Index No: ES-19-53

Advancements in Environmental Technologies for Sustainable Urban Regeneration: A Comparative Assessment

Ruwan Danuka Edirisinghe (1st Author)
Faculty of Graduate Studies
University of Colombo
Colombo, Sri Lanka
ruwanedirisinghe1@gmail.com

***Abstract* — The present study aims to appraise advancements in environmental technologies applicable to urban regeneration, with a special focus on urban brownfield redevelopment. The rapid literature review technique was employed as the research strategy, in the mixed method research design. Technological solutions proposed in the selected articles were comparatively assessed their practicality in an urban setting, in terms of cost, efficacy, physical space required and potential harm to the neighboring environment, by using a five-point scale scoring system. In this study, nanoremediation, thermal remediation methods (i.e. electrical resistance heating, thermal conduction heating and steam enhanced extraction), non-thermal physical remediation methods (electrokinetic remediation, non-thermal plasma technologies, air sparging, soil washing and replacement and passive treatment technologies such as permeable reactive barriers), chemical oxidation (advanced chemical oxidation and Fenton process), and nature-based solutions or bioremediation or gentle remediation technologies (biodegradation processes methods such as bioaugmentation, bioventing, bioprecipitation, biostimulation, landfarming, and phytoremediation methods such as phytostabilization, phytovolatilization and phytoextraction or phytomining and monitored natural attenuation) are presented. Each environmental restoration strategies provided has its own set of limitations, application possibilities and future development potential, as evidenced by this study. Nanoremediation, bioremediation and radio frequency heating in the current state of the art are found to be feasible for an urban area. Property developers and urban authorities could consider the application potential of these technologies in urban brownfield redevelopment in urban regeneration. An integrated approach for addressing the limitations of these technologies may be worth considering in research and developments in the urban sector.**

Keywords* — *Decontamination, Environmental-Technology, Green, Redevelopment, Remediation, Urban

I. INTRODUCTION

Despite the inequalities in socioeconomic development, urbanization is happening at a fast pace over the world. It is debatable whether these human-centred developments will coexist with the natural environment in the long run. Land resources, on the other hand, are limitedly available, particularly in urban areas. The author of this study supports the idea that urban development should not lead to gentrification. Furthermore, the urban environments are deteriorating, turning them into inhabitable places (i.e. urban brownfields) because of loss of vegetation, air pollution, water scarcity, contamination of lands, to name a few [1]. The process of urban redevelopment can be significantly more complicated than addressing physical aspects like renovating structures (e.g. neighborhood and quality of life) [2]. These concerns have raised the importance of sustainable renovation of urban environments to meet the present and future challenges in making the urban sector more livable to humans and other living beings while remaining in optimum harmony with natural environment.

Infrastructure expansion and industrialization in metropolitan areas at the expense of ecosystem health, as well as derelict properties that have become brownfields, are posing risks to landscape resilience, which necessitate redevelopment. However, regeneration of urban areas having poor environmental quality can be a practically challenging task in terms of investment and technology [3]. A soil is deemed polluted when the contaminant levels surpass the natural assimilation capacity of the soil system. Urban soils become contaminated by polychlorinated biphenyls (PCBs), heavy metals, hydrocarbons (e.g. Polycyclic Aromatic Hydrocarbons), phthalate, alkylbenzene, microplastics, and persistent organic pollutants (POPs) [4-7]. The sources of pollution can be of point and or non-point (e.g. industrial parks versus sediments transported through urban waterways). Toxins in the urban soils and aquatic systems lead to biomagnification, affecting human health [8]. Indicators such as the Bio Concentration Factor are used to estimate the transfer of contaminants from soil to plants. The World Health Organization has defined permissible limits for common contaminants in soil ($mg.kg^{-1}$) of 20 for arsenic, 5000 for iron and 100 for lead [9].

Previous studies propose interdisciplinary approaches and innovative technological solutions to remediate contaminated lands in an urban setting. The remediation process is started by characterizing the contaminated site, which may involve analysis of operating history of the site, invasive drilling for hydrogeological assessments, and use of unmanned aerial vehicles, Digital Elevation Models, LiDAR and GIS based approaches for soil mapping to comprehend the fate and transport of contaminants [10-11]. Contaminants are analyzed by using laboratory methods such as Titrimetry, Spectrophotometry, Graphite Furnace Atomic Absorption Spectrometry, Gas Chromatography, Mass Spectrometry and Inductively Coupled Plasma Mass Spectrometry [12].

Soil remediation technologies include nanoremediation, phytoremediation, physical and chemical methods such as subsurface heating technologies, soil replacement and chemical oxidation, by on-site or off-site basis, reducing the bioavailability of toxins, lessening the risks to the environment. Importantly, choice of remediation technologies would determine the technical and economic feasibilities [13]. Therefore, the understanding of advancements in environmental technologies is unarguably valuable for policymakers, authorities, urban designers and developers to make cities more sustainable. The present study explores advancements in technologies for environmental remediation in urban redevelopment. This critical appraisal from an interdisciplinary perspective shows the application and further research potentials of these technologies under different scenarios.

II. OBJECTIVES

This study aims to appraise technological advancements in contaminated land redevelopment, delimiting the study to identify technological solutions applicable to revitalization of urban brownfields, and to identify the future developmental potentials of these technologies.

III. METHODOLOGY

The present exploratory study adopted a rapid literature review technique [14] as the research strategy, with a deductive approach in a mixed method design. The search strategy comprised of defining inclusion and exclusion criteria, key words and synonyms and formulating search strings. Inclusion criteria comprised of contaminated land remediation, research papers and grey literature published in English and journal pre-proofs, whereas the exclusion criteria consisting the non-urban studies, non-English publication and abstract only publications. Predatory journals, publications published before year 2010, research papers with low scientific quality were eliminated from the primary screening process. The Google Scholar, Elsevier, ScienceDirect, Emerald, ResearchGate, Web of Science and MDPI were among the prominent databases employed in the search strategy. A total of 467 publications were screened and 68 were used in the analysis. The environmental technologies considered in this study were comparatively assessed in terms of cost, efficacy, physical space required and potential harm to the neighboring environment. The assessment criteria were ranked using a five-point-scale scoring system (i.e. 0,1,2,3 and 4 for no, low, medium, high and extremely high, respectively) [15]. The 'Impacts on Neighborhood' score was subtracted from the algebraic sum of the scores of the remaining three criteria in each remediation technology to arrive at the overall possibility ranking (Table 1).

IV. RESULTS AND DISCUSSION

Decontamination of urban lands to restore the ecological health has been addressed in literature mainly by integrating the applications of life sciences, physical sciences and engineering. In this study, nanoremediation, thermal remediation, air sparging, non-thermal physical remediation methods inclusive of electrokinetic remediation, chemical oxidation and bioremediation technologies are presented, with especial focus on their applicability to land redevelopment in the urban context.

The use of nanotechnology for remediation (i.e. nanoremediation) of polluted soils is becoming a promising solution. The underline principle of nanoremediation is the prevention of migration of contaminants by solidification and stabilization using engineered nanoparticles of having high surface area and reactivity (e.g. acting as adsorbents and reductants). Nanoparticles such as Nanoscale Zerovalent Iron (nZVI) can detoxify soils by immobilizing toxic ions such as heavy metals by adsorption (Fig. 1) [16-17]. Estimation of adsorption capacity is given in (1) [18].

$$q_e = \frac{(C_0 - C_e)}{m} V \tag{1}$$

Where, q_e adoption capacity at the equilibrium state (mg.g^{-1}), C_0 initial concentration of pollutant (mg. L^{-1}), C_e equilibrium concentration of pollutant (mg. L^{-1}), V volume of solution, m mass of nanomaterial (g)

Nanoscale elemental iron particles that are pyrophoric are coated with a passivating oxide (e.g. FeO(OH)) or natural or synthetic polymers (e.g. Carboxymethyl Cellulose or Poly Acrylic Acid) [19]. Commercially, nZVI are available in emulsified, aqueous or dry form (e.g. *NANO IRON s.r.o.* in Czech Republic). Nanomaterials of desired properties are mechanically injected into contaminated soils.

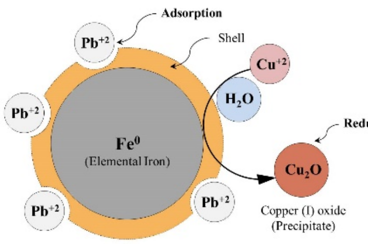

Fig. 1. The mechanism of nanoparticles immobilizing heavy metals

However, biological processes (e.g. microbial activity) in the soil can be negatively affected, despite the effective remediation provided by nZVI [20-21]. A few possible reasons for this may be the concentration of nZVI applied and the physical contact with nZVI (i.e. with the disruption of microbes' cell membranes), resulting in alterations in the composition of microbial communities in terms of species diversity and functionalities [22-24]. Encapsulation of nZVI with shells made out of soluble compounds such as Magnesium Hydroxide ($Mg(OH)_2$) may be worth considering in manipulating the reactivity and release of nZVI into the soil environment [25]. Alternatively, bioremediation (e.g. Phytoremediation) to decontaminate soils can be assisted with reactive nanomaterials such as nanoscale Titanium Dioxide (TiO_2 NPs) which is a photocatalyst [26]. Similar to nZVI, TiO_2 NPs could adversely affect the soil health [27], which could be moderated by encapsulation with Carboxymethyl Cellulose [28]. Other widely used nanomaterials include Multiwalled Carbon Nanotube (MWCNT) and magnetic nanoparticles applied for decontamination of soils polluted by heavy metals [29]. However, the efficiency of remediation could depend on the MWCNT concentration [30]. Other factors affecting the efficacy of the nanoremediation include the pH, temperature and physical properties of the contaminated soil (e.g. porosity and soil texture), and initial concentration, contact time and efficiency of diffusion of nanomaterials [31]. Nanoparticles are employed in environmental monitoring (i.e. tracer) apart from remediating degraded environments [32]. Overall, nanomaterials appear to be a viable option for soil remediation in an urban setting, as long as the potential risks to soil ecology are considered.

Soil thermal remediation is another approach to decontaminate polluted urban soils. In this method, subsurface soils are heated by employing Electrical Resistance Heating (ERH), Thermal Conduction Heating (TCH) and Steam Enhanced Extraction (SEE) methods on site to fluidize or vaporize pollutants, and Soil Vapor Extraction (SVE) assemblies are used to recover the vaporized pollutants (i.e. vapor collection wells or vacuum wells secured with vapor cap) for subsequent treatment. In the ERH, electrical current (i.e. alternative current) is applied through electrodes inserted into subsoil from which heat is produced by the electrical resistivity of soils, whereas TCH comprises electrical heaters to raise the temperature of subsoil by thermal conduction. Similar to TCH, the SEE heats subsurface soils by thermal conduction, using steam piping systems installed in soil layers. Alternatively, Low Temperature Thermal Desorption is used for ex-situ treatment of contaminated soils. However, previous authors present supporting and opposing arguments on soil remediation by thermal methods. Hydrocarbons such as Polycyclic Aromatic Hydrocarbons (PAHs) bound to clayey matter and organic carbons have been found effectively desorbed when the soil is thermally treated [33]. Pesticides such as Hexachlorocyclohexanes (HCHs) are degraded with thermal remediation [34]. Efficacy of thermal treatment for soils contaminated with PCBs can be improved by adding calcium hydroxide ($Ca(OH)_2$) [35]. On the other hand Microwave Coupled Infrared Radiation (MCIR) and Radio Frequency Heating (RFH) as non-ionizing radiation methods would provide comparatively lessened adverse impacts on microbial activities in the soil environment owing to thermal remediation [36]. RFH could be a low-cost and option [37]. Efficient decontamination of heavy metals such as Mercury (Hg) by thermal treatment at low temperatures ranging from 100 – 400^0C has been established in literature [38]. Flame retardants like Decabrominated Diphenyl Ether (BDE 209) in soils can be effectively treated thermally [39]. Importantly, removal of polyester microfibers in soils by thermal remediation has shown improved soil microbial activities [40]. Soils polluted with oily matter (e.g. lubricants) can be remediated by employing thermal desorption methods at low temperatures and Fluidized Bed Reactors [41]. Nonaqueous Phase Liquid (NAPLs) in soils can be removed thermally by vaporization [42-43]. However, this empirical evidence mostly resulted in temperatures above 300^0C may lead to waste of energy and detrimental effects on soil ecology.

Air Sparging (soil venting) is a physical treatment method to remove contaminants in the saturated zone of the soils. In this method, pressurized air is injected into the contaminated area, allowing volatile contaminants to volatilize, which are collected from vapor extraction vacuum wells situated in the vadose zone of the soil profile [44]. Contaminated air is then treated by means of biofiltration, adsorption and combustion. Air sparging method is applied for groundwater remediation as well. A fundamental limitation of the air sparging remediation method could be that the efficacy of the process can be affected by the permeability of the soil layers, which permits contaminants to migrate even more in the soil profile. However, compared to potential heat stress resulting from thermal methods, air sparging process may harmless to the soil's physical, chemical and biological properties.

Among the non-thermal physical remediation methods, Electrokinetic Remediation (ER) has been widely discussed in previous literature. In ER, an electric field is generated to remove contaminants using electromigration and electroosmosis phenomena, which can be coupled with biological and chemical methods as well [45-46]. Advanced oxidation process such as Non-thermal Plasma Technologies (NPT), for example, Dielectric Barrier Discharge (DBD), Pulsed Corona Plasma and Non-thermal Plasma Fluidized Bed (PFB) are emerging technologies in soil remediation [47-50]. The process of in situ vitrification offers a wider range of applications for treating soils contaminated with organic, radioactive and inorganic hazardous wastes [51]. Ultrasonic Desorption and coal agglomeration are employed in soils contaminated with oils [52]. Despite the sophistication of these technologies, pragmatic aspects in field implementation can be debatable. Similarly, conventional methods such as soil replacement and surfactant-aid soil washing [53] in an urban setting might not be practical due to potential adverse effects on neighboring load bearing structures supported on soils and other physical, legal and administrative constraints. However, passive treatment technologies such as Permeable Reactive Barriers (PRB) which are used for treating groundwater in a contaminated site and soil remediation by encapsulation (e.g. silica encapsulation) is another approach that can be adopted in metropolitan areas [54].

Urban soils can be decontaminated by chemical methods. More prevalent method is the In Situ Chemical Reduction (ISCR) or chemical oxidation, which encompasses hydrolysis, advanced oxidation, redox and mineralization. In some instances, the same chemical method is applied to remediate both contaminated soils and waters. Chemicals such as hydrogen peroxide, persulfate, potassium dichromate and alkali (e.g. NaOH) are typically used [55]. Although the Fenton oxidation as a pre-oxidative method to treat organic pollutants is not a novel approach in today's context, Photo-Fenton, Chelate Modified Fenton and Sono-Fenton processes are being reemerged in the field of soil remediation. In the Fenton method, in an aqueous medium, ferrous (Iron (II)) ions act as a catalyst to generate hydroxyl radicals and hydroxide ions by reacting with hydrogen peroxide (i.e. Haber-Weiss Reaction), from which resultant hydroxyl radicals oxidize the pollutant. The Fenton process can be applied to remediate soils contaminated with hydrocarbons [56]. Contrastingly, contaminates in dry soil may require wetting the soil to apply the Fenton process [57]. Studies have shown that, hydrocarbons such as PHAs in soils can be oxidized by ammonium persulfate, assisted with subsequent microbial degradation [58]. Despite the reported microbial activity, the Fenton method may be deemed more ecologically sound than ammonium persulfate-based treatment due to residual sulphate concerns. Chemical methods, on the other hand, can compromise the functionality of soil microorganisms [59-60]. Moreover, certain chemical remediation approaches seem to necessitate precise conditions, therefore the expected treatment efficacy in an urban context may be debatable.

Nature-based solutions (i.e. bioremediation) to remediate contaminated soils are becoming increasingly popular as a green initiative. The underlying principles of nature-based solutions are the stabilization and accumulation of contaminants with the aid of plants and microorganisms, and biomonitoring. Nature-based solutions widely discussed in the literature include biodegradation process such as bioaugmentation, bioventing, bioprecipitation, biostimulation and landfarming, and phytoremediation methods such as phytostabilization, phytovolatilization and phytoextraction or phytomining, and monitored natural attenuation. In bioaugmentation, cultured microorganisms are introduced into contaminated soils to accelerate the biodegradation rate. For example, *Sphingomondas* and *Mycobacterium* species can be used to remediate soils containing PAHs [61]. By supplying air, the bioventing technique, on the other hand, allows microorganisms already present in the soil to breakdown pollutants. Similarly, with the biostimulation approach, nutrients are provided to indigenous microbes to manage the limiting factors on biodegradation. With the help of microorganisms, the bioprecipitation process induces pollutants, particularly heavy metals, to precipitate. Phytostabilization is the process of immobilizing contaminants utilizing plants while reducing bioavailability and eliminating the means for contaminant migration (i.e. soil erosion). Because no organism is purposefully introduced to the soil environment, bioventing and biostimulation can be considered environmentally safe. In phytovolatilization, on the other hand, pollutants are absorbed by plants and then released into the environment as gases through evapotranspiration. Bioaccumulation of heavy metals such as Cd by hyperaccumulators like *Malva rotundifolia* has shown a Bioaccumulation Coefficient greater than 1.0 [62]. Empirical evidence shows that *Thlaspi elegans* grown in serpentine soils has over 15000 $mg.kg^{-1}$ (dry weight basis) accumulation rate of nickel (Ni) [63]. Urban soils contaminated with radionuclides can be effectively remediated by phytoextraction [64]. Genetic engineering approaches such as recombinant RNA and DNA technologies are applied to improve the efficiency of biological agents used in bioremediation measures [65-66]. However, despite the environmental friendliness of phytoremediation technologies; physical space, plant and microbial responses to environmental vulnerabilities, and the time required to remediate contaminated soils can all be limiting factors in an urban setting, compared to other biodegradation methods.

Table 1. Comparison of practicabilities of technologies in an urban setting

Env. Technology	**Limitations**				**Overall Possibility Rank**	**Reference**
	Cost Effectiveness	**Physical Space Saving**	**Efficacy**	**Impacts on Neighborhood**		
Nanoremediation	3	4	3	2	**8**	[67-68]
Thermal ERH, TCH	2	1	1	2	2	[69]
Thermal - RFH	3	3	3	1	**8**	[70]
Air Sparging	2	2	2	2	4	[71]
Chemical - ISCR	1	1	3	3	2	[72]
Chemical - Fenton	3	1	2	3	4	[73]
Electrokinetic	3	2	1	2	4	[74-75]
Non-thermal Plasma	3	1	1	2	5	[76]
Nature Based	3	2	3	0	**9**	**[77]**
Soil Replacement	1	0	4	4	1	[78]
Soil Washing	2	0	3	4	1	[79-80]
Vitrification	2	1	2	3	2	[81]
Encapsulation	2	3	3	1	7	[82]
Passive PRB	3	2	2	1	6	[83]

It is obvious from this research that the environmental restoration methods presented have their own set of limitations, application possibilities and further developmental potential. However, nanoremediation, radio frequency heating and bioremediation can be regarded as feasible for urban regeneration process, with especial focus on redevelopment of contaminated lands (Table 1).

V. CONCLUSION

By devising a rapid literature review process and adopting a mixed method research design, the present study assessed advancements in environmental technologies applicable to urban regeneration, with a special focus on land redevelopment. For an urban setting, nanoremediation, radio frequency heating, and bioremediation have all been recognized as viable solutions. However, the proposed environmental remediation methods have their own set of limitations, application possibilities and potential for future research. The application potential of these technologies in urban brownfield redevelopment toward sustainable urban regeneration can be considered by the property developers and urban authorities. Researchers in the field of urban development can explore the developmental potential of new technological avenues by integrating several methods discussed in this paper, addressing the limitations of the technologies, interdisciplinary manner.

REFERENCES

[1] R.F.M. Ameen and M. Mourshed, Urban environmental challenges in developing countriesd A stakeholder perspective. Habitat International, vol. 64, pp. 1-10, 2017, doi: 10.1016/j.habitatint.2017.04.002.

[2] E. Korol, Y. Gaydysheva and D. Passmore, Integration of organizational-technological and social aspects in the realization of the program of renovation of residential development. MATEC Web of Conferences, vol. 251, 2018, doi: 10.1051/matecconf/201825106031

[3] C.C. Egolum and F.I. Emoh, The Issues and Challenges of Urban Renewal in a Developing Economy. International Journal of Development and Economic Sustainability, vol.5, no.1, pp.32-44, 2017.

[4] H. Yu, Y. Liu, X. …and Y. Pan, Assessment of the spatial distribution of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in urban soil of China, Chemosphere, 2019, doi: 10.1016/j.chemosphere.2019.125392.

[5] D. Castillo-Nava, M. Elias-Santos, …and H. A. Luna-Olvera, Heavy metals (lead, cadmium and zinc) from street dust in Monterrey, Mexico: ecological risk index. International Journal of Environmental Science and Technology, pp. 1-10, 2020, doi: 10.1007/s13762-020-02649-5.

[6] T. Minkina, S. Sushkova, … and E. Antonenko, Polycyclic Aromatic Hydrocarbons in Urban Soils Within the Different Land Use: A Case Study of Tyumen, Russia. Polycyclic Aromatic Compounds, pp.1-16, doi: 10.1080/10406638.2018.154099.

[7] L. Yang, Y. Zhang, S. Kang, Z. Wang and C. Wud, Microplastics in soil: A review on methods, occurrence, sources, and potential risk. Science of The Total Environment, vol. 780, 2021, doi: 10.1016/j.scitotenv.2021.146546.

[8] V. Pecina, M. Brtnický, T. Baltazár, D. Juřička, J. Kynický and M.V. Galiová, Human health and ecological risk assessment of trace elements in urban soils of 101 cities in China: A meta-analysis. Chemosphere, 2020, doi: 10.1016/j.chemosphere.2020.129215.

[9] J. M. Nyika1, E. K. Onyari, M.O. Dinka and S.B. Mishra, Heavy Metal Pollution and Mobility in Soils within a Landfill Vicinity: A South African Case Study. Oriental Journal of Chemistry, vol. 35, pp. 1286-1296, 2019, doi: 10.13005/ojc/350406.

[10] C. Swyngedouw, Sampling Methods for Site Characterization. Environmental Geochemistry (Second Edition), pp. 13-24, 2018, doi: 10.1016/B978-0-444-63763-5.00003-3.

[11] A. Capolupo, S. Pindozzi, …and L. Boccia, Photogrammetry for environmental monitoring: The use of drones and hydrological models for detection of soil contaminated by copper. Science of the Total Environment, vol.514, pp.298–306, 2015, dio: 10.1016/j.scitotenv.2015.01.109.

[12] M. Zeiner, R. Pirkl and I. JuranovićCindrić, Field-Tests versus Laboratory Methods for Determining Metal Pollutants in Soil Extracts. Soil and Sediment Contamination, 2019, doi: 10.1080/15320383.2019.1670136.

[13] New Jersey Department of Environmental Protection, Findings & Recommendations for the Remediation of Historic Pesticide Contamination - Final Report March 1999. Retrieved from: https://www.nj.gov/dep/special/hpctf/final/costs.htm

[14] G. McCartney, W. Hearty, M. Taulbut, R. Mitchell, R. Dryden and C. Collins, Regeneration and health: a structured, rapid literature review. Public Health, vol. 148, pp. 69-87, 2017, doi: 10.1016/j.puhe.2017.02.022.

[15] M. Naseri-Rad, R. Berndtsson, K.M. Persson, and K. Nakagawa, An efficient guide for sustainable remediation practice in addressing contaminated soil and groundwater. Science of The Total Environment, 2020, doi:10.1016/j.scitotenv.2020.13

[16] M. Gil-Díaz, S. Diez-Pascual, A. Gonzalez, J. Alonso, E. Rodríguez-Valdes, J.R. Gallego and M.C. Lobo, A nanoremediation strategy for the recovery of an As-polluted soil. Chemosphere, vol. 149, 137-145, 2016, doi: 10.1016/j.chemosphere.2016.01.106.

[17] M. Radziemska, Z.M.Gusiatin, …and M.Brtnicky, Nano Zero Valent Iron (nZVI) as an Amendment for Phytostabilization of Highly Multi-PTE Contaminated Soil. Materials, vol.14, pp.1-10, 2021, doi:10.3390/ma14102559.

[18] M. Gil-Díaz, M.A.Álvarez, J.Alonso and M. C. Lobo, Efectiveness of nanoscale zero-valent iron for the immobilization of Cu and/or Ni in water and soil samples. Scientific Reports, vo.10, 2020, doi: 10.1038/s41598-020-73144-7.

[19] Z. Dongsheng, G. Wenqiang, … and L. Youzhi, Removal of heavy metal lead(II) using nanoscale zero-valent iron with different preservation methods. Advanced Powder Technology,vol.30,pp. 581-589, 2019, doi:10.1016/j.apt.2018.12.013.

[20] M. Anza, O. Salazar, …and C. Garbisu, The Application of Nanoscale Zero-Valent Iron Promotes Soil Remediation While Negatively Affecting Soil Microbial Biomass and Activity. Frontiers in Environmental Science, vol. 7, 2019, doi: 10.3389/fenvs.2019.00019.

[21] C. Fajardo, J. Garcıa-Cantalejo, … and M.Martin, New insights into the impact of nZVI on soil microbial biodiversity and functionality. Journal of Environmental Science and Health Part A, 2018, doi: 10.1080/10934529.2018.1535159.

[22] C. Fajardo, S. Sánchez-Fortún, …and M. Martín, Evaluation of nanoremediation strategy in a Pb, Zn and Cd contaminated soil. Science of the Total Environment, vol.706, pp.1-11, 2020, doi: 10.1016/j.scitotenv.2019.136041.

[23] Z. Shen, Z. Chen, Z. Hou, T. Li and X. Lu, Ecotoxicological effect of zinc oxide nanoparticles on soil microorganisms. Front. Environ. Sci. Eng., 2015, doi: 10.1007/s11783-015-0789-7.

[24] Y. Hu, M. Zhang, R. Qiu and . Li, Encapsulating nanoscale zero-valent iron with a soluble Mg(OH)2shell for improved mobility and controlled reactivity release. Journal of Materials Chemistry A, 2017, doi: 10.1039/c7ta08605a.

[25] A.D. Zand, A.M. Tabrizi and A.V. Heir, Co-application of biochar and titanium dioxide nanoparticles to promote remediation of antimony from soil bySorghum bicolor: metal uptake and plant response. Heliyon, vol. 6, 2020, doi: 10.1016/j.heliyon.2020.e04669.

[26] M. Simonin, A.Richaume, J.P.Guyonnet, A. Dubost, J.M.F. Martins and T.Pommier, Titanium dioxide nanoparticles strongly impact soil microbial function by affecting archaeal nitrifiers. Scintific Reporters, vol.6, pp. 1-10, doi: 10.1038/srep33643.

[27] J. Virkutyte, S. Al-Abed, H.Choi and C.Bennett-Stamper, Distinct structural behavior and transport of TiO2nano- and nanostructured particles in sand. Colloids and Surfaces A: Physicochem. Eng. Aspects, vol. 443, pp. 188–194, 2014, doi: 10.1016/j.colsurfa.2013.11.004.

[28] D.Baragañoa, J.Alonsob, J.R.Gallegoa, M.C.Lobob and M.Gil-Díazb, Magnetite nanoparticles for the remediation of soils co-contaminated with As and PAHs. Chemical Engineering Journal, vol. 399, 2020, doi: 10.1016/j.cej.2020.125809.

[29] X. Chen, J. Wang, K. Hayat, D. Zhang and P. Zhou, Small structures with big impact: Multi-walled carbon nanotubes enhanced remediation efficiency in hyperaccumulatorSolanum nigrumL. under cadmium and arsenic stress. Chemosphere, vol. 276, pp.1-12, 2021, doi: 10.1016/j.chemosphere.2021.130130.

[30] Y. Gong, Y. Liu, Z. Xiong and D. Zhao, Immobilization of Mercury by Carboxymethyl Cellulose Stabilized Iron Sulfide Nanoparticles: Reaction Mechanisms and Effects of Stabilizer and Water Chemistry. Environ. Sci. Technol., vol. 48, 2014, doi: 10.1021/es404418a.

[31] X. Gong, H. Danlian, Y. Liu, Z. Guangming, R. Wang, P. Xu, C. Zhang, M. Cheng, W. Xueab and S. Chenab, Roles of multiwall carbon nanotubes in phytoremediation: cadmium uptake and oxidative burst in Boehmeria nivea (L.) Gaudich. Environ. Sci.: Nano, vol. 6, pp. 851-862, 2019, doi: 10.1039/C8EN00723C.

[32] S. Su, W. Wu, J. Gao, J. Lub and C. Fan, Nanomaterials-based sensors for applications in environmental monitoring. Journal of Materials Chemistry, vol.22, 2012, doi:10.1039/C2JM33284A.

[33] Y. Cheng, H. Sun, E. Yang, J. Lv, B. Wena, F. Sun, L. Luo and Z. Liu, Distribution and bioaccessibility of polycyclic aromatic hydrocarbons in industrially contaminated site soils as affected by thermal treatment

. Journal of Hazardous Materials, vol. 411, 2021, doi: 10.1016/j.jhazmat.2021.125129.

[34] C. M. Dominguez, A. Checa-Fernandez, A. Romero and A. Santos, Degradation of HCHs by thermally activated persulfate in soil system: Effect of temperature and oxidant concentration. Journal of Environmental Chemical Engineering, pp.1-10, 2021, doi:10.1016/j.jece.2021.105668.

[35] U. Roland, F. Holzer and F. Kopinke, Influenceof Low-and High-frequency Heating on Biodegrading Microorganisms in Soil: Microbial Degradation, Journal of Microwave Power and Electromagnetic Energy, vol.47, pp.280-289, 2013, doi:10.1080/08327823.2013.11689865.

[36] K. Yang, M. Fan, …and Y. Wang, An effective thermal treatment of toluene-contaminated soil by uniform heating from microwave coupled infrared radiation (MCIR). Journal of Soils and Sediments,vol.21, pp.1329–1336, 2021, doi: 10.1007/s11368-020-02855-1.

[37] S. Srirattana, K. Piaowan, G.V. Lowry and T. Phenrat, Electromagnetic induction of foam-based nanoscale zerovalent iron (NZVI) particles to thermally enhance non-aqueous phase liquid (NAPL) volatilization in unsaturated porous media: Proof of concept. Chemosphere, vol. 183,pp.323-331,2017,doi: 10.1016/j.chemosphere.2017.05.114.

[38] M. Park, M. Kim and Y. Hong, The kinetics of mercury vaporization in soil during low-temperature thermal treatment. Geoderma, vol.363, 2020, doi: 10.1016/j.geoderma.2019.114150.

[39] C. Ko, Y. Yang, J.I.W.W. Liu and Y. Shih, Thermal treatment of decabrominated diphenyl ether in its highly contaminated soil in Taiwan. Chemosphere, vol.287, 2021, doi: 10.1016/j.chemosphere.2021.131924.

[40] Q.Q. Guo, M.R. Xiao and G.S. Zhang, The persistent impacts of polyester microfibers on soil bio-physical properties following thermal treatment. Journal of Hazardous Materials, vol. 420, 2021, doi: 10.1016/j.jhazmat.2021.126671.

[41] U. Samaksaman, T. Peng, J. Kuo, C. Lu and M. Wey, Thermal treatment of soil co-contaminated with lube oil and heavy metals in a low-temperature two-stage fluidized bed incinerator, Applied Thermal Engineering, 2015, doi: 10.1016/j.applthermaleng.2015.09.024.

[42] Q. Xie, K.G. Mumford, B.H. Kueper and C. Zhao, A numerical model for estimating the removal of volatile organic compounds in laboratory-scale treatability tests for thermal treatment of NAPL-impacted soils. Journal of Contaminant Hydrology, vol.226, 2019, doi:10.1016/j.jconhyd.2019.103526.

[43] G.C. Scholes, J.I. Gerhard, G.P. Grant, D.W. Major, J.E. Vidumsky, C. Switzer and J.L. Torero, Smoldering Remediation of Coal-Tar-Contaminated Soil: Pilot Field Tests of STAR. Environ. Sci. Technol., vol. 49, pp. 14334−1434, 2015, doi: 10.1021/acs.est.5b03177.

[44] M.L. Brusseau, Soil and Groundwater Remediation. Environmental and Pollution Science, pp. 329-354, 2019, doi:10.1016/B978-0-12-814719-1.00019-7.

[45] C. Cameselle, S. Gouveia, … and B. Belhadj, Advances in Electrokinetic Remediation for the Removal of Organic Contaminants in Soils. Organic Pollutants - Monitoring, Risk and Treatment, 2013, doi: 10.5772/54334.

[46] D. Liyanage and J. Walpita, Organic pollutants from E-waste and their electrokinetic remediation. Handbook of Electronic Waste Management, pp. 171-189, 2020, doi: 10.1016/B978-0-12-817030-4.00006-1.

[47] C. Du and J. Yan, Remediation of Phenanthrene-Contaminated Soil Using Non-thermal Plasma Fluidized Bed. Plasma Remediation Technology for Environmental Protection, pp.7-20, 2017, doi: 10.1007/978-981-10-3656-9_2.

[48] H. Xu, L. Cang, Y. Song and J. Yang, Influence of electrode configuration on electrokinetic-enhanced persulfate oxidation remediation of PAH-contaminated soil. Environmental Science and Pollution Research, 2020, doi: 10.1007/s11356-020-10338-6.

[49] J. Zhan, A. Zhang, …and Y. Liu, Remediation of Perfluorooctanoic Acid (PFOA) polluted soil using Pulsed Corona Discharge Plasma. Journal of Hazardous Materials, 2019, doi: 10.1016/j.jhazmat.2019.121688.

[50] C.A. Aggelopoulos, P. Svarnas, M.I. Klapa and C.D. Tsakiroglou, Dielectric barrier discharge plasma used as a means for the remediation of soils contaminated by non-aqueous phase liquids. Chemical Engineering Journal, vol.270, pp. 428–436, 2015, doi: 10.1016/j.cej.2015.02.056.

[51] M.D.F. Rodríguez, M.C.G. Gómez, …and J.V.Tarazona, Soil Pollution Remediation. Encyclopedia of Toxicology (Third Edition), pp. 344-355, 2014, doi: 10.1016/B978-0-12-386454-3.00579-0.

[52] J. Li , X. Song , G. Hu and R. W. Thring, Ultrasonic desorption of petroleum hydrocarbons from crude oil contaminated soils. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering, vol.48, pp.1378-1389, doi:10.1080/10934529.2013.781885.

[53] Y. Li, X. Liao, … and Q. Lin, The combined effects of surfactant solubilization and chemical oxidation on the removal of polycyclic aromatic hydrocarbon from soil. Science of the Total Environment, vol. 647, pp. 1106–1112, 2019, doi: 10.1016/j.scitotenv.2018.07.420.

[54] V.O. Akpoveta, Process optimization of silica encapsulation technique as a unique remediation technology for the treatment of crude oil contaminated soil. Egyptian Journal of Petroleum, vol. 29, pp. 113–119, 2020, doi: 10.1016/j.ejpe.2019.12.004.

[55] E. J. Ordoñez-Frías, V. I. Domínguez-Rodríguez and R. H. Adams, Remediation of soil contaminated by di(2-ethylhexyl) phthalate by chemical oxidation or bioremediation. nternational Journal of Environmental Science and Technology, pp. 1-10, 2020, doi: 10.1007/s13762-020-03007-1.

[56] A. Gharaee, M. R. Khosravi-Nikou and B. Anvaripour, Hydrocarbon contaminated soil remediation: A comparison between Fenton, sono-Fenton, photo-Fenton and sono-photo-Fenton processes. Journal of Industrial and Engineering Chemistry, vol. 79, pp.181–193, 2019, doi: 10.1016/j.jiec.2019.06.033.

[57] M. Farzadkia, M. Dehghani and M. Moafian, The effects of Fenton process on the removal of petroleum hydrocarbons from oily sludge in Shiraz oil refinery, Iran. Journal of Environmental Health Science & Engineering, vol.12, pp.1-7, 2014,doi: 10.1186/2052-336X-12-31.

[58] R. Medina, P.M.D. Gara, A. J. Fernández-González, J. A. Rosso and M.T.D. Pann, Remediation of a soil chronically contaminated with hydrocarbons through persulfate oxidation and bioremediation. Science of the Total Environment, vol. 618, pp. 518–530, 2018, doi: 10.1016/j.scitotenv.2017.10.326.

[59] E. Kakosová, P. Hrabák, … and L. Vrtoch, Effect of various chemical oxidation agents on soil microbial communities. Chemical Engineering Journal, 2016, doi:10.1016/j.cej.2016.12.065.

[60] E. Martinez-Pascual, T. Grotenhuis, …and M. Vinas, Coupling chemical oxidation and biostimulation: effects on the natural attenuation capacity and resilience of the native microbial community in alkylbenzene-polluted soil. Journal of Hazardous Materials, 2015, doi: 10.1016/j.jhazmat.2015.06.061.

[61] L.K. Redfern, C.M. Gardner, E. Hodzic, P.L. Ferguson, H. Hsu-Kim and C.K. Gunsch, A new framework for approaching precision bioremediation of PAH contaminated soils. Journal of Hazardous Materials, vol. 378, 2019, doi: 10.1016/j.jhazmat.2019.120859.

[62] M. Wu, Q. Luo, S. Liu, Y. Zhao, Y. Long and Y. Pan, Screening ornamental plants to identify potential Cd hyperaccumulators for bioremediation. Ecotoxicology and Environmental Safety, vol. 162, 35–41, 2018, doi: 10.1016/j.ecoenv.2018.06.049.

[63] N. Koleli, A. Demir, … and R. Binzet, Heavy Metal Accumulation in Serpentine Flora of Mersin-Findikpinari (Turkey) – Role of Ethylenediamine Tetraacetic Acid in Facilitating Extraction of Nickel. Soil Remediation and Plants, pp. 629–659, 2015, doi:10.1016/b978-0-12-799937-1.

[64] L. Yan, Q.V. Le, … W. Peng, Phytoremediation of radionuclides in soil, sediments and water. Journal of Hazardous Materials, 2020, doi:10.1016/j.jhazmat.2020.1247

[65] P. Kumar and G. Baul, Recombinant DNA Technology for Bioremediation of Pollutants. In: Fulekar M.H. (eds) Bioremediation Technology, 2010, doi: 10.1007/978-90-481-3678-0_8.

[66] A. Kumar, S. Devi and D. Singh, Significance and Approaches of Microbial Bioremediation in Sustainable Development. Microbial

Bioprospecting for Sustainable Development, 2018, doi:10.1007/978-981-13-0053-0_5.

[67] Araújo, R., Castro, A. C. M., & Fiúza, A. (2015). The Use of Nanoparticles in Soil and Water Remediation Processes. Materials Today: Proceedings, 2(1), 315–320. doi:10.1016/j.matpr.2015.04.055

[68] G. Medina-Pérez, F. Fernández-Luqueño, ... and M. Miranda-Arámbula, Remediating Polluted Soils Using Nanotechnologies: Environmental Benefits and Risks. Pol. J. Environ. Stud. Vol. 28, (3), 2019, pp. 1013-1030, doi: 10.15244/pjoes/87099

[69] P.L. O'Brien, T.M. DeSutter, ...A.F. Wick, Thermal remediation alters soil properties – a review. Journal of Environmental Management, vol. 206, pp. 826–835, 2018, doi:10.1016/j.jenvman.2017.11.0

[70] G. Huon, T. Simpson, ...U. Roland, In Situ Radio-Frequency Heating for Soil Remediation at a Former Service Station: Case Study and General Aspects. Chemical Engineering & Technology, vol. 35(8), pp. 1534–1544, 2012, doi:10.1002/ceat.201200027

[71] S. Khalid, M. Shahid...C. Dumat, A comparison of technologies for remediation of heavy metal contaminated soils. Journal of Geochemical Exploration, vol. 182, pp. 247–268, 2017, doi:10.1016/j.gexplo.2016.11.021

[72] L. Huysegoms, S. Rousseau and V. Cappuyns, Chemical or Natural? Including LCA in Social CBA to Compare Remediation Alternatives for a Dry-Cleaning Facility. Sustainability, vol. 11(7), 2019, doi:10.3390/su11071975

[73] Z. Zhou, X. Liu, ...W. Ouyang, Persulfate-based advanced oxidation processes (AOPs) for organic-contaminated soil remediation: A review. Chemical Engineering Journal, vol. 372, pp. 836-851, 2019, doi:10.1016/j.cej.2019.04.213

[74] B. Gidudu and E.M.N. Chirwa, The combined application of a high voltage, low electrode spacing, and biosurfactants enhances the bio-electrokinetic remediation of petroleum contaminated soil. Journal of Cleaner Production, 2020, doi:10.1016/j.jclepro.2020.1227

[75] D. Wen, R. Fu and Q. Li, Removal of Inorganic Contaminants in Soil by Electrokinetic Remediation Technologies:A Review. Journal of Hazardous Materials, 2020, doi:10.1016/j.jhazmat.2020.123345

[76] H. Zhang, D. Ma, R. Qiu, Y. Tang and C. Du, Non-thermal plasma technology for organic contaminated soil remediation: A review. Chemical Engineering Journal, vol. 313 pp. 157-170, 2017, doi: 10.1016/j.cej.2016.12.067.

[77] X. Wan, M. Lei and T.Chen, Cost–benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. Science of The Total Environment, 2016, doi:10.1016/j.scitotenv.2015.12

[78] D. Lavee, T. Ash and G. Baniad, Cost-benefit analysis of soil remediation in Israeli industrial zones. Natural Resources Forum, vol. 36, pp. 285–299, 2012.

[79] W. Chen and H. Li, Cost-Effectiveness Analysis for Soil Heavy Metal Contamination Treatments. Water, Air, & Soil Pollution, vol. 229(4), 2018, doi:10.1007/s11270-018-3784-3

[80] Voglar, D., & Lestan, D. (2014). Chelant soil-washing technology for metal-contaminated soil. Environmental Technology, vol. 35(11), 1389–1400. doi:10.1080/09593330.2013.869265

[81] J.E. Vidonish, K. Zygourakis, ...P.J.J. Alvarez, Thermal Treatment of Hydrocarbon-Impacted Soils: A Review of Technology Innovation for Sustainable Remediation. Engineering, vol. 2(4), pp. 426–437, 2016, doi:10.1016/j.eng.2016.04.005

[82] L.Liu, W. Li, W. Song and M. Guo, Remediation techniques for heavy metal-contaminated soils: Principles and applicability. Retrieved_from:https://www.sciencedirect.com/science/article/pii/S0048969718309215

[83] S.W. Jeen, R.W. Gillham and A. Przepiora, Predictions of long-term performance of granular iron permeable reactive barriers: Field-scale evaluation. Journal of Contaminant Hydrology, vol. 123(1-2), pp. 50–64, 2011, doi:10.1016/j.jconhyd.2010.12.00