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Global Use of Bioremediation Technologies for Decontamination of Ecosystems

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Abstract

A global survey examining the use of bioremediation technologies for addressing environmental pollution problems has been carried out. There were respondents from all continents (except Antarctica), though North America was comparatively over-represented. Despite a high aspiration to apply bioremediation techniques, this was not borne out in current practice. Air pollution was the lowest priority. Otherwise, a clear association was seen between the per capita income of a region and the concerns, remediation techniques and research practice adopted. For example, contamination of groundwater had higher priority in developed countries/regions. Toxic metals and aromatic hydrocarbons were the most common concern, while alkyl halides were of greater concern in North temperate (comparatively economically developed) countries than elsewhere. Only 15-35% of respondents used online databases to guide the design of their experiments, and these were largely restricted to North America and Europe, three quarters of US respondents used modelling software compared with about a third elsewhere. Consequently, while the developed economies made higher use of low-cost in situ bioremediation technologies (e.g. Monitored Natural Attenuation), their developing counterparts appeared to focus on the more expensive, sometimes ex situ, technologies. Despite the significant investment in and widespread availability of online resources, their limited use emphasizes the need to explore avenues for improved training and the development of more user-friendly resources. In this regard, this survey has produced a bioremediation research wish list to guide such developments. The data from this survey may also contribute to policy-decision making worldwide.

Keywords: Microbial bioremediation; Phytoremediation; Xenobiotics; Bioinformatics; Mathematical modelling; Global survey

Introduction

Contamination of ecosystems by xenobiotic compounds (including various organic petroleum hydrocarbons, pesticides and other agrochemicals, pharmaceutical products and heavy metals) causes ecological problems leading to serious environmental problems [1-5]. Attempts at remediating contaminated sites have used conventional but often costly approaches, such as 'pump and treat', excavation and removal, soil vapour extraction, and other chemical treatments [6]. These methods are time consuming, invasive, disruptive to natural habitats and usually result in a rearrangement of the problem [3]. Using these methods, it is estimated that the cost of reinstatement of all contaminated sites in the United States alone is approximately US $1.7 trillion [7]. Lately however, bioremediation has proven to be a safe, effective, low-cost and environmentally friendly alternative for sustainable remediation of environments contaminated by hazardous and recalcitrant pollutants [3,8-11]. Bioremediation uses biological processes and naturally occurring microbial catabolic activity to eliminate, attenuate or transform contaminants to less hazardous products such as carbon dioxide, water, inorganic salts, and microbial biomass [10,12-14].

Bioremediation generally has high public acceptance and can be carried out in various environmental media for a wide variety of organic and inorganic compounds [14]. However, bioremediation research and practice are currently still hampered by an incomplete understanding of the genetics and genome-level characteristics of the organisms used, the metabolic pathways involved, and their kinetics. The result of this is an inability to model and predict the behaviour of these processes, and hence a difficulty in developing natural bioremediation processes in the field [15-20].

Bioremediation techniques can take place *in situ* and *ex situ*, and have been widely characterized [3,14,21-23]. While the former may lead to minimal disruption of sites and elimination of handling costs, they usually require longer periods of treatment and extended monitoring. They can also be constrained by geological, hydro-geological and other environmental factors, resulting in a low efficiency of contaminant removal [3,15,23]. The latter (such as land farming, biopiling, composting and bioreactor treatment) involve the removal of materials by excavation, pumping or dredging, which allows greater process control though there will be some disruption to the site. They are also more thorough and enable environmental conditions of contaminated material to be easily modified and monitored, leading to greater efficiency of treatment. However excavation and transport of materials add significantly to remediation costs, leading to a preference for *in situ* techniques [14,15,21].

There have been various reports of biodegradation and bioremediation activities utilizing particular bacteria or plant species, with various degrees of success [16,17,20,24,25]. However, no investigations have been found relating to trends and possible drivers in the global use of these techniques. Kinya and Kimberly [18] surveyed the extent to which remediation firms and research centers have implemented strategies for clean-up of soils and groundwater, comparing clean-up costs, and related opinions on the use of nonindigenous microorganisms for bioremediation. However the survey, which was quite detailed, focused on one country and one compound-the USA and Tricholoroethylene (TCE) respectively.

Therefore, information on the following is not well known: (1) the demography of the relative acceptance and global use of bioremediation, (2) the factors driving such usage, (3) the barriers limiting its implementation, and (4) the extent of application of current biotechnological advances within the sector. Lekakis [26] used Greece as a case study to explore the relationship between economic indices (Gross Domestic Product, and per capita income) and public spending on Research and Development (R&D) for environmental protection and conservation. Summersgill [27] provided information on costs and market conditions and use of remediation technologies across Europe. The study which covered a three-year period (2001-2003), elaborated on the prominence of particular remediation technologies in member states and the reasons behind such prominence. It highlighted market changes that have occurred during that period in five European countries, and showed that the primary driving force was cost. Jalal and Rogers [28] carried out a similar study among Asian countries and showed marked variability between rich and poorer countries in the perception and approach to remediation issues. These reflected their relative abilities to invest in R & D for novel techniques such as bioremediation. Rivett, Petts et al. [29] also observed marked contrasts in levels of importance accorded to process-based remediation techniques versus physical methods like land filling. There was a lack of centralized information on remediation activity, even in some first-world countries, and differences in levels of funding for the development and provision of remediation information. Thus, economic barriers may limit certain countries' access to the growing body of information on degradation of xenobiotics by micro-organisms.

Available historical data on the usage of bioremediation technologies for decontamination of polluted sites are somewhat uninspiring. The UK Environment Agency [30] reported that of the 391 contaminated land sites addressed during the 2000-2007 period, *in situ* bioremediation was used on only 4. *Ex situ* bioremediation was proposed, but not actually used, on only 2 sites. Phytoremediation - the use of plants for land remediation - was not even mentioned. Relatively higher figures have been reported for the United States. According to the US-EPA [31], of the 997 source-control-treatment projects carried out during the 1982-2005 period, 240 were classified as 'innovative technologies', of which there were 60 *ex situ* and 53 *in situ* bioremediation projects-a small percentage (~12%) overall. These two reports indicate that the contribution of bioremediation to environmental site clean-up has been very small. Information on researchers' preferences has also not been found.

Molecular tools, other '*omics*' technologies, and decision-support software for selection of 'gentle' remediation approaches have been documented [8,19,32-35]. A number of software tools for modelling environmental perturbations have also been developed [36-38]. However, information on the extent of use of such tools and technologies is restricted to certain countries. Therefore, in order to get a coherent picture of the status of bioremediation activities, a global survey was conducted to investigate drivers and barriers to the use of bioremediation, evaluate global differences in priority areas and identify specific needs of the bioremediation sector.

Survey methodology

A number of survey methods exist, each with their own pros and cons. These include postal/email questionnaires, face-to-face interviews, focus groups, telephone interviews, and internet/web-based surveys [39,40]. The online web-form approach was adopted in this instance to take advantage of the reach, flexibility and popularity of the World Wide Web, including the possibility of reaching a geographically dispersed audience, receiving responses in real time, enhanced convenience for responders, automated data collection and processing, and the mitigation of costs that would otherwise be incurred in travel, printing and posting of paper questionnaires.

The survey targeted individuals involved in bioremediation, and actively working within Multinational Companies, Government Agencies, Academia, Not-for-Profit Organisations and Non-Governmental Organisations, Agriculturists and 'Other' research groups, to whom emails containing links to the survey web-form were sent. The mailing list used for the campaign was generated using 'Google' searches with the terms 'bioremediation', 'biodegradation', 'biocatalysis', 'environmental biotechnology', 'environmental remediation', 'environment+conference' and 'environmental contamination', with specific attempts made to reach websites of bioremediation conferences, especially the Battelle's 6th International Conference on remediation of chlorinated and recalcitrant compounds held in Monterey California. The contact email addresses within these websites were programmatically identified and obtained using Perl [41] scripts, available from the author. No geographical restrictions to its distribution were imposed. On inspection the list showed a good mix of potential respondents from all the continents. For simplicity the survey form consisted of a single web page at http://www.mycib.ac.uk/~sbztch/Bioremediation-survey/.

Survey Content

The goal of the survey was to obtain the views of respondents on issues relevant to bioremediation and its research. The main sections contained questions on (i) the particular environments in which respondents were investigating pollution problems; (ii) the particular contaminants they usually had to deal with, in order of importance; (iii) the preferred treatment methods; (iv) the specific methods used to identify micro-organisms for particular contaminants and bioremediation efforts; (v) how the respondents dealt with mixtures of contaminants or incomplete field-level remediation; and (vi) the use of chemical, biological, pathway databases and other modelling software resources. Information on the practice and use of phytoremediation as an alternative were also canvassed. The questionnaire closed with an open-ended section requiring respondents to outline three issues or problems that they thought would make their research/work a lot easier if some online resource could address them.

Survey Schedule and Response

The survey was conducted from the spring of 2009 to early 2010, and the authors are not aware of any substantial bioremediation surveys since then. Of the initial 1464 emails sent out, 273 resulted in error messages and of the 1191 that had arrived, there were 93 responses representing a 7.8% response rate. Given the reported steady decline in survey response rates in recent decades particularly for unsolicited email surveys [42,43], the length and technical nature of this survey, the advent of email-spam engines, and the expected response rates for such email surveys [44,45], the response level was

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sufficiently high [2,44,46,47] to be judged a good estimate of the wider population and provides relevant data to prioritize R&D within the sector.

Table 1 shows the geographic distribution of the responses, which included all continents except Antarctica. The majority of the respondents were from North America. Using the number of research publications and citations as an estimate a country's research base, the observed profile might reflect the relative size of the research bases of the countries represented. It appears to agree with national rankings extracted from the Essential Science Indicators database of Thomas Reuters [48], which was computed from citations in the field of environment/ecology for the period 1999-2009. Other possible influences might include language barrier or insufficient access to IT/Internet infrastructure in some areas. Table 2 shows the sectorial distribution of respondents. Active Bioremediation researchers (academic and multinational companies) were the major respondents, constituting 81% of the total, though governments and other organizations were also represented. It was not possible to organise the addresses contained in the initial mailing list according to sectors, making a comparison with the distribution of respondents difficult.

Continent	Percentage of Total Response
North America	43
Europe	16.1
Asia	15.1
Africa	12.9
Oceania	7.5
South America	4.3

Table 1: Response profile for Survey, organized according to Continents

*One respondent did not indicate country.

Sector	Percentage of Total Response
Academic	44
Multinational companies	37
Government agencies	7
Agriculturalists	3
Not for profit organisations	1
Other research groups	8

Table 2: Response Profile for Survey, organized according to sectors

Survey Results and Discussions

Contaminated media

Figure 1 shows the distribution of the environmental media whose contamination was thought to be important enough to warrant remediation. More than three quarters of the respondents were very concerned about soil contamination, irrespective of location. However, while respondents from North America and Europe also expressed strong concerns about groundwater pollution, the results suggest that their African and South American counterparts appeared more concerned about the pollution of surface-water bodies, suggesting that these economies focus more on contamination that is immediately visible. It is difficult to make conclusive statements about South America given the low number of respondents from the continent. However, the data appear to suggest that the more developed economies can, in contrast to the developing ones, deal with 'hidden' issues, whose effect might only become a problem in the long run. Although the observed response could simply reflect higher reliance on potable groundwater and surface water in the developed and developing economies respectively, it might also point to the possibility that routine monitoring of groundwater resources is not a priority in the developing world, or that the relevant technologies and/or legislation are yet to be fully implemented in these areas.

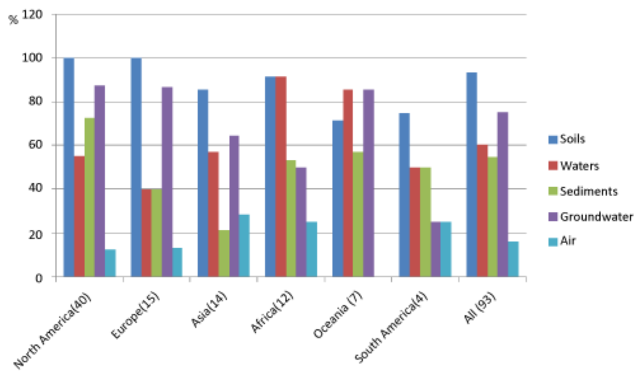

Figure 1: Distribution of contaminated environments under investigation. All figures expressed as percentages of the total number of respondents from each continent, which are shown in parenthesis.

Concern over pollution of water bodies (lakes, rivers etc.) was expressed in all the continents, with the lowest figures being for Europe. It is well known that in many cases groundwater contamination results from soil pollution via leaching and surface-water contamination can also result from soil pollution via surface run off [49-51]. Given this interconnection between the various environmental media, the high focus on soil contamination in the developing world may actually be appropriate, because soil occupies a central position in the water-soil-groundwater complex [50] and focusing on it might be the best use of scarce financial resources. The lowest levels of concern were observed for air pollution. This is probably reflective of recent worldwide campaigns for reduced emissions of greenhouse and other gaseous air pollutants. However, the incidence of diseases and health hazards attributed to inhalation of toxic fumes particularly in developing countries like Nigeria [52,53] indicate a continuing need in this area. The observed responses might also be related to the major contaminants of concern in the various areas.

Major Contaminants of concern

Figure 2 shows the distribution of the high-priority contaminants that respondents were dealing with, organized by continents (a) and by climatic zones (b). The BTEX (Benzene, Toluene, Ethylbenzene and Xylene), PAHs (Polycyclic Aromatic Hydrocarbons) and toxic metals

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were clearly of greatest concern in all climatic zones. There were however marked differences in the distributions, for chlorinated solvents, particularly TCE (Trichloroethane) and PCE (Perchloroethane). Only 33% of respondents from Africa and 22-28% from Asia highlighted TCE and PCE as highly important, while 45-60% from Europe and 62-75% of respondents from North America (both in the North temperate region) were concerned about these.

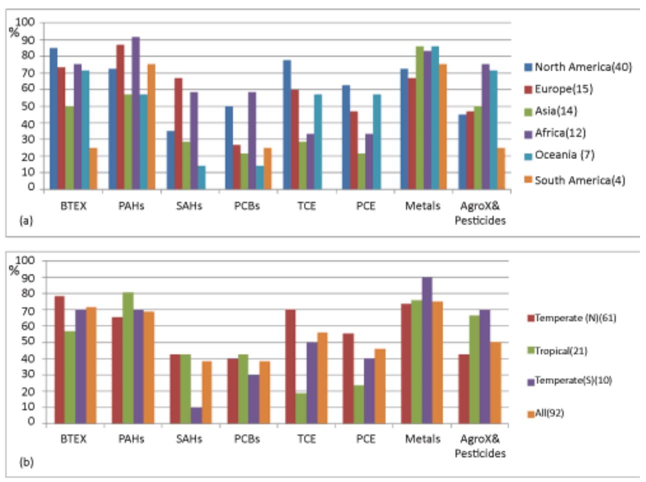

Figure 2: Major contaminants encountered, distributed according to (a) continents and (b) climatic zones. All results expressed as percentages of total respondents in each category: **BTEX**: Benzene, Toluene, Ethylbenzene and Xylene; **PAH**: Polycyclic Aromatic Hydrocarbons; **SAH**: Saturated Aliphatic Hydrocarbons; **PCB**: Polychlorinated Biphenyls; **TCE**: Trichloroethane; **PCE**: Perchloroethane; Metals; and **AgroX and Pesticides**: Agrochemicals and Pesticides. Lines of latitude used for delineations into climatic zones were as follows: Temperate (North): 23.5°N-66.6°N; Tropical: 23.5°N-23.5°S; Temperate (South): 23.5°S-66.6°S. There were no respondents from the Polar Regions. For this study all of China was captured under Temperate (South).

Both TCE and PCE tend to be relatively mobile in the environment, and are very quickly transported to underlying aquifers and groundwater resources [54]. This connection with possible pollution of groundwater resources supports the observation in the previous section, where the concern for groundwater pollution was found to be greater in North America and Europe, compared to elsewhere. Chlorinated solvents (like TCE and PCE) were contaminants of concern in the developed, more industrialized countries, whereas for the developing countries it was pesticides and agrochemicals. Figure 2 also shows that Polychlorinated Biphenyls (PCBs) and Saturated Aliphatic Hydrocarbons (SAHs) were considered less of a priority, especially in the temperate southern zone. Reports of microbial detoxification of metals have been reported and the use of plants for remediating metal-contaminated areas has also been popular [55-57]. The importance attached to metal pollution, from the survey further emphasizes the potential usefulness of phytoremediation in the overall scheme.

Preferred vs. Actual treatments methods

The preferred methods for the treatment of contaminated areas are shown in Figure 3. More than half of respondents (51%) would prefer to use environmentally friendly approaches including microbial remediation (35%) and phytoremediation (16%). However, historical information [30,31] suggests the opposite has actually been the case. Considering the relative low cost and low energy requirements of bioremediation technologies [6,58-60], the gulf between aspiration (as shown here) and practice might be due to various factors involving the risk-averse nature of the contaminated-land industry, or difficulties in project design. The latter include identifying appropriate organisms for removing specified contaminants, optimizing environmental conditions for their action, ascertaining extents of eventual clean-up, and the incomplete understanding of all the mechanisms and processes involved. These lead to difficulties in modeling, simulating and/or controlling these processes for improved outcomes.

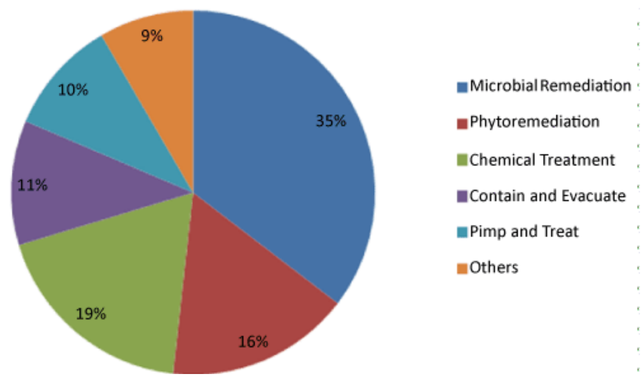

Figure 3: Pie chart of preferred bioremediation methods

Identification of microorganisms used for remediation

Figure 4 shows the methods reported for identifying appropriate microbes. About half of the respondents obtained this information from the scientific literature. A similar proportion assayed samples from the polluted area to find organisms that might have perfected systems to degrade such contaminants and/or overcome their toxicity. A slightly lower proportion of respondents (about 43%) used soil-microcosm tests and enzyme assays, while about 35% used molecular biology techniques, such as High performance Liquid Chromatography and Fluorescence in-situ Hybridization. A much smaller number used more technologically advanced and costly methods like BIOLOG substrate-utilization kits, bacterial biosensors, and DNA-Hybridization methods (including microarrays).

The figure shows that, while more North American researchers used soil-microcosm tests and enzyme assays, researchers from the rest of the world used more of the traditional methods, particularly those involving assays of contaminated environments for thriving bacterial species. These results also show that the more bio-technologically advanced methods were used more in North America than elsewhere. The trend only differed for the environmental assay method, for which the rest of the world showed strong representation.

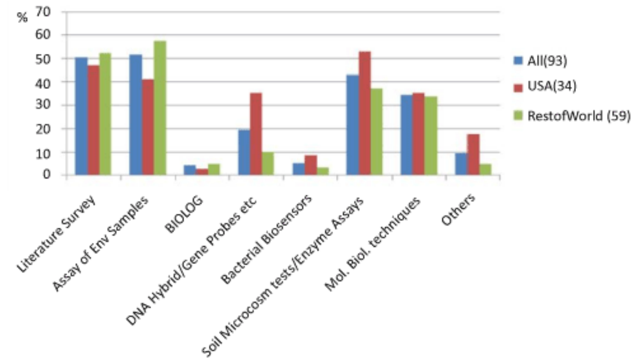

Figure 4: Methods for identifying candidate microbes, expressed as percentages of the total number of respondents in each category, shown in parenthesis

It is remarkable that only half of the respondents sought information from published literature, given the vast amount of information available in both print and online repositories like PubMed, Web of Science, Scopus and Web of Knowledge. This could be because the information is currently not in a form that can be easily accessed and used, or that wading through copious textual output is time-consuming and discouraging, or even that it is difficult to easily detect general trends and patterns from reading individual articles. It may also be that the process conventionally requires submission of multiple queries in order to glean useful information. This finding is particularly pertinent, given the recent advances and improvements in text/data mining software [61] and point to a potential area for the application of bioinformatics/computational biology techniques to bioremediation research.

Use of information resources and modelling software for guidance

The survey also sought to find out the extent of use of biochemical, enzyme and pathway databases, and the usage of existing biodegradation modelling software resources. Figure 5 shows that only 35.5% and 15.6% of respondents respectively used chemical/biological and enzyme/pathway databases. About two thirds of all respondents did not consult any such resources at all. A more detailed examination indicated that the database-using respondents predominantly came from North America, Europe and South America. The high percentage for Oceania may be an artifact of the low number of respondents from that area. Thus we have a situation where useful information resources are available, but many researchers who could benefit from them are not. Figure 6 shows that the use of existing biodegradation modeling software (including BIOPLUME III, MODFLOW, and MT3DMS) is very limited and more predominant in North America. The pace of successful bioremediation could definitely be enhanced by more extensive use of such resources. Their lack of use could arise from ignorance of their availability or a lack of adequate training to use them.

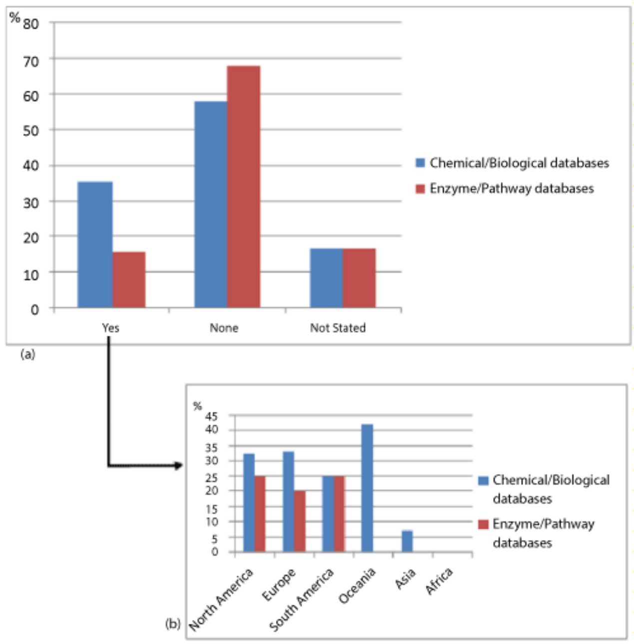

Figure 5: Use of information resources. (a) Database use across all continents expressed as percentage of total number of responses received per category. (b) Distribution of database users, comprised of weighted averages

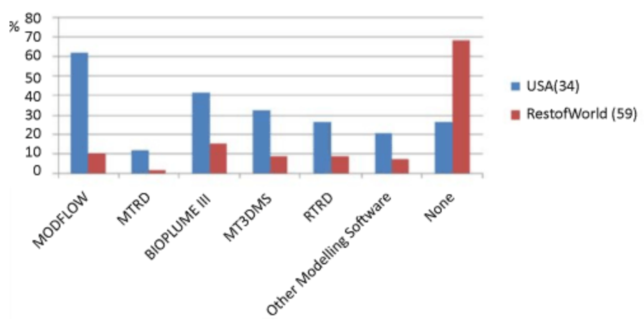

Figure 6: Use of modeling software for information and guidance (expressed as percentages of total responses for each category)- MODFLOW: U.S. Geological Survey Modular Three-Dimensional Groundwater Flow Model; MTRD: a 3D contaminant transport model for simulating the dynamics of dissolved constituents in groundwater flow systems; RT3D: another software package for simulating three-dimensional, multispecies, reactive transport in groundwater; MT3DMS; an enhancement of MTRD enabling Multi Species application; BIOPLUME III: a 2D finite difference model for simulating natural attenuation of organic contaminants in groundwater

Application of bioremediation techniques

Figure 7 compares the broad bioremediation methods being employed within industry, namely monitored natural attenuation (MNA), bio-augmentation and bio-stimulation. Table 3 lists the

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specific techniques employed under each of the broad headings. The use of low-cost *in situ* technologies (like MNA) featured quite prominently, particularly in North America and Europe, where it accounts for over 60% of the bioremediation methods being used. This finding points to a strong concern within the developed countries for better maintenance of ecological balance and preventing a disruption of naturally occurring populations.

Methods	% Response*
Monitored Natural Attenuation	53.8
Bio-stimulation methods:	
Composting	44.1
Addition of Fertilizers/Nutrients	48.4
Bio Venting and Air Sparging	38.8
Groundwater Treatment and Recirculation	43
Other Bio-stimulation methods	10.8
Bio-augmentation methods:	
Enrichment Cultures from site	47.3
Pure Cultures specific for contaminant	20.4
Commercial Cultures/consortia	26.9
Other Bio-augmentation methods	2.2
Phyto-remediation	32.3
Other methods	6.5

Table 3: Specific Bioremediation methods used within the sector

*% of all r

Responses received for each category, as respondents had multiple choices

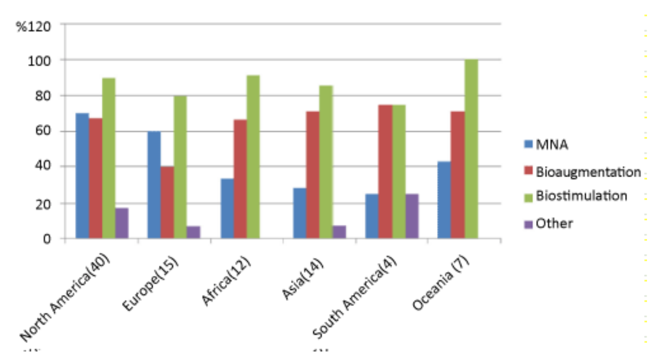

Figure 7: Graphs of broad remediation methods used. All figures are expressed as the percentage of respondents in each category whose totals are shown in parenthesis

MNA has been shown to require 1) elaborate modeling, 2) evaluation of contaminant degradation rates and pathways, and 3) a prediction of contaminant concentrations at migration distances and time points downstream of exposure points [62-65]. This is to determine which natural processes will reduce contaminant concentrations below risk levels before potential courses of exposure are completed, and to confirm that degradation is proceeding at rates consistent with clean-up objectives. These results appear to suggest that regions which employ computational and modeling resources are better able to use low-cost bioremediation technologies like MNA, whereas the others tend to use the more traditional and less cost-effective technologies. In all the continents, researchers were found to favor the use of bio-stimulation methods. Less disruption of ecological balance is apparently a global concern.

Phyto-remediation issues

The survey also sought to find out the extent of application of phyto-remediation within the bioremediation industry, particularly the proportion of the respondents that had utilized the technique, their degree of success and the specific plant species used. About half of the respondents to these questions stated that they had successfully used phyto-remediation in decontaminating polluted areas. Specifically, of the 33 respondents (35% of total respondents) that had successfully utilized phyto-remediation, 45% used it for Heavy metals (Lead, Cadmium, Arsenic, Chromium etc). Another 45% used it to remove petroleum hydrocarbons (including BTEX chemicals, PAH, TCE etc), and the remainder, for other substances like Trinitrotoluene (TNT), Nitroamines and radioactive isotopes.

For this purpose, the stated plant species were Poplar, Willow, various grass species (Vetivar grass, Prairie grass, reed canary grass, shell weed), Chinese ladder fern, legumes (e.g. cowpea), *Pteris vittata* (particularly for Arsenic), Tamarisks, Eucalyptus, Water Hyacinth, Clover, Alfalfa, Sunflower, Birch, Bamboo, Wattle, *Phanerochaete chrysosporium* and *Pisolithus tinctorious*, among others. These findings are consistent with previously published literature [56,66-76]. Phyto-remediation methods were also often used in combination with other chemical and microbial methods. In some cases they formed a second level of treatment for the remediation of contaminated environments. Remarkably, no mention was made of *Jatropha curcas* despite its documented usefulness for phyto-remediation, particularly for heavy metal-contaminated media [77,78].

Stated Barriers to effective development

The final section of the survey contained an open-ended question requiring respondents to suggest three issues that they thought would make their remediation research easier if some appropriate online resource were available. Table 4 outlines the broad themes contained in the responses and constitutes the respondents' wish list. Opinion was diverse, though the most common theme (constituting a quarter of the responses) was for improved modeling software to predict outcomes. A range of other resources and software tools were also proposed, but more than a third of the responses could not be accommodated within these simple overarching themes. These included socioeconomic, health and safety, management, regulatory and policy issues, cost considerations, and the need for more data from the tropics, for which there is currently a dearth of information.

Themes	Percentage (%)
Improved systems for modeling activities and pathways (metabolic/biochem./biorem.); enabling identification of organisms to use, and predicting outcomes under particular environmental conditions and relevant physical, chemical and biological properties.	24.7

Searchable database of bioremediation case studies, with site-specific information, results and key lessons learnt	12.4
Decision support system (using a systems biology approach); for predicting, evaluating, optimizing activities of microbes, enzymes, pathways etc. and recommending remediation approaches	11.3
Improved/specialized data/text mining facilities for bioremediation research	8.2
Better availability and presentation, of relevant/useful data (in easily usable forms)	5.1
Others	38

Table 4: Bioremediation industry 'wish list'

Conclusions

This global survey has examined the use of bioremediation technologies for addressing environmental problems. Rather than a detailed focus on any particular compound or technology, its intent was to obtain a wide picture of the current situation in the bioremediation research space. The response level was sufficiently high and provides background information to prioritize research and development work within the sector. Several conclusions are highlighted. Respondents showed a preference for environmentally friendly remediating methods even though current practice appears to be the opposite. This was thought to point to an information gap resulting in incomplete understanding of relevant bioremediation mechanisms and difficulty in monitoring and controlling bioremediation projects in the field.

Although remediation of contaminated areas is a common international concern, the context, awareness and approach taken to address the problem have been found to be country specific. This agrees with the findings of Rivett et al. [29], which indicate that the factors driving the use of bioremediation include economics/cost considerations, relative perceptions or ignorance of the extent of contamination, country-specific policies and bio-safety legislation, and stronger focus on an environmental medium such as soil at the expense of others. They also observed a marked contrast in importance accorded process-based remediation versus physical methods like land filling, and the lack of centralized information on remediation activity. There were also differences in levels of funding support for the development of and provision of remediation information.

The relative importance attached to particular contaminants and contaminated media was found to vary in different parts of the world, with the developed nations being able to deal with apparently hidden but important pollution issues. This might be connected to the availability of more sophisticated monitoring systems in place and a stronger appreciation of the impact on health and well-being. The developed economies-North America and Europe-expressed concern and tackled issues that are not immediately perceptible but with long term benefit (for example pollution of groundwater resources). Their developing counterparts, however, appeared to focus on the more visible surface media, like soils and surface water bodies. If this status quo remains, African, South American and Asian countries could be at long term risk of major environmental catastrophes, arising from unmitigated pollution of groundwater resources.

One useful point emanating from this analysis is that researchers appear to benefit from using database and modeling resources. The observed limited use of available information resources could be due to the resources not being user-friendly. There is therefore a further role here for bioinformatics to support bioremediation research, perhaps initially with a literature-focused resource. Table 4 provides a prioritized list to help focus any such developments.

The study has established that the use of low-cost in situ bioremediation technologies is higher in the developed economies (North America and Europe) while the relatively more expensive, sometimes *ex situ*, technologies are used more in the developing regions. The possible implications of this have been discussed. When the findings of this survey are related to the GDP per capita of the continents (see Table 5) there appears to be a connection between development/wealth and bioremediation practice. This finding approximates to the relationship described in Environmental Kuznets Curves (EKC), a concept propounded by Grossman and Krueger [79,80].

Continent	GDP per capita (in $US)
North America	32,296
Oceania	29,909
Europe	25,467
South America	9,254
Asia	2,539
Africa	1,560
Antarctica	N/A

Table 5: Listing of continental GDP per capita (excluding Antarctica). Source: [85]

EKCs describe the relationship between environmental quality and the level of per capita GDP. It hypothesizes that the relationship has an inverted 'U' shape (see Figure 8), where increases in per capita income gradually increase environmental deterioration/decay, until a turning point where it begins to steadily decrease [81]. So such GDP growth not only creates the conditions for environmental improvement by raising demands for improved environmental quality, it also makes resources available for supplying the desired improvement [82]. The concept has been a subject of numerous reviews and critical analysis [81,83,84]. It has been found to hold true for some indices of environmental quality (like air quality/emissions, Biological Oxygen Demand and Chemical Oxygen Demand), and not for others (including carbon emissions and deforestation). It has also been argued that favorable policy and institutional interventions are also necessary for sustained environmental improvement. The EKC discourse however agrees on the existence of some relationship between nations' wealth status and their environmental-pollution experience, a position supported by this survey. These results complement available information and can contribute to bioremediation policy decisions worldwide.

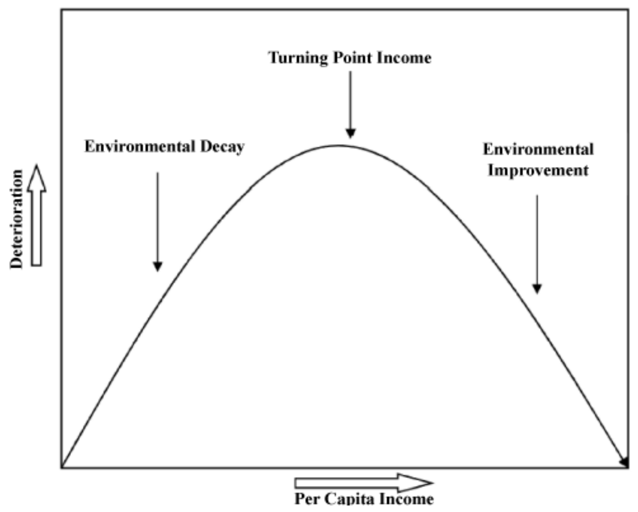

Figure 8: Graphical representation of Environmental Kuznets Curve. Source: Yandle et al. [81]

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