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Review

Soil Remediation: Towards a Resilient and Adaptive Approach to Deal with the Ever-Changing Environmental Challenges

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Abstract: Pollution from numerous contaminants due to many anthropogenic activities affects soils quality. Industrialized countries have many contaminated sites; their remediation is a priority in environmental legislation. The aim of this overview is to consider the evolution of soil remediation from consolidated invasive technologies to environmentally friendly green strategies. The selection of technology is no longer exclusively based on eliminating the source of pollution but aims at remediation, which includes the recovery of soil quality. "Green remediation" appears to be the key to addressing the issue of remediation of contaminated sites as it focuses on environmental quality, including the preservation of the environment. Further developments in green remediation reflect the aim of promoting clean-up strategies that also address the effects of climate change. Sustainable and resilient remediation faces the environmental challenge of achieving targets while reducing the environmental damage caused by clean-up interventions and must involve an awareness that social systems and environmental systems are closely connected.

Keywords: soil contamination; green remediation; resilience; climate change

1. Introduction

Protection, prevention, and remediation of soil are key goals in new environmental policies and strategies (European Green Deal and Agenda 2030), which aim at the comprehensive and sustainable transformation of major production, consumption, and trade systems [1–3]. Although soil is a valuable and non-renewable ecological system, it has always been subject to widespread degradation due to anthropic activities. The most severe risks are point source and diffuse soil pollution. Process industry, transport, urban sprawl, agriculture, and illegal dumping or landfill without adequate resource recovery [4] are currently among the main sources of pollutants [5,6]. The direct release or indirect deposition of organic and inorganic pollutants (including heavy metals, mineral oils, and polycyclic aromatic hydrocarbons) into the soil occurs from these activities, which has hazardous effects on the environment and human health [7]. Although the specific effects on soil and the risks to organisms are known for some pollutants, many uncertainties remain about their long-term impacts and their interactions with biodiversity and climate change.

The remediation of contaminated soils and sites is, therefore, a significant step in the protection of the environment and living organisms, and must be included in the broader multidisciplinary scenario of strategic green transition.

Various methods are currently applied to treating contaminated soils and water [8–11]. However, many of the traditional technologies (physical, chemical, and thermal) are currently considered outdated, as their only remediation objective is to remove contamination without any consideration of the side effects.

In addition, these techniques have proven to be extremely expensive in both energetic and economic terms and also highly invasive, thus, further impacting the already compromised environmental situation [12,13]. The environmental regulations of industrialized countries have also been modified in recent years, evolving towards assessing remediation through accurate risk analyses. Environmental Protection Agency (EPA) proposed the concept of “Green Remediation” (GR) to address the problem of soil contamination, in which remediation technologies are applied to the sustainable recovery of contaminated sites [14–17]. This new strategy involves innovative solutions and approaches that meet both the criteria of sustainable development and remediation. However, to address the new environmental challenges such as climate change, food security, and natural disasters, and to limit the damage they cause, further green remediation approaches are necessary for contaminated soils.

Extreme events such as heatwaves, floods, droughts, water shortages, forest fires, typhoons and tornadoes are occurring with increasing frequency and intensity, so effective countermeasures must be put in place to reduce their impact on soil remediation.

A sustainable and resilient remediation approach can be a solution to this problem. This integrated approach aims to optimise remediation outcomes, maximise the social and economic benefits, and reduce the environmental damage caused by remediation. The scope of this review is to provide an overview of the current issues around the green and sustainable remediation technologies by examining new approaches to resilience and the ability of a remediation system to address climate change.

2. Green Strategy

2.1. Green Remediation

The technical and scientific tools for exploring innovative solutions in soil remediation are constantly developing, in line with new international environmental policies and the challenges faced [14,16]. The evolution of remediation approaches is illustrated in Figure 1.

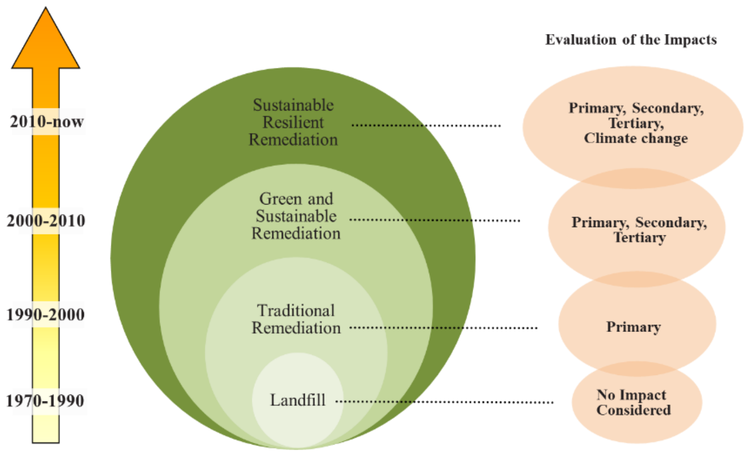

Figure 1. The evolution of remediation approaches to environmental impacts from the second half of the 20th century to the present. Primary impacts denote those associated with the situation of contaminated sites and site contaminants. Secondary impacts are those derived from remediation activity, such as the use of energy and materials, as well as after remediation monitoring. Tertiary impacts are those associated with site redevelopment and final destinations.

In the past, contaminated soil was considered to be hazardous waste and landfilling was the most common method of disposal, due to low implementation costs. This approach was due to mistakenly equating contaminated soil with waste and, thus, waste treatment technologies were applied to soil remediation. Traditional techniques were exclusively aimed at removing contaminants and the effects of soil contamination (primary impacts) through highly invasive physical, chemical, thermal, and inertization treatments. These techniques did not consider the impact of the remediation process, such as waste generation, energy consumption, social acceptance, or the potential opportunities for economic growth and environmental sustainability. The landfill solution is, unfortunately, still used in countries with poor environmental cultures and limited economic resources [18,19]. The cleaning up of contaminated sites has, however, progressed in recent years, due to the increased attention given to environmental issues by international institutions and organisations [10,20,21]. Currently, the protection of soil functions is considered essential in the remediation process.

In the early 2000s, new remediation strategies were required as alternatives to the technologies of the time and the concept of "Green Remediation" emerged [14]. In addition to having the ultimate goal of cleaning up the soil, this new approach is addressed to reduce the environmental impacts of the contamination itself and the remediation techniques employed (secondary impacts). Interest in GR is increasing in all industrialized countries, as it includes new technologies that address the problem of remediation and also consider the socio-economic effects. This new vision of remediation, founded on Natural Based Solutions (NBS), also leads to a greater consideration of soil quality and a reduction in the use of limited environmental renewable resources.

In recent years, there has also been an increase in the publication of technical standards to ensure the efficient application of GR [22,23]. Thus, the management of a contaminated site involves the identification of best management practices (BMPs) in addition to the best available technology. BMPs improve the environmental footprint of remediation activities by considering environmental, social and economic elements [24].

In the GR approach, the prioritised remediation technologies are less-invasive and energy-passive. Suitable BMPs should be chosen to ensure that the approach is site-specific while maintaining the remediation targets.

Technology screening is, therefore, based on the assessment of environmental and socio-economic sustainability. The chosen technology must be sufficiently sustainable to overcome the negative side effects within a life cycle, through the use of BMPs that minimize secondary emissions and the production of waste. The social impacts on local communities can be addressed through the involvement of stakeholders.

The main principles of the BMPs applied to remediation [14] are summarized in Table 1.

Table 1. Main core elements of BMPs for green remediation strategies.

Minimization/Reduction	Maximization/Increase	Conservation/Protection of
Energy use Greenhouse gas emissions Air pollutants emission Water use Waste production Soil and habitat disturbance	Use of renewable energy Energy efficiency Waste reuse Materials management	Material resources Water quality Ecosystem services Soil quality Productive use of the contaminated site

These principles can be applied to all stages of remediation, from preliminary site investigation to site closure, and thus inform the process of selecting the most appropriate techniques.

2.2. Green and Sustainable Remediation

An integrated evaluation of the environmental, social, economic, and technological sectors for each phase of the remediation project is required to achieve these goals. This is the core principle of the innovative "Green and Sustainable Remediation" (GSR) movement [16], in which the decision-making process to identify the best solution involves policymakers, professional organizations, and all stakeholders. Thus, technology screening is based on the assessment of environmental and socio-economic sustainability. The sustainability of the chosen technology must involve overcoming the negative side effects within a life cycle through BMPs that minimize secondary emissions and waste production. Finally, the social impacts on local communities are addressed through the involvement of stakeholders.

The remediation of contaminated sites is only possible by applying this method, as soil quality and functionality is preserved and long-term environmental sustainability ensured.

The GSR complements the GR, as it retains all of the green principles but considers the environmental impact throughout the life of the project, rather than only in the remediation implementation phase [16]. Thus, the evaluation of the environmental footprint includes the tertiary impact of remediation, i.e., the impact associated with post-remediation effects of the site, such as redevelopment actions [25,26].

The practical implementation of the GSR strategy has been facilitated by new environmental policies designed to provide mitigation and adaptation solutions to environmental challenges (such as climate change, food security and safety). These synergistic actions, which consider both nature and society provide a sustainable and efficient alternative to traditional approaches [27]. They also represent a valuable long-term economic opportunity, with several benefits for the environment, economy, and society [28,29]. However, NBS such as phytoremediation or bioremediation in contaminated sites do not always support long-term environmental sustainability [30]. The implementation of a remediation project, even if based on natural green solutions, cannot be considered the best sustainable solution without any post-remediation activities being comprehensively evaluated.

Selecting sustainable remediation should not imply a deviation from the core goal of any remediation action, i.e., to achieve the desired level of environmental protection through the appropriate technologies. This level of protection can vary greatly, depending on the specific conditions of the site and the type of contamination. Therefore, sustainable remediation projects also require a detailed assessment of specific site characteristics and risk to ensure the regulatory requirements are met [22]. Only with such a site-specific assessment is it possible to determine the properties (e.g., solubility, mobility, volatility . . .) and behavior (leaching, persistence, transformation . . .) of the contaminants at that specific site [31].

In addition, the environmental benefit, life cycle impact, energy savings, resource recovery, waste reuse and socio-economic effects of a sustainable remediation project should be considered. The technique selected should ensure environmental and human safety and long and short-term sustainability. Thus, the sustainability of the remediation approach should be evaluated qualitatively and quantitatively using appropriate tools.

Many technologies can be considered sustainable, but this can only be confirmed over the long term through a detailed investigation of the current and future social, environmental and economic impacts of the remediation project.

Life cycle assessment (LCA) [32] is one of the most integrated quantitative methods to quantify the environmental impacts associated with the remediation technique, i.e., the secondary impacts of contamination [33]. For example, LCA allows quantifying material and energy consumption and emissions from the site characterization phase to the final treatment of any waste produced by the remediation process. When combined with qualitative models (such as a health risk assessment), this tool can assist in the decision-making in selecting and planning green remediation strategies for specific contaminated sites and targets [30,34]. With a view to sustainability, the recovery of energy and materials is an essential aspect in evaluating technologies [35,36]. Resilience and sustainability should be integrated into the remedial project life cycle.

Thus, in the design of a remediation intervention, it is necessary to identify objectives that comply with sustainability and resilience, including considerations of local climate changes impacts and the final use of the site.

Any LCA that considers resilience in a remediation project must aim to predict the frequency of severe climatic events and their potential effects not only on the area to be remediated, but also on the economy and on the local community. Technologies must also be evaluated in terms of protection of human health and the environment.

After identifying the specific climatic impacts to which a site may be exposed, it is essential to assess the vulnerability of the site to each potential impacts and the appropriate corrective actions during all the phases of remediation should be identified, from site characterization to long-term monitoring.

A remediation project must be adaptive so it can incorporate frequent updates and new forecasting information about climate change.

The future effectiveness of current remedies can then be considered. For resilience assessment, climate models of the site should be inserted in the LCA consideration and procedures [37–39]. Socio-economic factors that involve stakeholder participation should also be considered in concepts of resilience [40–42].

2.3. Sustainable Resilient Remediation

Awareness of the necessity of sustainable actions has recently increased in the scientific community, government, and industry organisations. However, many of the realized environmental strategies on climate change have not been completely successful [30] thus a comprehensive green transformation is yet to be implemented. Change must be cultural and behavioural to effectively counteract the now compelling evidence for global climate change.

Thus, the age of climate crisis has arrived, with increasingly frequent and extreme weather and climatic events. In Europe, there is an increasing occurrence of river and coastal floods, heatwaves, droughts, hydrogeological instability, wildfires, windstorms, typhoons, and tornadoes [43,44]. This inevitably has implications for soil remediation, and so any planning should consider the potential climate events in the site-specific context.

This adaptation to climate change must also be considered in sustainable green remediation strategies. This leads to an extension of the concept to one of sustainable resilient remediation (SRR). This SRR solution is an optimised GSR that is resilient to climate threat. To ensure the long-term effectiveness of remediation interventions and to protect the environment and human health, the impacts of climate change must be considered in any projects. The protection of environmental quality over time can also support the considerable financial investment required for the remediation of contaminated sites.

The climates of all global regions have experienced rapid change, including that of the Mediterranean, which is typically characterized by cold and rainy winters and hot and dry summers, during which water availability is often limited.

The Mediterranean area has been observed to be warming rapidly in recent years and the average annual temperature has increased by 1.4 °C from pre-industrial levels [44,45]. This trend suggests that summer rainfall in the Mediterranean area could drastically decrease in the future. This will aggravate the lack of water, and periods of drought will become more frequent and with longer duration while rainy periods will become both rarer and more violent.

The sea level of the Mediterranean has also risen by 60 mm in recent years. This will continue to increase due to the rising average temperatures leading to glacier melting at the North Pole [43,44].

This increase in extreme meteoric events and the reduction in precipitation has led to soil degradation processes becoming increasingly evident. Appropriate tools for the management and planning of remediation interventions based on future climate scenarios are, therefore, required. The impacts of climate change on soil can significantly influence the effects of remediation and compromise the long-term protection and effectiveness of applied green technologies.

Many contaminated sites exist throughout the world, with an estimated 2.8 million of contaminated sites where polluting activities have taken place in Europe [46].

Many of these sites are located in areas highly threatened by extreme weather events, which can undermine the effectiveness of the site remediation project. Contaminated industrial areas close to the sea may, for example, be at risk. As industries developed, many processing plants were built on the seashore to facilitate the discharge of residues into the sea, with the belief that the dilution effect would reduce the risk posed by the released materials.

2.4. Effects of Global Change on Contaminant Behaviour

Location is not the only issue affecting contaminated sites. The changing of climatic variables (e.g., temperature, winds, precipitation, currents, and snow cover) can also influence the behavior of contaminants (bioavailability, toxicity, transport, transfer, deposition and fate) and the organisms that may potentially inhabit them (i.e., their migration and distribution) [47].

Table 2 summarises the main effects of changing climatic variables on the environmental behavior of organic and inorganic soil contaminants. However, the effect of each variable can lead to secondary knock-on effects that increase the environmental risk and are difficult to predict.

Table 2. Main impacts of major environmental/climatic events on organic and inorganic soil contaminants. For each alteration of the climatic variables, the possible processes that organic or inorganic contaminants might be subjected to, are marked with a dot.

		Bioavailability Change	**Toxicity Change**	**Volatilization**	**Mobilization/ Transport**	**Deposition on Soil**	**Transfer in Food Chain**	**Atmospheric Deposition**
Climatic Variables		Inorganic Contaminant						
Temperature	Heatwave	•		• (Hg, As)	•	• (Hg, As)	•	•
	Freezing	•		• (Hg, As)	•	• (Hg, As)	•	•
Precipitation	Drought	•	•	•	•	•	•	•
	Rainfall	•	•	•	•	•	•	•
Wind	Erosion			•	•	•		•
	Wind Storm			•	•	•		•
Flooding	Hypoxia	•	•	•	•	•	•	•
	Transport	•	•	•	•	•	•	•
Fire		•	•		•		•	•
Secondary Effects								
pH alteration		•	•	•	•		•	
Salinity		•			•		•	
Climatic Variables		Organic Contaminant						
Temperature	Heatwave	•	•	•	•		•	•
	Freezing	•	•	•	•		•	•
Precipitation	Drought	•	•	•	•	•	•	•
	Rainfall	•	•	•	•	•	•	•
Wind	Erosion	•	•	•	•	•	•	•
	Wind Storm	•	•	•	•	•	•	•
Flooding	Hypoxia	•	•	•	•	•	•	•
	Transport	•	•	•	•	•	•	•
Fire		•	•	•	•	•	•	•
Secondary Effects								
pH alteration		•	•	•	•	•	•	•
Salinity			•			•	•	•

For example, the amount of rainfall can change the balance between the gas and liquid phases of the soil within the pore system. The bioavailability, toxicity, and volatilization of some metals (such as mercury) may then be altered, resulting in long-distance transport.

Soil erosion induced by climate change can also cause the migration and transport of metals, as the direct loss of surface soil can lead to both landslides and the loss of significative quantities of soil organic matter. The fractions of metals strongly bonded to humic materials can thus be transported and lost at a distance from the original site [48,49].

Organic matter affects both the retention and bioavailability of heavy metals, so its decomposition, due to temperature increase, may release more contaminants into the soil solution, resulting in increased uptake by plants [50]. Although this increase can be viewed as an advantage in remediation techniques such as phytoextraction, it can cause the dangerous and uncontrolled process of contaminant biomagnification in living beings.

The increased frequency and intensity of forest fires is also a consequence of climate change. Soil properties are significantly altered by the heatwave accompanying a fire, in terms of both immediate effects and delayed modifications resulting from the changes in the soil's physical, chemical, and biological composition [51]. Apart from the dramatic impact on the biological activity of the soil, a fire greatly affects organic matter content. Organic matter is the most important erosion-preventing agent of the soil, due to its ability to form stable aggregates. In general, the higher the temperature, the greater the change in organic matter. At around 600/700 °C, practically all organic matter in the soil will be destroyed. This has immediate consequences on particle size distribution, aggregation, permeability, porosity, and plasticity, which are all parameters associated with soil erodibility.

The destruction of organic matter by fire can also dramatically affect the behavior of metals in the soil. Their altered mobility can lead to significant quantities of heavy metals leaching into groundwater [52], which can be a major source of environmental contamination. This should also be considered for green technologies that leave traces of metals in the soil during the remediation process.

In addition persistent organic pollutants (POPs) are significantly influenced by environmental changes, and particularly by increased rainfall and temperature. An increase in rainfall can result in a greater runoff of pesticides and POPs, and potential deposition in uncontaminated environments, while decreased rainfall may increase their persistence in soil [53]. Rising temperatures are generally combined with higher solar intensity and can also severely affect organic compounds such as polycyclic aromatic hydrocarbons (PAHs). Low molecular-weight PAHs are observed to volatilise more rapidly with increased temperatures and light intensity. However, the subsequent partial photo-degradation of these PAHs at the highest solar intensities can result in the formation of intermediates that are more toxic than the original compounds [54].

Contaminated sites can, thus, be considered under threat from climate change, which may reduce the efficiency of the technologies used. The efficiency of technologies can be improved through appropriate adaptive measures that can be used during the remediation process (Figure 2).

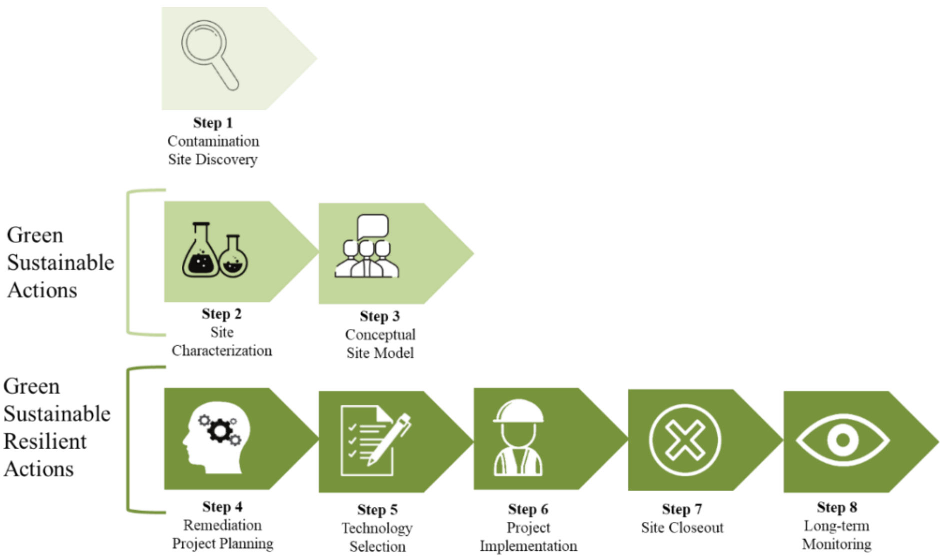

Figure 2. Framework of a contaminated soil remediation project. The steps are subdivided according to the principles of sustainability and resilience applied to the activities of each phase.

This implementation must be based on the assessment of the risks of a changing climate, to ensure appropriate adaptation strategies developed to increase the resilience of the remediation procedures. Thus, starting from the characterization phase (step 2) in addition to the traditional investigations on the nature of the contamination of soil, groundwater, etc.; it is also necessary to examine the vulnerability of the site to climate changes that could affect the effectiveness of the remediation and the risk assessment concerning potential receptors. When creating the conceptual model (step 3), the potential resilience to the impacts of local climate change can be evaluated, to ensure that the remediation process avoids any unexpected problems, such as a depletion of natural resources or an increase in unwanted emissions. These aspects should be considered in the executive remediation project (step 4), in which the concept of resilience should be integrated into remediation activities. The planning of the project, which is considered the basis of the clean-up intervention, must also involve all interested parties in the remediation and site development.

In terms of SRR, the selection of the most appropriate technology (step 5) is conducted to identify the remediation technologies of the site with the lower environmental impacts. These technologies should achieve the remediation targets, while opportunities for economic development should also be evaluated. The technologies chosen must be characterized by a high degree of adaptability in order to be able to respond to any impacts due to climate change that may occur in the geographical area of the contaminated site.

Unexpected environmental impacts can occur in the execution phase (step 6), so the technology must include appropriate resilience measures to address extreme weather events and, thus, reduce the potential negative impacts. The technology adaptability can also minimize the risks to the local community and the environment resulting from remediation.

The closure process (step 7) includes both a regulatory phase linked to achieving remediation targets and considerations of resilience, which can enable the redevelopment and reuse of a site based on the socio-environmental characteristics of the area. After remediation is completed, climatic parameters (e.g., expected rainfall, groundwater rises or falls, soil erosion, landslides) should continue to be evaluated in the long-term monitoring phase (step 8). In this way, it is possible to tackle any critical issues and the level of risk for a site can then be identified.

3. Resilient Phytoremediation

In GSR projects, bioremediation and phytoremediation are among the most widely used NBS. Bioremediation technologies mainly involve microorganisms whereas phytoremediation technologies involve both plants and microorganisms of the rhizosphere to clean contaminated soil.

Phytoremediation was first developed in the late 1900s as a green strategy to decontaminate soils affected by heavy metals. Due to its ecological (non-invasive, self-sustaining, and solar-driven technology, suitable for a wide range of target contaminants), economic (low implementation and maintenance costs), and socially beneficial characteristics, phytoremediation has been readily accepted by stakeholders, policymakers, and remediation workers. Phytoremediation is based on mechanisms such as degradation, extraction, and immobilisation, either separately or in combination, and can treat a wide range of inorganic (heavy metals, radionuclides) and organic (hydrocarbons, polycyclic aromatic hydrocarbons, pesticides, pharmaceuticals) pollutants [55–57]. Thus, phytoremediation technologies can be classified according to their decontamination processes, and include phytoextraction, phytodegradation, rhizodegradation, phytostabilization, and phytovolatilization.

These in-situ remediation methods are well aligned with current sustainability principles. In addition to preserving soil quality, phytoremediation can minimize the environmental footprint of remediation through energy and resource efficiency. Recently luminescent solar concentrators (LSC) have also been considered to promote phytoremediation. Due to their structural characteristics, LSC panels consent significant energy savings through the optimum use of solar spectrum radiation [58]. However, the sustainability of a process or technology can only be fully assessed by considering the management of the product after its useful life, which for phytoremediation is the phytobiomass produced [36,59,60].

Biomass valorization is, thus, an advantage in new sustainable phyto-management strategies [59]. Phytobiomass was initially considered to be a waste product, but it has emerged as a valuable resource that can be reused in further production processes [61]. For example, energy can be recovered from phytobiomass through direct combustion, or through the production of biofuels after the conversion processes. New integrated phytoremediation-bioenergy approaches are therefore promising sustainable strategies from environmental (decontamination of contaminated sites, waste reduction), economic (bioenergy production) and social (green redevelopment) perspectives.

These strategies ensure sustainable and cost-efficient environmental protection and encourages a culture of re-use and a circular economy.

However, the development of new phytoremediation strategies should follow the principles of the SRR, and in response to climate change adapt to environmental stresses. Nature-based technologies are also vulnerable to climate change. Rapid changes in climatic and environmental conditions can directly influence plants' growth, resistance, production, and productivity [62,63], but can also act indirectly by affecting soil quality and functionality [48,64].

Few studies examine the potential cumulative effects of climate change on phytoremediation. However, both the positive and negative effects of individual environmental variables on different phytoremediation approaches have been predicted and evaluated. For example, several studies have been conducted on to the influence of atmospheric carbon dioxide (CO_2) on the effectiveness of heavy metal phytoremediation [65,66]. CO_2 production through human activity has increased considerably since pre-industrial times and is now widely recognised as a significant factor in global warming [67].

A generally positive effect of increased CO_2 on plant growth and carbon assimilation has been observed [65,68] and, thus, the application of phytoremediation on a large scale could represent an excellent strategy for fixing atmospheric CO_2 [12], thus mitigating its emissions.

Luo et al. (2019) [69] evaluated the effect of various CO_2 concentrations on the phytoremediation efficiency of *Noccaea caerulescens*. They investigated changes in the plant's growth, characteristics, and metal detoxification capacity under three atmospheric CO_2 condition scenarios: elevated, at 550 $\pm$ 50 ppm (concentration expected from 2050 to 2070); ambient controls, at 400 $\pm$ 25 ppm; and decreased, at 280 $\pm$ 25 ppm. Their results showed that the elevated CO_2 treatment increased phytoremediation efficiency due to a higher biomass yield and metal accumulation in *N. caerulescens* plants, and a reduction in oxidative damage and the time required for Cd, Cu and Zn removal. This positive effect of increased CO_2 concentrations on the plants has been extensively reported [70–72].

However, this increase in CO_2 does not necessarily contribute to improving phytoremediation efficiency. As the technology is an in situ NBS, the possible interactions with other environmental factors should be considered. Yang et al. (2021) [66] reported an improvement in the phytoremediation efficiency of Cd at high levels of atmospheric CO_2 (550 ppm) under monoculture conditions for *Festuca arundinacea*. However, the opposite effect was observed for this plant when intercropped with *Echinochloa caudata* (wild weed). At the same CO_2 concentrations (550 ppm), the ability of *F. arundinacea* to reduce Cd in the intercrop decreased by 215.0%. Thus, this study well demonstrates that, in the phytoremediation design, it is essential also to assess the main interactions between possible environmental variables to achieve an effective, resilient and sustainable remediation system in the context of the ongoing evolution of contaminant behavior [73].

Although a single variable (such as elevated CO_2 concentrations) can positively influence the outcomes of phytoremediation, secondary and synergistic effects must also be considered [50]. An increase or change in the CO_2 balance and other greenhouse gases (GHG) results in a gradual rise in temperatures. Several studies have investigated the effects of the high temperatures predicted for the coming years on different plant species and the uptake efficiency of metals [62,74–78]. However, conflicting results emerge, as these effects may be combined with other environmental factors (e.g., drought, irrigation regime, CO_2, contaminated soils). The site-specific conditions may not enable an effective comparison of remediation techniques. New technologies applicable to phytoremediation have been explored in recent years, which mitigate possible extreme weather conditions. The adaptation and resistance of plants in an environment subject to rapid and drastic changes are a significant concern in phytoremediation practice.

Plant growth-promoting rhizobacteria (PGPRs) are widely used in assisted phytoremediation techniques, to increase the efficiency of remediation technology [79,80]. These could also represent an effective strategy to increase the resistance of plants to climate change.

PGPRs act at the rhizosphere level and can relieve the abiotic stresses caused by excessive salinity, drought, alkalinity and extreme temperatures, thus improving plant health and adaptation to the environment. In phytoremediation, their use as microbial inocula is aimed at increasing the absorption of metals by the plant and at sustainably improving biomass production [80,81]. The use of PGPRs thus increases the ability of plants to counteract the potentially harmful effects of abiotic stresses [82,83]. Due to their versatile metabolic activity, PGPRs can act on the plant, facilitating the absorption of nutrients through structural and morphological changes at the root level, as induced by specific molecules (phytohormones, antioxidants, extracellular polymers) produced under stress conditions. PGPRs in conditions of saline stress can also increase the fixation of nitrogen, the solubilization of inorganic phosphorus and other essential elements, or create hydrating biofilms, which can reduce or cancel the inhibition of water stress in the plant's development [79,84,85]. PGPRs are, therefore, beneficial to the development of a healthy and well-branched root system, and significantly contribute to the stabilization of the soil by preventing erosion. More recent investigations involve developing climate-resistant metal hyperaccumulation plants using molecular techniques [86]. This involves the transfer of genes that produce stress-tolerance proteins in plants through genome editing. Transgenic plants can therefore be the development, which via this "induced stress resilience" can achieve phytoremediation under changing stress conditions [86]. The potential creation of metal hyperaccumulators, under high temperature stress conditions, by altering a specific gene (addition or deletion) through non-transgenic molecular manipulation are being explored [87].

In any risk analysis, the effects of climate change on in situ phytotechnology conditions (such as floods, erosion, or storms) should be considered, in addition to the individual effects of different climate stressors on specific phytoremediation components (plants, soil, contaminants, microbes). Few studies have been conducted on this topic and many aspects of the effects require clarification, to ensure phytoremediation techniques effectively adapt to climate change.

Rising sea levels are a major concern for many contaminated sites. Flooding can facilitate the transport of toxic contaminants to neighbouring environments and may increase soil salinity. O'Connor et al. (2019) [88] formulated a conceptual model to examine the resilience of a phytoremediation system applied to a brownfield redevelopment context under various sea-level rise scenarios and hydroclimatic conditions. Four potential scenarios by 2100 were expected: No change; a low rise (30.5 cm to 121.9 cm); a modest rise (0.40 m to 0.63 m); and a high sea-level rise (80 cm to 200 cm). The study included an LCA assessment and demonstrated the vulnerability of phytoremediation to sea-level rises in extreme scenarios. However, the model was found to be resilient to a moderate sea-level rise, and other hydrological features could further enhance its resilience.

In conclusion, as a phytoremediation strategy can cover a relatively long time period and making significant changes during its implementation can be difficult, any possible damage must be addressed in the planning stages. Various resilience options should be assessed without underestimating the plant species' high levels of natural adaptability and resilience, such as adaptation measures to accelerate the remediation time, preventing further damage due to side effects, or applying compensatory measures (e.g., ecological restoration).

4. How Far from Resilient Remediation Are We

By factoring resilience into remediation strategies, adaptation to climate change can be evaluated in a specific region in the near future. Climate change raises problems on a global level that must be addressed collectively by all those involved in remediation. However, action must be taken locally for contaminated sites. Generic strategies cannot be applied to a specific site and should be addressed concurrently with the local characteristics and the type of end-use envisaged. Therefore, it is essential to understand the dynamics of the relationships among the specifics of contaminated sites, the reclamation interventions selected, and the development vision of the stakeholders in the particular regions.

Various time frames can be considered in terms of climate change and the related risks in the construction of forecasting scenarios. Different remediation technologies must be compared in the frameworks we have discussed, and the potential efficiency, the degree of tuning of the strategy, and the reversibility of any actions should be considered.

Extreme events linked to climate change may evolve at a speed that is difficult to manage within the current limitations of territorial control. In areas where contaminants are still present, future scenarios should be anticipated, and tools that can support the development of more resilient strategies in an increasingly uncertain and unpredictable future should be applied.

Multiple scenarios should be developed when defining conceptual models that consider resilience, rather than a single vision of the future, when facing situations with high levels of uncertainty. These scenarios must be modular so they can be continuously updated, to identify the factors affecting the resilience of the selected technologies that are implemented over a medium- to long-term time frame.

A remediation project should offer possible solutions that can reduce the causes and effects of climate change, through the creation of specific design scenarios. The introduction of resilience in remediation can increase the awareness of how adaptive the chosen technology must be, to ensure it can address the increasing risks due to climate change.

The simulation of potential scenarios (high wind, salinity, flooding, temperature variations) in greenhouses or other specific built structures can enable the testing of remediation protocols that could be implemented in the event of drastic climate change. Such studies can provide data to support decision-making tools and can reduce the cost of addressing of future damage.

However, issues that hinder implementation should be considered. First, no current regulations require assessments of resilience when selecting the technologies to be used, and if they are considered they remain optional. Second, a major concern is the lack of knowledge by both legislators and stakeholders about the potential risks climate change can bring to technologies applied to resilience. Few long-term studies of the ageing processes that can affect residual contaminants after remediation have been conducted, and few models are capable of predicting hydrological variations following climate change [89]. Considerable uncertainty therefore remains about how monitoring systems that are resilient to changes in the climate can be implemented. Although several model assessments of climate change have been conducted for some geographical areas, they are qualitative and not site-specific. Therefore, significant improvements are required when selecting the significant parameters to be introduced into the forecasting models, to obtain quantitative assessments of future climatic conditions at the local site scale. Such improvements will facilitate planning for extreme weather events but must consider the risk of compromising the efficiency of the selected remediation technology.

Third, for countries in which administrative bureaucracy prevails over environmental concerns, convincing stakeholders, and particularly controlling institutions, to consider climate mitigation, adaptation, and resilience in the development of brownfield sites is extremely difficult. The application of SRR technologies can be considered too expensive. Further limitations to the level of acceptability of a remediation project, including considerations of resilience, could lead to the opposite outcome: the soil to be reclaimed could then be excavated and transported to landfill, as a rapid (and mistaken) method of avoiding any potential (and very frequent) legal appeals, which can lead to many years of delay in approving any reclamation.

The resilience assessment process must also involve the whole of society. Public opinion suggests an increased sensitivity to environmental issues. Information and communication are important when a community is faced with a planned remediation intervention that involves disturbance and considers possible unexpected events. Technological choices can be shared through reliable communication, which can be extremely important when constructing remediation scenarios.

Our focus on the importance of soil in environmental equilibria demonstrates how some remediation interventions have been particularly invasive, due to a lack of knowledge of the real characteristics of soil pollution. They are aimed at the destruction of this matrix rather than at identifying recovery and conservation strategies.

Regarding soil as a complex system that is essential to the health of the environment can inspire new ideas that involve technology, politics, ethics, economics, and society.

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References

1. UN—United Nations. Transforming our world: The 2030 agenda for sustainable development. In *A/RES/70/1 Resolution Adopted by the General Assembly on 25 September 2015*; UN General Assembly: New York, NY, USA, 2015; pp. 1–41.
2. EC—European Commission. *The European Green Deal—COM(2019) 640 Final*; European Commission: Brussels, Belgium, 2019; pp. 1–24.
3. EC—European Commission. *Pathway to a Healthy Planet for All EU Action Plan: "Towards Zero Pollution for Air, Water and Soil"—COM(2021) 400 Final*; European Commission: Brussels, Belgium, 2021; pp. 1–22.
4. Pietrelli, L.; Ferro, S.; Vocciante, M. Eco-friendly and cost-effective strategies for metals recovery from printed circuit boards. Renew. *Sustain. Energy Rev.* **2019**, *112*, 317–323. [CrossRef]
5. Triassi, M.; Alfano, R.; Illario, M.; Nardone, A.; Caporale, O.; Montuori, P. Environmental pollution from illegal waste disposal and health effects: A review on the "triangle of death". *Int. J. Environ. Res. Public Health* **2015**, *12*, 1216–1236. [CrossRef] [PubMed]
6. Zhang, Q.; Wang, C. Natural and human factors affect the distribution of soil heavy metal pollution: A review. *Water Air Soil Pollut.* **2020**, *231*, 350. [CrossRef]
7. Cachada, A.; Rocha-Santos, T.A.P.; Duarte, A.C. Soil and pollution: An introduction to the main issues. In *Soil Pollution: From Monitoring to Remediation*; Duarte, A.C., Cachada, A., Rocha-Santos, T.A.P., Eds.; Academic Press: New York, NY, USA, 2018; pp. 1–28.
8. Wan, X.; Lei, M.; Chen, T. Review on remediation technologies for arsenic-contaminated soil. *Front. Environ. Sci. Eng.* **2019**, *14*, 24. [CrossRef]
9. Li, C.; Zhou, K.; Qin, W.; Tian, C.; Qi, M.; Yan, X.; Han, W. A review on heavy metals contamination in soil: Effects, sources and remediation techniques. *Soil Sediment. Contam.* **2019**, *28*, 380–394. [CrossRef]
10. Liu, L.; Li, W.; Song, W.; Guo, M. Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Sci. Total Environ.* **2018**, *633*, 206–219. [CrossRef]
11. Dhaliwal, S.S.; Singh, J.; Taneja, P.K.; Mandal, A. Remediation techniques for removal of heavy metals from the soil contaminated through different sources: A review. *Environ. Sci. Pollut. Res.* **2020**, *27*, 1319–1333. [CrossRef]
12. Song, Y.; Kirkwood, N.; Maksimović, Č.; Zhen, X.; O'Connor, D.; Jin, Y.; Hou, D. Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review. *Sci. Total Environ.* **2019**, *663*, 568–579. [CrossRef]
13. Vocciante, M.; Dovì, V.G.; Ferro, S. Sustainability in ElectroKinetic Remediation Processes: A Critical Analysis. *Sustainability* **2021**, *13*, 770. [CrossRef]
14. *EPA 542-R-08-002*; Green Remediation: Incorporating Sustainable Environmental Practices into Remediation of Contaminated Sites. EPA—U.S. Environmental Protection Agency: Washington, DC, USA, 2008.
15. *EPA 542-F-09-004*; Green Remediation: Best Management Practices for Site Investigation. EPA—U.S. Environmental Protection Agency: Washington, DC, USA, 2009.
16. *GSR-1*; Green and Sustainable Remediation: State of the Science and Practice. ITRC—Interstate Technology & Regulatory Council: Washington, DC, USA, 2011.
17. Pedron, F.; Petruzzelli, G. Green remediation strategies to improve the quality of contaminated soils. *Chem. Ecol.* **2011**, *27*, 89–95. [CrossRef]
18. Lamb, D.T.; Venkatraman, K.; Bolan, N.; Ashwath, N.; Choppala, G.; Naidu, R. Phytocapping: An alternative technology for the sustainable management of landfill sites. *Crit. Rev. Environ. Sci. Technol.* **2014**, *44*, 561–637. [CrossRef]
19. Idowu, I.A.; Atherton, W.; Hashim, K.; Kot, P.; Alkhaddar, R.; Alo, B.I.; Shaw, A. An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences. *Waste Manag.* **2019**, *87*, 761–771. [CrossRef] [PubMed]
20. EU—European Union. *Council Directive 1999/31/EC on The Landfill of Waste*; European Union: Brussels, Belgium, 1999.
21. EC—European Commission. *Thematic Strategy for Soil Protection—COM(2006)231 Final*; European Commission: Brussels, Belgium, 2006.
22. *E2876-13*; Standard Guide for Integrating Sustainable Objectives into Cleanup. ASTM—American Society of Testing and Materials: Conshohocken, PA, USA, 2013.

23. ISO—International Organization for Standardization. *ISO 18504:2017—Soil Quality—Sustainable Remediation*; ISO: Geneva, Switzerland, 2017.
24. Simon, J.A. Best management practices for sustainable remediation. In *Sustainable Remediation of Contaminated Soil and Groundwater*; Hou, D., Ed.; Butterworth-Heinemann: Oxford, UK, 2020; pp. 75–91. ISBN 9780128179826.
25. Hou, D.; Song, Y.; Zhang, J.; Hou, M.; O'connor, D.; Harclerode, M. Climate change mitigation potential of contaminated land redevelopment: A city-level assessment method. *J. Clean. Prod.* **2018**, *171*, 1396–1406. [CrossRef]
26. Hou, D.; O'Connor, D. Green and sustainable remediation: Concepts, principles, and pertaining research. In *Sustainable Remediation of Contaminated Soil and Groundwater*; Hou, D., Ed.; Butterworth-Heinemann: Oxford, UK, 2020; pp. 1–17.
27. Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S. *Nature-Based Solutions to Address Global Societal Challenges*; Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., Eds.; IUCN—International Union for Conservation of Nature: Gland, Switzerland, 2016.
28. Eggermont, H.; Balian, E.; Azevedo, J.M.N.; Beumer, V.; Brodin, T.; Claudet, J.; Fady, B.; Grube, M.; Keune, H.; Lamarque, P.; et al. *Nature-Based Solutions: New Influence for Environmental Management and Research in Europe*; GAIA—Ecological Perspectives for Science and Society, Ed.; GAIA: Oekom Verlag, 2015; Volume 24, pp. 243–248. Available online: https://www.biodiversa.org/898/download (accessed on 22 December 2021).
29. Faivre, N.; Fritz, M.; Freitas, T.; de Boissezon, B.; Vandewoestijne, S. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environ. Res.* **2017**, *159*, 509–518. [CrossRef]
30. Wang, L.; Rinklebe, J.; Tack, F.M.G.; Hou, D. A review of green remediation strategies for heavy metal contaminated soil. *Soil Use Manag.* **2021**, *37*, 936–963. [CrossRef]
31. Zhang, X.; Chen, J.; Hu, B.X.; Yu, Y.; So, J.; Zhang, J.; Dai, Z.; Yin, S.; Soltanian, M.R.; Ren, W. Application of risk assessment in determination of soil remediation targets. *Stoch. Environ. Res. Risk Assess.* **2020**, *34*, 1659–1673. [CrossRef]
32. *ISO 14040:2006*; ISO—International Organization for Standardization Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
33. Søndergaard, G.L.; Owsianiak, M. LCA of soil and groundwater remediation. In *Life Cycle Assessment: Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer: Cham, Switzerland, 2018; pp. 927–959.
34. Hou, D.; Qi, S.; Zhao, B.; Rigby, M.; O'connor, D. Incorporating life cycle assessment with health risk assessment to select the "greenest" cleanup level for Pb contaminated soil. *J. Clean. Prod.* **2017**, *162*, 1157–1168. [CrossRef]
35. Vocciante, M.; de Folly D'Auris, A.; Franchi, E.; Petruzzelli, G.; Ferro, S. CO_2 footprint analysis of consolidated and innovative technologies in remediation activities. *J. Clean. Prod.* **2021**, *297*, 126723. [CrossRef]
36. Vocciante, M.; Caretta, A.; Bua, L.; Bagatin, R.; Franchi, E.; Petruzzelli, G.; Ferro, S. Enhancements in phytoremediation technology: Environmental assessment including different options of biomass disposal and comparison with a consolidated approach. *J. Environ. Manag.* **2019**, *237*, 560–568. [CrossRef]
37. Reddy, K.R.; Cameselle, C.; Adams, J.A. *Sustainable Engineering: Drivers, Metrics, Tools, and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2019; ISBN 978-1-119-49393-8.
38. Reddy, K.R.; Kumar, G.; Du, Y.J. Risk, sustainability and resiliency considerations in polluted site remediation. In *Proceedings of the 8th International Congress on Environmental Geotechnics, ICEG 2018, Hangzhou, China, 28 October–1 November 2018. Environmental Science and Engineering*; Zhan, L., Chen, Y., Bouazza, A., Eds.; Springer: Singapore, 2018; Volume 1, pp. 145–163.
39. Reddy, K.R.; Sadasivam, B.Y.; Adams, J.A. Social Sustainability Evaluation Matrix (SSEM) to quantify social aspects of sustainable remediation. In *Proceedings of the ICSI 2014: Creating Infrastructure for a Sustainable Infrastructure*; American Society of Civil Engineers: Reston, VA, USA, 2014; pp. 831–841.
40. Cundy, A.B.; Bardos, R.P.; Church, A.; Puschenreiter, M.; Friesl-Hanl, W.; Müller, I.; Neu, S.; Mench, M.; Witters, N.; Vangronsveld, J. Developing principles of sustainability and stakeholder engagement for "gentle" remediation approaches: The European context. *J. Environ. Manag.* **2013**, *129*, 283–291. [CrossRef]
41. Kumar, G.; Reddy, K.R. Addressing climate change impacts and resiliency in contaminated site remediation. *J. Hazardous. Toxic Radioact. Waste* **2020**, *24*, 04020026. [CrossRef]
42. Ridsdale, R.D.; Harclerode, M. Stakeholder roadmap: A guide to effective active engagement using social methodologies (Platform Presentation). In Proceedings of the Tenth International Conference on Remediation and Management of Contaminated Sediments, New Orleans, LA, USA, 11–14 February 2019.
43. Forzieri, G.; Cescatti, A.; e Silva, F.B.; Feyen, L. Increasing risk over time of weather-related hazards to the European population: A data-driven prognostic study. *Lancet Planet. Health* **2017**, *1*, e200–e208. [CrossRef]
44. IPCC—Intergovernmental Panel on Climate Change. Summary for policymakers. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2021.
45. IPCC—Intergovernmental Panel on Climate Change. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; IPCC: Geneva, Switzerland, 2019.
46. Pérez, A.P.; Rodríguez Eugenio, N. *Status of Local Soil Contamination in Europe—Revision of the Indicator "Progress in the Management Contaminated Sites in Europe"*; EUR 29124 EN; Publications Office of the European Union: Luxembourg, 2018.

47. Maco, B.; Bardos, P.; Coulon, F.; Erickson-Mulanax, E.; Hansen, L.J.; Harclerode, M.; Hou, D.; Mielbrecht, E.; Wainwright, H.M.; Yasutaka, T.; et al. Resilient remediation: Addressing extreme weather and climate change, creating community value. *Remediation* **2018**, *29*, 7–18. [CrossRef]
48. Biswas, B.; Qi, F.; Biswas, J.K.; Wijayawardena, A.; Khan, M.A.I.; Naidu, R. The fate of chemical pollutants with soil properties and processes in the climate change paradigm—A review. *Soil Syst.* **2018**, *2*, 51. [CrossRef]
49. Casazza, M.; Lega, M.; Liu, G.; Ulgiati, S.; Endreny, T.A. Aerosol pollution, including eroded soils, intensifies cloud growth, precipitation, and soil erosion: A review. *J. Clean. Prod.* **2018**, *189*, 135–144. [CrossRef]
50. Rajkumar, M.; Prasad, M.N.V.; Swaminathan, S.; Freitas, H. Climate change driven plant–metal–microbe interactions. *Environ. Int.* **2013**, *53*, 74–86. [CrossRef]
51. Thomaz, E.L. Effects of fire on the aggregate stability of clayey soils: A meta-analysis. *Earth-Sci. Rev.* **2021**, *221*, 103802. [CrossRef]
52. Terzano, R.; Rascio, I.; Allegretta, I.; Porfido, C.; Spagnuolo, M.; Khanghahi, M.Y.; Crecchio, C.; Sakellariadou, F.; Gattullo, C.E. Fire effects on the distribution and bioavailability of potentially toxic elements (PTEs) in agricultural soils. *Chemosphere* **2021**, *281*, 130752. [CrossRef]
53. Noyes, P.D.; McElwee, M.K.; Miller, H.D.; Clark, B.W.; Van Tiem, L.A.; Walcott, K.C.; Erwin, K.N.; Levin, E.D. The toxicology of climate change: Environmental contaminants in a warming world. *Environ. Int.* **2009**, *35*, 971–986. [CrossRef]
54. Marquès, M.; Mari, M.; Audí-Miró, C.; Sierra, J.; Soler, A.; Nadal, M.; Domingo, J.L. Climate change impact on the PAH photodegradation in soils: Characterization and metabolites identification. *Environ. Int.* **2016**, *89–90*, 155–165. [CrossRef]
55. Pedron, F.; Grifoni, M.; Barbafieri, M.; Petruzzelli, G.; Rosellini, I.; Franchi, E.; Bagatin, R.; Vocciante, M. Applicability of a Freundlich-like model for plant uptake at an industrial contaminated site with a high variable arsenic concentration. *Environments* **2017**, *4*, 67. [CrossRef]
56. Conte, A.; Chiaberge, S.; Pedron, F.; Barbafieri, M.; Petruzzelli, G.; Vocciante, M.; Franchi, E.; Pietrini, I. Dealing with complex contamination: A novel approach with a combined bio-phytoremediation strategy and effective analytical techniques. *J. Environ. Manag.* **2021**, *288*, 112381. [CrossRef] [PubMed]
57. Pietrini, I.; Grifoni, M.; Franchi, E.; Cardaci, A.; Pedron, F.; Barbafieri, M.; Petruzzelli, G.; Vocciante, M. Enhanced lead phytoextraction by endophytes from indigenous plants. *Soil Syst.* **2021**, *5*, 55. [CrossRef]
58. Pedron, F.; Grifoni, M.; Barbafieri, M.; Petruzzelli, G.; Franchi, E.; Samà, C.; Gila, L.; Zanardi, S.; Palmery, S.; Proto, A.; et al. New Light on Phytoremediation: The use of luminescent solar concentrators. *Appl. Sci.* **2021**, *11*, 1923. [CrossRef]
59. Grifoni, M.; Pedron, F.; Barbafieri, M.; Rosellini, I.; Petruzzelli, G.; Franchi, E. Sustainable valorization of biomass: From assisted phytoremediation to green energy production. In *Handbook on Assisted and Amendments Enhanced Sustainable Remediation Technology*; Vara Prasad, M.N., Ed.; John Wiley & Sons: Chichester, UK, 2020.
60. Grifoni, M.; Rosellini, I.; Petruzzelli, G.; Pedron, F.; Franchi, E.; Barbafieri, M. Application of sulphate and cytokinin in assisted arsenic phytoextraction by industrial *Cannabis sativa* L. *Environ. Sci. Pollut. Res.* **2021**, *28*, 1–12. [CrossRef]
61. EC—European Commission. *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC*; European Commission: Brussels, Belgium, 2009.
62. Hasanuzzaman, M.; Nahar, K.; Alam, M.M.; Roychowdhury, R.; Fujita, M. Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *Int. J. Mol. Sci.* **2013**, *14*, 9643–9684. [CrossRef]
63. Bellard, C.; Bertelsmeier, C.; Leadley, P.; Thuiller, W.; Courchamp, F. Impacts of climate change on the future of biodiversity. *Ecol. Lett.* **2012**, *15*, 365–377. [CrossRef]
64. Hamidov, A.; Helming, K.; Bellocchi, G.; Bojar, W.; Dalgaard, T.; Ghaley, B.B.; Hoffmann, C.; Holman, I.; Holzkämper, A.; Krzeminska, D.; et al. Impacts of climate change adaptation options on soil functions: A review of European case-studies. *Land Degrad. Dev.* **2018**, *29*, 2378–2389. [CrossRef]
65. Wang, S.; Zhang, Y.; Ju, W.; Chen, J.M.; Ciais, P.; Cescatti, A.; Sardans, J.; Janssens, I.A.; Wu, M.; Berry, J.A.; et al. Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. *Science* **2020**, *370*, 1295–1300. [CrossRef]
66. Yang, G.; Luo, Y.; Sun, L.; Cao, M.; Luo, J. Influence of elevated atmospheric CO_2 levels on phytoremediation effect of Festuca arundinacea intercropped with Echinochloa caudata. *Chemosphere* **2021**, *270*, 128654. [CrossRef]
67. Allen, M.R.; de Coninck, H.; Dube, O.P.; Hoegh-Guldberg, O.; Jacob, D.; Jiang, K.; Revi, A.; Rogelj, J.; Roy, J.; Shindell, D.; et al. Technical Summary: Global warming of 1.5 °C. In *An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response*; Masson-Delmotte, V.P., Zhai, H.-O., Pörtner, D., Roberts, J., Skea, P.R.S., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., et al., Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019.
68. Karavolias, N.G.; Horner, W.; Abugu, M.N.; Evanega, S.N. Application of gene editing for climate change in agriculture. *Front. Sustain. Food Syst.* **2021**, *5*, 296. [CrossRef]
69. Luo, J.; Yang, G.; Igalavithana, A.D.; He, W.; Gao, B.; Tsang, D.C.W.; Ok, Y.S. Effects of elevated CO_2 on the phytoremediation efficiency of *Noccaea caerulescens*. *Environ. Pollut.* **2019**, *255*, 113169. [CrossRef] [PubMed]
70. Dier, M.; Sickora, J.; Erbs, M.; Weigel, H.J.; Zörb, C.; Manderscheid, R. Positive effects of free air CO_2 enrichment on N remobilization and post-anthesis N uptake in winter wheat. *Field Crop. Res.* **2019**, *234*, 107–118. [CrossRef]
71. Högy, P.; Keck, M.; Niehaus, K.; Franzaring, J.; Fangmeier, A. Effects of atmospheric CO_2 enrichment on biomass, yield and low molecular weight metabolites in wheat grain. *J. Cereal Sci.* **2010**, *52*, 215–220. [CrossRef]

72. Li, X.M.; Zhang, L.H.; Li, Y.Y.; Ma, L.J.; Chen, Q.; Wang, L.L.; He, X.Y. Effects of elevated carbon dioxide and/or ozone on endogenous plant hormones in the leaves of Ginkgo biloba. *Acta Physiol. Plantarum.* **2011**, *33*, 129–136. [CrossRef]
73. Magdziak, Z.; Gąsecka, M.; Goliński, P.; Mleczek, M. Phytoremediation and environmental factors. In *Phytoremediation: Management of Environmental Contaminants*; Ansari, A.A., Gill, S.S., Gill, R.R., Lanza, G., Newman, L., Eds.; Springer: Cham, Switzerland, 2015; Volume 1, pp. 45–55. ISBN 9783319103952.
74. Li, Y.; Zhang, Q.; Wang, R.; Gou, X.; Wang, H.; Wang, S.; Xiao, G.; Liu, W.; Xu, Q.; Sun, Z.; et al. Temperature changes the dynamics of trace element accumulation in *Solanum tuberosum* L. *Clim. Chang.* **2012**, *112*, 655–672. [CrossRef]
75. Öncel, I.; Keleş, Y.; Üstün, A.S. Interactive effects of temperature and heavy metal stress on the growth and some biochemical compounds in wheat seedlings. *Environ. Pollut.* **2000**, *107*, 315–320. [CrossRef]
76. Xiao, G.; Liu, W.; Xu, Q.; Sun, Z.; Wang, J. Effects of temperature increase and elevated CO_2 concentration, with supplemental irrigation, on the yield of rain-fed spring wheat in a semiarid region of China. *Agric. Water Manag.* **2005**, *74*, 243–255. [CrossRef]
77. Sardans, J.; Peñuelas, J.; Estiarte, M. Warming and drought change trace element bioaccumulation patterns in a Mediterranean shrubland. *Chemosphere* **2008**, *70*, 874–885. [CrossRef]
78. Qaderi, M.M.; Kurepin, L.V.; Reid, D.M. Effects of temperature and watering regime on growth, gas exchange and abscisic acid content of canola (*Brassica napus*) seedlings. *Environ. Exp. Bot.* **2012**, *75*, 107–113. [CrossRef]
79. Franchi, E.; Fusini, D. Plant Growth-Promoting Rhizobacteria (PGPR) assisted phytoremediation of inorganic and organic contaminants including amelioration of perturbed marginal soils. In *Handbook of Assisted and Amendment: Enhanced Sustainable Remediation Technology*; Prasad, M.N., Ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2021; pp. 477–500.
80. Franchi, E.; Cosmina, P.; Pedron, F.; Rosellini, I.; Barbafieri, M.; Petruzzelli, G.; Vocciante, M. Improved arsenic phytoextraction by combined use of mobilizing chemicals and autochthonous soil bacteria. *Sci. Total Environ.* **2019**, *655*, 328–336. [CrossRef] [PubMed]
81. Prakash, J. Plant growth promoting rhizobacteria in phytoremediation of environmental contaminants: Challenges and future prospects. In *Bioremediation for Environmental Sustainability*; Kumar, V., Saxena, G., Shah, M.P., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 191–218.
82. Enebe, M.C.; Babalola, O.O. The influence of plant growth-promoting rhizobacteria in plant tolerance to abiotic stress: A survival strategy. *Appl. Microbiol. Biotechnol.* **2018**, *102*, 7821–7835. [CrossRef] [PubMed]
83. Shah, A.; Nazari, M.; Antar, M.; Msimbira, L.A.; Naamala, J.; Lyu, D.; Rabileh, M.; Zajonc, J.; Smith, D.L. PGPR in Agriculture: A sustainable approach to increasing climate change resilience. *Front. Sustain. Food Syst.* **2021**, *5*, 211. [CrossRef]
84. Dimkpa, C.; Weinand, T.; Asch, F. Plant–rhizobacteria interactions alleviate abiotic stress conditions. *Plant. Cell Environ.* **2009**, *32*, 1682–1694. [CrossRef]
85. Qin, Y.; Druzhinina, I.S.; Pan, X.; Yuan, Z. Microbially mediated plant salt tolerance and microbiome-based solutions for saline agriculture. *Biotechnol. Adv.* **2016**, *34*, 1245–1259. [CrossRef]
86. Sarma, H.; Islam, N.F.; Prasad, R.; Prasad, M.N.V.; Ma, L.Q.; Rinklebe, J. Enhancing phytoremediation of hazardous metal(loid)s using genome engineering CRISPR–Cas9 technology. *J. Hazard. Mater.* **2021**, *414*, 125493. [CrossRef]
87. Sanz-Fernández, M.; Rodríguez-Serrano, M.; Sevilla-Perea, A.; Pena, L.; Mingorance, M.D.; Sandalio, L.M.; Romero-Puertas, M.C. Screening Arabidopsis mutants in genes useful for phytoremediation. *J. Hazard. Mater.* **2017**, *335*, 143–151. [CrossRef]
88. O'Connor, D.; Zheng, X.; Hou, D.; Shen, Z.; Li, G.; Miao, G.; O'Connell, S.; Guo, M. Phytoremediation: Climate change resilience and sustainability assessment at a coastal brownfield redevelopment. *Environ. Int.* **2019**, *130*, 104945. [CrossRef]
89. Libera, A.; de Barros, F.P.J.; Faybishenko, B.; Eddy-Dilek, C.; Denham, M.; Lipnikov, K.; Moulton, D.; Maco, B.; Wainwright, H. Climate change impact on residual contaminants under sustainable remediation. *J. Contam. Hydrol.* **2019**, *226*, 103518. [CrossRef]