evaluation tools used in this study can contribute greatly to the weighing of advantages and disadvantages of alternative remediation activities and help to reduce the negative impact of various remedial projects.

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