A review on the geoenvironmental and geoecological integrated technology for environmental remediation in Vietnam: approaches, contributions, challenges and perspectives

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Abstract. Geoenvironmental and geoecological integrated technology (GGIT) is a cost-effective and environment-friendly technology that encompasses the applications of earth science principles and functions of geological environment and ecosystems to assimilate and minimize the spread of pollutants, to enhance the sorption capacity and environmental remediation. On the basis of the integrated approaches such as system, anthropogenic activities – ecosystem – environment interaction, effectiveness and feasibility, GGIT has provided significant applications in Vietnam such as waste containment and remediation and environmental protection. The results of a pilot scale using iron mine drainage sludge and common reed (Phragmites australis) for wastewater treatment in a Pb-Zn mine in northern Vietnam indicated the effective and potential application of GGIT. However, GGIT has many challenges in limited funding conditions, constraints in the initial development of GGIT, incomplete transfer to users, and quantitative assessment of pollutant cleanup by natural environments and ecosystems. Environmental pollution quote, impacts to exposed organisms, increasing demands for application of low-cost technologies, the availability of potential sorbents, indigenous plants, and ecosystems for environmental remediation, and collaboration will promote development, contribution, and implementation of GGIT applications in Vietnam.

Keywords: geoecology, geoenvironment, pollutant, remediation, Vietnam.

1. Introduction
The geogenic, industrial, agricultural, pharmaceutical, and domestic effluent sources have generated considerable amounts of waste materials to the surrounding environment [1]. An increasing ecological and global public health concerns associated with contaminants have highlighted the need for environmental remediation. The requirements of cost-effective and environment-friendly methods have created new demands for geoenvironmental and geoecological integrated technology (GGIT). Geoenvironmental technology refers to the application of the principles of earth sciences and geological environment functions for minimizing dispersion and assimilating pollutants and for designing remediation measures [2]. Geoecological technology implies the ecosystem functions for assimilating and remediating pollutants in geological environment [3]. GGIT is defined as the technology applying earth science principles and functions of geological environment and ecosystems aiming to minimize the dispersion, to assimilate pollutants, and to enhance the resilience capacity of geological environment by using the geological formations and ecosystems.

Geoenvironmental technology has been applied as for remediation of contaminated environments by using various geological formations (e.g., iron oxides, laterite, clay minerals, and calcite) [4, 5, 6,
7]. Typically, this technology has been demonstrated in the practical sites including ferrihydrite adsorption for Se cleanup of Kenneecott Utah Copper mine; permeable reactive barriers for As, Se, Mo removal from Monticello Mill tailings site; successive alkalinity producing system for Al, Cu, Fe, Mn, Zn remediation in Summitville mine, and anoxic limestone drains for Pb, Zn, Cu removal from Valzinc mine [8, 9, 10, 11]. Constructed wetland systems with different designs (horizontal and vertical flow, free water surface, and integrated constructed wetland) as well as plant species themselves have been recognized as geoeological technology and widely used for environmental cleanup [12, 13]. The integration of geoenvironmental and geoecological technologies for higher treatment effectiveness has been implemented [14, 15]. Practical results of GGIT applications are often found to be cost-effective and environment-friendly.

With the low nation's GDP per capita point, Vietnam has ranked as a developing country where industrialization is increasingly being embraced as the primary mean to prosperity. According to the Vietnam national report at the United Nations Conference on Sustainable Development (Rio+20), during the 20 years’ implementation of national sustainable development, Vietnam has obtained remarkable achievements in socioeconomic development. However, the country has also faced many inherent or emerged challenges, particularly in the fields of environment, including (1) serious pollution due to underdeveloped industrial technology and excessive use of chemical fertilizers, (2) environmental degradation as a consequence of the wars (bombs, landmines, agent orange, or dioxin), (3) wasteful and fossil-based production and consumption, (4) inefficiency energy in supply, building, planning and consumption, (5) depletion of natural resources, particularly mineral and water resources, and (6) biodiversity reduction [16]. Being one of the countries that possess favorability of potential contaminant sorbents and high biodiversity ecosystems, the perspectives of GGIT application may help Vietnam overcome many the country’s challenges and shortcomings towards environmental protection and sustainable development.

This paper aims to introduce the overview of GGIT in Vietnam with special emphasis on environmental pollution quote, approaches, contributions, challenges, and perspectives for environmental remediation.

2. Geoenvironmental and geoecological integrated technology in Vietnam

2.1. Demands for GGIT application

The socio-economic development, together with negative impacts of climate change and natural disasters, has caused much pressure on the environment. It is reported by the Ministry of Natural Resources and Environment of the Socialist Republic of Vietnam that water quality in 3 river basins of Cau, Nhue - Day and Dong Nai has exceeded the allowable limits; dust pollution in urban areas keeps increasing, environmental pollution in industrial zones/clusters and craft villages is increasing; agricultural pollution due to inappropriate use of fertilizers and pesticides has not improved; oil pollution in coastal waters keeps deteriorating; solid waste has not been collected and treated appropriately, especially hazardous wastes [17]. Biodiversity is degrading rapidly, species are facing risks of reducing in quantity and a higher level of threats. In addition, the degradation of ecosystems and the decrease in number of species and genetic resources have not reduced. Environmental security is being threatened, especially water resources, transboundary pollution and losses of minerals [17].

Water quality in upstream of rivers is generally good [18]. However, in cities and towns, industrial and domestic wastewater without treatment is discharged directly into most rivers, lakes, and canals. Consequently, water quality declined sharply, many parameters such as BOD$_5$, COD, coliform, total N, total P were higher than allowable limits regulated by the Ministry of Natural Resources and Environment [18].

Surface water in some rural areas in the Red River delta and the Mekong River delta has been polluted by organic matters and microbial from discharge of domestic and livestock wastewater [18]. Soil environment in agricultural areas is polluted and degraded due to the lack of scientific cultivation,
use of fertilizers and pesticides [18]. Domestic solid wastes in rural areas continue to increase but the management has not been received adequate attention [18].

Many industrial areas have been severely degraded. Approximately 70% of the more than 1 million m$^3$ of wastewater per day from industrial zones is discharged directly into the receiving water without treatment that causes environmental pollution of surface water [19]. Approximately 57% of operating industrial zones does not have treatment system [19]. The amount of solid wastes in industrial areas increased. Waste disposal or treatment in the industrial areas was inadequate, especially management, transportation and registration for waste sources.

Environment of the craft villages was also degraded. Water pollution was seriously contaminated in various villages for food processing, paper recycling (organic pollution), textile and dyeing (wastewater contains many chemicals), and metal recycling (heavy metals contamination) [20]. Solid wastes were generally discharged directly into the environment [20].

Vietnam possesses a wide range of mineral resources. The country has some of the world's biggest resources of phosphate (apatite), bauxites, rare earths, and large, commercially viable deposits of oil, coal, gold, gemstones, copper, zinc, tin, chromite, manganese, titanium (mineral sands), graphite and other minerals [22, 23]. Vietnam produces approximately 3.5 million tons of crude oil/year and its mineral production including coal (about 10.7 million tons/year), cement (1.6 million tons), phosphate (300,000 tons), chromite (3.5 million tons), iron ores, gold, cassiterite (3,000 tons), graphite, kaolin and many other minerals produced to serve domestic demand [22]. Mining activities also release pollutants that pose adverse effects on exposed environment and ecosystems. Typically, most soil and water samples in some of the largest mines in Vietnam such as Pb-Zn Cho Don, Cu Sinh Quyen, Sn Ky Lam and Sb Mau Due have been contaminated with heavy metals such as As, Pb, Zn, Cu, and Cd (Tables 1, 2).

**Table 1.** Average concentrations of heavy metals in soil samples in mine sites

| Parameter | Unit  | Pb-Zn Cho Don | Cu Sinh Quyen | Sn Ky Lam | Sb Mau Due | Regulated limits |
|-----------|-------|----------------|---------------|-----------|------------|------------------|
| As        | mg/kg | 542            | 27.5          | 479       | 60.6       | 12               |
| Zn        | mg/kg | 970            | 149           | 184       | 242        | 200              |
| Pb        | mg/kg | 2040           | 31.6          | 71.8      | 55.8       | 70               |
| Cd        | mg/kg | 2.35           | 0.3           | 0.3       | 0.9        | 2                |
| Cu        | mg/kg | 126            | 327           | 235       |            | 50               |
| Ni        | mg/kg | 39.0           | -             | -         | -          | -                |

*Source:* [21]

**Table 2.** Average concentration of heavy metals in water samples in mine sites

| Parameter | Unit  | Pb-Zn Cho Don | Cu Sinh Quyen | Sn Ky Lam | Sb Mau Due | Regulated limits |
|-----------|-------|----------------|---------------|-----------|------------|------------------|
| pH        | -     | 6-8.5          | **3.49-4**    | **4.02-8.08** | **3.78-5** | 6-8.5            |
| As        | ppm   | **0.01**       | 0.004         | **0.01**  | 0.0002     | 0.01             |
| Zn        | ppm   | 0.06           | **0.64**      | 0.03      | **3.75**   | 0.5              |
| Pb        | ppm   | **0.03**       | 0.002         | 0.003     | 0.01       | 0.02             |
| Cd        | ppm   | 0.0004         | **0.006**     | 0.0002    | **0.04**   | 0.005            |
| Cu        | ppm   | 0.002          | **0.14**      | 0.02      | **0.13**   | 0.1              |
| Ni        | ppm   | 0.009          | **0.48**      | 0.01      | **1.24**   | 0.1              |

*Source:* [21]
Environmental pollution causes synchronous impacts on the community health [17]. It also brings environmental conflicts in the community due to poor management policies and mechanisms [17]. Environmental pollution and biodiversity degradation directly influence the country’s sustainable development and national security, causing significant economic losses and adverse impacts on natural ecosystems [17] which highlight need for effective application of remediation technologies.

2.2. Approaches

**Figure 1.** Framework for solving environmental problems based on GGIT
2.2.1. **System approach.** System approach is the recognition of the earth through their system structure, hierarchy and motivation; thereby, it is a comprehensive and dynamic approach [24]. This is the most dialectical approach for dealing with environmental problems.

Anthropogenic activities such as industrial, agricultural, pharmaceutical, domestic effluents have discharged large amounts of wastes into the surrounding environments. Therefore, they have established a system of the industry – ecosystem – environment. In case without effective treatment system, the pollutants from these activities will be impossible to disperse widely and quickly into other ecosystems and surroundings. The generation and movement of pollutants depend on the interaction of three components. GGIT is the solution to prevent and cleanup contaminants as well as to minimize their spread among components. In addition, it is a sustainable and integrated technical solution for environmental remediation towards sustainable development. It is important to determine the most vulnerable zones that are seriously affected from anthropogenic activities for GGIT applications.

2.2.2. **Interactive approach to anthropogenic activities – ecosystem - environment.** The balance of natural ecosystems as well as geological environment has existed which may be disrupted by anthropogenic activities. Each anthropogenic activity can release specific type of pollutants that will react with the containing environment and ecosystem. Natural environment and ecosystem can adsorb or absorb, assimilate, metabolize and decompose pollutants or minimize the dispersion or leaching of these pollutants. When the pollution loads exceed resilience and recovery of environment and ecosystem, it is necessary to apply additional geological formations and constructed ecosystems for capacity enhancement such as planting species themselves or in constructed wetlands (phytoremediation), using limestone or calcium sulfate to neutralize environment, using clay rich and non-fracture layers for landfill, and using natural sorbents for sorption of pollutants. The application of natural formations and ecosystems makes GGIT a cost-effective and environment friendly technology that can remediate or minimize the spread of pollutants in the ecosystem - environment systems.

2.2.3. **Effective and feasible approach.** Procedure of GGIT ensures the effectiveness in the prevention and treatment of environmental pollution: the ability to prevent and cleanup pollutants as well as minimize expense and duration of remediation. In addition, it also ensures high feasibility: accepted by treatment systems and institutions; successfully deployed and applied in the study sites and replicated in similarly polluted areas; consistent with the characteristics and culture of contaminated areas.

2.3. **Contributions**

Since 1986, Vietnam has been implementing “Doi moi” policy. As results, Vietnam has sustained an impressive growth in access to infrastructure services, particularly since the early 1990s. The country’s GDP growth during 2000-2008 averaged at 7.85%. Both the size of the economy and the productive capacity of all sectors increased. GDP per capita in 2016 was over 2164 USD (current price), as 6 times increase from the 2000 level. Population has increased from approximately 61 to 95 million people (2016). Consequently, a volume of water and solid wastes has dramatically increased. Along with the development of economics and infrastructure, the awareness on environmental protection has been strengthened and integrated in all development activities as implementation of Strategic Environment Assessment as stipulated by the Law on Environmental Protection. Accordingly, all national projects have to report the environmental impact assessment. In this context, GGIT has had new application that requires a need for waste containment and remediation, and environmental protection.

GGIT has contributed to find suitable areas for sanitary landfill of solid wastes. Many landfill sites have been implemented including Ha Noi (Nam Son, Kieu Ky, Xuan Son, Nui Thong, Cau Dien), Ho Chi Minh (Phuoc Hiep, Da Phuoc), Hai Phong (Trang Cat, Dinh vu, Do Son), Da Nang (Khanh Son), Hue (Thuy Phuong), Thai Nguyen (Da Mai, Song Cong), Nam Dinh (Loc Hoa), Khanh Hoa (Ru Ri, Luong Hoa), Tien Giang (Tan Lap, Long Binh, Binh Phu, Vinh Binh, Tan Thuan)...[25]. The following characteristics should be considered for landfill site selection: (1) Any material with high
hydraulic conductivity, high permeability and with a high water table is probably an unfavorable site; (2) Flat areas are favorable sites, provided an adequate layer of material with low hydraulic conductivity, low permeability, such as clay and silt, is present above any aquifer.

The use of indigenous plant species for phytoremediation of contaminated soils and water has been studied and applied, mainly in pilot scales. Screening of indigenous plant species in metal mine sites showed potential species for phytoremediation such as Ageratum houstonianum Mill., Brassica juncea, Cynodon dactylon, Cyperus rotundus, Eleusine indica, Equisetum ramosissimum, Houttuynia cordata Thunb., Pennisetum purpureum, Potamogeton oxyphyllus Miq., Pteris vittata L., and Vetiveria zizanioides [26, 27].

Constructed wetland ecosystems have also used for environmental remediation. Phragmites australis, Saccharum spontaneum L., and V. zizanioides are common species used in the constructed wetlands in Vietnam [26, 28, 29]. This technology has been applied in wastewater treatment from hospital, breeding areas, industrial zones, and craft villages.

Natural sorbents such as laterite, bentonite, zeolite, goethite, and clay minerals have been applied for sorption of contaminants. The application of As natural sorbents at household scale has been used popularly as the solution of seriously arsenic problem in the Red River delta. The sorption capacity of Pb, As, Cd, Zn, and Mn by natural laterite from Vinh Phuc Province (Northern Vietnam) was 1550, 756, 397, 281, and 143 mg/kg, respectively [30]. High removal efficiency of heavy metals by laterite was also reported [31]. The modification of laterite, basalt, and clay sorbents by addition of sodium silicate solutions showed high sorption capacity of heavy metals such as Cd, Cu, Pb, Zn, Cr and As [8]. The highest sorption capacity of As (III), As (V), Cd, Cu, Pb, Zn, Cd, and Cr (VI) by modified basalt from Phuoc Long (Central Highland, Vietnam) was 1200, 4090, 16950, 73790, 15720, 30370, and 6830 mg/kg, respectively; those by modified laterite from Hanoi was 1330, 1750, 7610, 41400, 46960, 11090, and 8880 mg/kg [8].

The preliminary application of GGIT has conducted at pilot scale for remediation of wastewater from a lead-zinc mine in northern Vietnam. In this pilot site, drainage sludge form an iron processing mine was used as sorbents of multiple heavy metals and a common species was used at constructed wetland system (P. australis). The results demonstrated that the removal efficiency of Zn, Pb, Mn, and As by iron mine drainage sludge - surface constructed wetland system was 78.9, 73.5, 91.2, and 80.5%, respectively; that by iron mine drainage sludge - subsurface flow constructed wetland system was 81.7, 81.1, 94.1, and 83.1% which reflected that subsurface flow constructed wetland showed higher removal efficiency than the surface system.

While much advancement has been made in GGIT, it is mainly applied for landfill site selection and remediation.

2.4. Challenges

In Vietnam, researches and technologies applied in the environmental remediation are commonly organic matters and suspended solids in water. Particularly, remediation technologies of heavy metal contaminated environment have performed at small scales. The enforcement of Environmental Law and investment or funding conditions is possibly the main obstacles for the applications of environmental remediation in general and GGIT in particular. In addition, quantitative assessment of assimilating and remediating pollutants by natural environments and ecosystems is also one of big challenges for GGIT.

There are constraints in the initial development of GGIT and in particular uncertainties exist for long-term performance, reducing confidence level of GGIT application. GGIT transfer to users is incomplete. Standardization of materials and test procedures and development of guidelines for construction and operation are required for various GGIT applications. Regulatory agencies as well as industry have significant depositories of data on GGIT facilities that have not been made available in a format that can be used by stakeholders or fully analyzed for obtaining representative conclusions.

The major challenge for academia is to retain and expand GGIT in both research and education to meet new demands and requirements of environmental protection and sustainable development, in
particular under reduced funding conditions. GGIT research, educational initiatives and its effective application can be undertaken through multi-component multidisciplinary platforms with participation of universities as well as industry and professional organizations, policy makers, and users and other stakeholders. Better integration and collaborations between these stakeholders would contribute to the advancement of the field but will need very great efforts from all of them.

2.5. Perspectives
Increasing demand in GGIT due to cost effectiveness: remediation cost is one of the most important criteria for choosing treatment technologies. The use of natural materials and plant species indicates the low cost by GGIT application.

Fixation of pollutants: Co-disposal and co-utilization of hazardous waste materials are the mainstream development to avoid the harmful effects of the pollutants to be disposed.

Increased application of vegetation and diverse ecosystems: The adequate selection of plants and ecosystems eliminates or reduces the use of more costly engineering artifacts in pollution remediation. Screenings of indigenous plant species indicate the high potential of using these plants for environmental remediation such as *A. houstonianum* Mill., *B. juncea*, *C. dactylon*, *C. rotundus*, *E. indica*, *E. ramosissimum*, *H. cordata* Thunb., *P. australis*, *P. oxyphyllus* Miq., *P. purpureum*, *P. vittata* L., *S. spontaneum* L., and *V. zizanioides* [26, 27, 28].

Increased application of natural minerals: A number of hundreds of iron deposits/occurrences and other minerals (e.g., bentonite, vermiculite, laterite) [22, 23, 32] is widely distributed in Vietnam which reflects the great potential for using these materials as sorbents of contaminants.

Collaboration between GGIT stakeholders (e.g., scientists, engineers, policy makers, managers, and community) will promote development and contribution as well as implementation of new GGIT application.

Enforcement of law and implementation of policies, strategies concerning environment and sustainable development creates institutional fundamentals for GGIT development and new application.

Renovation of GGIT education for development of human and engineering attitude, vision, creativity capacity and skills based on strong fundamental natural, liberal arts and interdisciplinary knowledge and approaches will provide high qualification human resources for GGIT.

3. Conclusions
Geoenvironmental and geoecological integrated technology is rather new in Vietnam, but it has many contributions to solve environment problems. The reduced funding conditions, initial development, incomplete transfer to users, and quantitative assessment are the main challenges for GGIT. The increasing demand for application of low-cost and environment friendly technologies, the availability of potential sorbents, indigenous plants, and ecosystems for environmental remediation, and collaboration will promote perspectives for GGIT applications in Vietnam.

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