Published in final edited form as:
Int J Phytoremediation. 2013 ; 15(9): 889–899.

Phytotechnologies – Preventing Exposures, Improving Public Health

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Abstract

Phytotechnologies have the potential to reduce the amount and/or toxicity of deleterious chemicals/agents, and thereby, prevent human exposures to hazardous substances. As such, phytotechnologies are a tool for primary prevention within the context of public health. Research advances demonstrate that phytotechnologies can be uniquely tailored for effective exposure prevention for a variety of applications. In addition to exposure prevention, phytotechnologists have advanced the use of plants as sensors to delineate environmental contaminants and potential exposures. The applications presented in this paper are at various stages of development and are presented in a framework to reflect how phytotechnologies can help meet basic public health needs for access to clean water, air, and food resources. As plant-based technologies can often be integrated into communities at minimal cost and with low infrastructure needs, their use in improving environmental quality can be applied broadly to minimize potential contaminant exposure. These natural treatment systems concurrently provide ecosystem services of notable value to communities and society. In the future, integration and coordination of phytotechnology activities with public health research will allow technology development that focuses on prevention of environmental exposures. Such an approach will lead to an important role of phytotechnologies in providing sustainable solutions to environmental exposure challenges that improve public health and potentially reduce the burden of disease.

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Keywords

phytotechnologies; sustainability; exposure prevention; primary prevention; public health; airborne pollution; water contamination; food safety; developing countries

Introduction-Public Health and Phytotechnologies

In its 2002 report, "The Future of Public Health for the 21st Century," the Institute of Medicine (IOM) points out that public health is at risk when poor environmental conditions, such as compromised water, air, food, and housing, undermine health (IOM 2002). Remediation technologies are designed to disrupt contamination pathways leading from the environment to the receptor, thus reducing exposures to hazardous substances. For example, a groundwater remediation technology, if effective, prevents the spread of a contaminant plume, thereby protecting drinking water supplies. The net result is that humans are not exposed to the contaminants through ingestion pathways. Similarly, engineering controls put in place to decrease the dispersion of harmful mine tailing dusts act to prevent inhalation of potentially harmful mineral particles that, in some cases, are associated with metal contaminants. Therefore, remediation technologies, including phytotechnologies, can be considered a primary prevention strategy within the context of public health.

"Phytotechnologies" are plant-based approaches used to detect, degrade, remove or contain contaminants in soil, groundwater, surface water, sediments, or air (ITRC 2009). Primary prevention strategies act to prevent disease and/or dysfunction before their biological onset. Because certain environmental exposures are linked to disease or dysfunction, mitigating these harmful exposures is considered an important form of primary prevention (Cengage 2002). While society is familiar with the important role of sanitation for preventing environmental exposures to communicable diseases, we tend to be less cognizant of the important role that environmental remediation plays in preventing disease. Clean-up goals, rather than health benefits, tend to be the most practical milestones used to determine the success of a remediation technology. While the clean-up goals are a necessity, a given remediation technology's important public health role in accomplishing primary prevention may be underappreciated and, in some cases, not utilized to its full potential.

All remediation technologies, including phytotechnologies, have advantages and disadvantages. Some benefits of using phytotechnologies compared to conventional methods of cleanup are the relatively low capital costs, high community acceptance, aesthetic and ecological value, and sustainability (see Table 1) (ITRC 2009); EPA 2010). In terms of capital costs, many phytotechnology applications simply involve the cultivation of a plant *in situ* allowing for the conservation of important resources such as energy and water. Such *in situ* technologies do not transfer pollution from one medium to another (e.g., excavation and shipment of contaminated soil to hazardous waste landfills). Over the life-cycle of a phytotechnology-based clean-up effort, secondary pollution associated with remediation can be substantially reduced. Continuing with the "excavate and haul" example, mechanical and energy intensive remediation systems are involved in the movement of hazardous waste and these systems have substantial energy and materials footprints both at the point of use and along their construction process and supply chain. Phytotechnologies also have ancillary positive impacts on the surrounding environment, providing ecosystem services with tangible, quantifiable value for public health and social welfare (Holzman 2012). In terms of aesthetics and community acceptance, the importance of the community appeal of phytotechnologies is worth re-emphasizing. Public engagement and community acceptance is required and can be key to the long-term success of a clean-up operation (ATSDR 2010). Phytotechnologies may have strong community acceptance, in part, because covering a contaminated site with vegetation creates an open green space and such spaces have been shown to reduce stress, particularly in urban environments (Grahn and Stigsdotter 2003). This added psychological benefit reinforces the public health value of phytotechnologies, considering the World Health Organization (WHO) definition of health: "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO 1948).

For these reasons, phytotechnology research and applications offer the potential to provide useful, sustainable tools for achieving primary prevention by minimizing exposures and improving the quality of water, air and food resources. The following sections explore examples of ways in which phytotechnologies, and related advances in the science of plant contaminant interactions, may be used to reduce the levels of toxicants in environmental media, thus reducing human exposures to hazardous substances.

Advances in Phytotechnology Research and Application

Research advances demonstrate that phytotechnologies can be uniquely tailored for effective exposure prevention for a variety of applications. The phytotechnology applications here within are at various stages of development and are presented in a framework to reflect basic public health needs for access to clean water, air, and food resources.

Phytotechnologies and Clean Water Systems

Many phytotechnologies are designed to improve water quality by addressing fugitive contaminants in groundwater, or as processes to treat contaminated water before its discharge to receiving waters (ITRC 2009). Recent projects have demonstrated the unique abilities of some phytotechnologies in this area, such as wetland systems to partially or completely remove trace contaminants that would otherwise require substantial energy to remove or are not amenable to removal by other means. For example, Schröder and colleagues have studied and developed wetland treatment systems as a polishing step for wastewater to remove trace pollutants remaining in the waste stream following traditional wastewater treatment (Schröder *et al.* 2007). Specifically, they have looked at plants' ability to take up and detoxify pharmaceuticals through metabolic processes, a concept proposed by Sandermann in 1994 referred to as the "green liver concept" (Sandermann 1994). This approach proactively addresses the emerging issue of pharmaceuticals in water systems without the need for extensive energy and materials footprints or the operations and maintenance burden of current alternative treatment systems. The wetlands approach also offers ecological benefits and reduces the need for advanced secondary oxidation, which is not practical for many treatment facilities. Although it is just a single example, these research findings emphasize the untapped potential of plants to improve the quality of water resources.

Reducing Exposures to Airborne Contaminants

Air pollution is an extensive and complex problem, and although development of phytotechnologies to remove airborne pollutants is just beginning, plants are widely recognized to improve air quality, particularly in urban environments (Baumgardner *et al*. 2012). Recent research has focused on improving our understanding of how plants may act to impede pollution transport or as a means of sequestering airborne pollutants.

One example is the work being done by Mendez and Maier (2008) to stabilize mine tailings sites in arid and semi-arid environments. As an extension of a large greenhouse study on the efficacy of native plant species, they have initiated a phytostabilization trial on the Iron King Mine-Humboldt Smelter Superfund (IKMHSS) site. The study included air sampling before and during the establishment of native plants on the tailings. Dust particles in the samples were fractionated and analyzed, and showed that both arsenic and chromium concentrations exceeded Arizona Hazardous Air Pollutant (HAPS) guidance levels. Furthermore, high levels of these contaminants were found in both large and small dust particle size fractions. These findings indicate the potential importance of aerosols as a route of exposure for the community living adjacent to the IKMHSS site. Preliminary results showed a 60% reduction in PM1 and PM2.5 (i.e., particulate matter of 1 μm and 2.5 μm diameter, respectively) moving across plots that were densely vegetated. The dust flux data currently being collected will be used to initiate and validate a dust model to predict the amount and location of windblown dust downwind from the site (Mendez and Maier 2008; Csavina *et al.* 2011; Solís-Dominguez *et al.* 2012). This study represents an integrated approach to quantifying the potential for plant-based remediation strategies to stabilize mine tailings. The project also serves as a model for how mining-impacted communities may adopt an effective and sustainable intervention technology: using native plants to reduce potential exposures to harmful substances found in mine tailings.

Research by Schnoor and colleagues has yielded promising results in using plants to remove polychlorinated biphenyls (PCBs) from air. This group's studies have demonstrated that the waxy cuticle of hybrid poplar leaves and the tree's bark can remove a significant fraction of semi-volatile PCBs (PCB3, 15, 28, 52, and, 77) from air with only a half-hour residence time in controlled laboratory experiments (Beebe *et al.* 2010). Airborne exposure of PCBs in small atmospheric chambers indicated the importance of living leaves and bark to capture PCBs; thus, the reduction effect was not simply due to surface deposition. This work is important in establishing that poplars not only take up PCB through their root systems (Zhai *et al.* 2010; Zhai, *et al.* 2011), but also capture airborne PCB through their leaves and bark to reduce air pollution. Plant cuticles comprise the continuous layer of cutin, a polymeric lipid, secreted by the epidermis and covering the aerial portions of the plant, which are principally responsible for this strong scavenging effect by plants for hydrophobic organic chemicals (Chen *et al.* 2008). The greater the fraction of cutin produced by the aerial portion of any plant, the larger will be the sorption of organic contaminants. Providing basic mechanistic answers to PCB-plant interactions likely will aid scientists in the development of technologies needed to reduce airborne PCB exposures. This notion is critical given recent issues facing New York City schools in which indoor concentrations of PCBs are well above levels of concern (Navarro 2011); Jorgensen 2012). New affordable and effective remediation technologies are needed to remove PCB congeners from the air and reduce exposures to children during a very vulnerable period of development (Wolff 2008). Phytotechnologies may be one sustainable solution for this potentially widespread exposure scenario.

Contaminant Uptake into Food Crops

Anthropologenic activities have increased the concentration of many naturally occurring and xenobiotic compounds in urban soils. In some cases, concentrations of hazardous substances are significantly greater than the natural background levels for local soils, presenting potential health risks. Thus, the increased interest in urban gardening – growing food crops in and around urban soils – is an emerging exposure pathway, although one where risks are not always well defined (Brown and Jameton 2000; Saumel *et al.* 2012). Past land use may contribute to the loading of certain contaminants into urban soils (Table 2) (EPA 2011). Analysis of soil contaminants is expensive, and unless all past uses of a given urban plot are known, anticipating potential soil contaminants is difficult, if not impossible. Therefore, understanding plant-soil-contaminant interactions is increasingly important, and will provide necessary information on how to prevent plant uptake of contaminants when exposure pathways could undermine public health.

As understanding of food crops in urban soils advances, “best practices” are likely to emerge, and provide healthier practices for urban gardening. For example, soil amendments, in general, can improve the overall soil quality for growing plants. However, more research is needed to identify which specific soil amendments are effective in binding contaminants to decrease bioavailability. For example, adding phosphate to lead-contaminated soil can enhance lead binding to material in the soil in a non-bioavailable form, and added iron can similarly bind arsenic; however, interactions between the amendments and mixtures of metals require further study (Ryan *et al.* 2004; Kumpiene *et al.* 2006, Mench *et al.* 2006; and Hartley and Lepp 2008). Phytotechnology researchers also have investigated what types of soil amendments are effective at immobilizing contaminants, specifically to reduce uptake of toxicants into the edible portions of food crops. Many studies have shown the uptake of hydrophobic compounds by *Cucurbita pepo* ssp *pepo* (pumpkin), including contaminants common in agricultural soils (weathered DDT) and in urban soils (PCBs) (White 2010); Isleyen *et al.* 2012). Denyes and colleagues reported a successful intervention to prevent PCB uptake into pumpkin through the use of biochar soil amendments. Application of less than 3% by weight of this carbon-based material reduced PCB uptake by at least 50% (Denyes *et al.* 2012). This important observation is the type of research that will help improve the safety of urban gardening.

Phytotechnology based basic research provides insight into hazardous substances that may be present in food resources worldwide. For example, arsenic uptake into rice is a plant bioaccumulation issue that has recently caused concern about human exposure because arsenic can exert toxicity at very low levels and is consumed as a staple crop by billions of people around the world (Suk and Davis 2008; Sanchez-Soria *et al.* 2012; Kozul-Horvath *et al.* 2012). Strategies to reduce arsenic in rice grain require that scientists elucidate the mechanisms of arsenic accumulation within the grain, or alternatively, identify plant varieties that exclude uptake of arsenic. A team of investigators led by Meharg have been using sophisticated imaging technologies to determine how arsenic is transported into and out of the rice grain (Carey *et al.* 2011), improving understanding of plant transport mechanisms, and providing insight to other factors that contribute to increased or reduced arsenic uptake. Thus, research that documents the occurrence and mechanisms of plant contaminant uptake is important to understanding and preventing human exposures and poor public health outcomes.

Phytotechnologies – Use in Exposure Assessment

Phytotechnology approaches may also be used to assess and map exposure pathways (e.g., fate and transport) of contaminants. Balouet and colleagues have investigated the use of plant sampling and environmental forensic applications (also referred to as “phytoforensics”), essentially using plants as biosensors for detecting contaminants in groundwater (Burken *et al.* 2011). Researchers have also used plants to delineate subsurface contaminant plumes, both in the saturated and vadose subsurface horizons (Struckhoff *et al.* 2005). The approach, which initially analyzed volatile compounds in plant tissue samples taken to the laboratory, has now advanced to *in planta* sampling approaches for more rapid and sensitive detection and delineation of subsurface pollutants and as indicators of subsurface degradation (Vroblesky *et al*. 1999; Limmer *et al.* 2011).

These methods have also been utilized to identify potential vapor intrusion (VI) exposure pathways that link groundwater to indoor air exposures. There is a correlation between VI and plant uptake because the root-zone of plants occupies the same geologic space as building basements. Both plant roots and basements represent a negative pressure potential to draw the pollutants into the above ground plant tissues or living spaces of residential structures. Measuring VI is difficult in the complex indoor environment filled with anthropogenic compounds; however, this type of exposure pathway has serious health implications. Bennett and colleagues have shown that the fraction of pollution inhaled from an indoor source is about 1,000 times greater than that from an outdoor source (Bennett *et al.* 2002). In homes subject to VI, higher concentrations of benzene, trichloroethylene (TCE) and perchloroethylene (PCE) can considerably increase cumulative cancer risk for residents (EPA 2008). This new phytoforensics detection technology is an exciting example of how phytotechnologies can be used to evaluate risk of hazardous substances without the need to enter homes and without complex assessment procedures. This method has been applied for TCE and PCE, the most prevalent groundwater contaminants in the United States, particularly on industrial and military sites (Toccalino and Norman 2010).

Another novel application of plant-based sensing technologies is to quantify past exposures. Phytoforensic methods can be used not only to detect contaminants in the subsurface at the time of sampling, but also to identify the previous contamination history of the subsurface to reveal historical exposures. Novel analytical techniques and a unique application of dendrochronology and dendrochemistry have been applied to reconstruct potential contaminant exposure from previous contaminant releases using contamination trapped in tree core rings to reveal the history of contamination at a site (Balouet *et al.* 2012). These methods have been validated as forensic tools (Balouet *et al.* 2009), and are relevant to public health because today's disease incidences are likely to be related to past exposures. Technology that allows detection and quantification of past exposures will be an invaluable tool for establishing a link between exposure and disease, particularly in diseases with long latency periods.

In addition to their ability to accumulate data on current and past contamination in environmental media, phytoforensic technologies have reduced environmental impact compared to alternative approaches. The secondary impacts of phytoforensic sampling are minimal: the samples can be a tree branch or tree core the size of a pencil. Traditional approaches of subsurface sampling, such as extracting soil cores, require large equipment mobilization and energy inputs and the equipment can cause considerable damage to property. While phytoforensic approaches have certain limitations—namely the requirement that appropriate vegetation is present for sampling—the technology is most effective in shallow soil profiles where environmental contamination would have the greatest human exposure potential (Struckhoff *et al.* 2005).

Phytotechnologies: A Sustainable Tool for Exposure Prevention

Phytotechnologies offer a variety of environmental assessment and remediation tools to promote primary prevention in public health by mitigating potential exposure pathways upstream of the exposure scenario. As society has become increasingly industrialized and global population has increased, there are few areas of the world that are not impacted by air, water or soil contamination. The challenge, as availability of clean resources declines, is to develop sustainable and economically feasible technologies that can be used to improve the quality of impacted resources and reduce exposures, whether in water, soil food, or air.

Phytotechnologies may play an important role in providing sustainable solutions for the reduction of exposures. Phytotechnologies are affordable and robust, qualities that are likely to make it socially, culturally and politically accepted on a global basis. Phytotechnologies are particularly feasible solutions for remote areas and developing countries with minimal utility infrastructure because they are solar-driven. Further, given the low costs of establishing phytotechnologies as barriers to exposure, as well as the stress-related benefits of green open spaces, it may be beneficial to routinely adopt phyto-barriers to minimize risks for exposure pathways thought to cause diseases, even if more invasive and costly approaches are also needed.

One of the conclusions of the IOM's Executive Summary of "The Future of Public Health for the 21st Century," is the need for integrating multiple sectors to promote public health—linking government, academia, and community partnerships (IOM 2002). Phytotechnologies offer an excellent model for such integration. Connecting phytotechnologists with public health researchers will help ensure that technology development efforts are focused on the prevention of environmental exposures. While public health researchers are well versed in human exposures to toxicants, they are in need of primary prevention solutions that are sustainable. The sustainable nature of phytotechnologies (both in terms of economics and energy consumption) further reinforces their potential to reduce exposures within resource-constrained public health agencies worldwide. Moreover, the need for phytotechnology based solutions to reduce exposures will only increase in the future, given the conditions of climate change and the need to conserve water and other ecosystem services. If coordinated with epidemiology studies, phytotechnology field applications could provide important information on how effective these technologies are at reducing disease or exposure.

In conclusion, practitioners of phytotechnologies are well positioned to contribute to the exposure prevention needs faced by the world today. Phytotechnology is a technology driven science that can be effective in remediating and protecting the environment, but also in protecting people from the harmful effects of hazardous substances. Collaboration with public health researchers will be the most effective means of achieving exposure reduction, and perhaps most importantly, the linkages between phytotechnology and public health provides an interdisciplinary model to guide development of other remediation technologies. Multiple approaches are needed to solve complex environmental contamination scenarios, and we caution that phytotechnology is not always the best solution, but rather – it is important that all methods of remediation be considered for primary prevention in the context of public health.

Acknowledgments

This manuscript is based on a series of presentations and breakout sessions linking human health and phytotechnologies initiated at the 2009 International Phytotechnologies Society Conference in St. Louis, MO, USA. **2011 Health Sessions**: Tracy Punshon, Dartmouth College; Raina M. Maier, University of Arizona; Stanislaw Gawronski, Warsaw University of Life Sciences, Poland; Mackenzie J. Denyes, The Royal Military College of Canada; Lee Newman, SUNY – ESF; Heather Henry, NIEHS; **2010 Health Sessions**: Joel G. Burken Missouri University of Science and Technology; Steven Rock, USEPA; Jerald L. Schnoor, University of Iowa; Jean-Christophe Balouet, Environment International; Lee A Newman, SUNY-ESF; Nelson Marmiroli, University of Parma; Peter Schröder, Helmholtz Zentrum München (Marimoli 2012). **2009 Health Plenary**: William A. Suk, NIEHS. These sessions were funded, in part, by the National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program (SRP) which advances its mission to reduce the public health burden of hazardous substances through interdisciplinary research. This paper is not intended to be a comprehensive review; rather, the phytotechnology research presented herein are examples to illustrate the linkages of plant-based remediation to primary prevention in the context of public health. The authors would like to thank Jason White, Thaddeus Schug, Kimberly Thigpen-Tart, and Payal Chokshi for their assistance in editing and formatting (PC) this document. This article may be the work product of an employee or group of employees of the National Institute of Environmental Health Sciences (NIEHS), National Institutes of Health (NIH), however, the statements, opinions or conclusions contained therein do not necessarily represent the statements, opinions or conclusions of NIEHS, NIH or the United States government.

References

ATSDR (Agency for Toxic Substances and Disease Registry). Leading Change for Healthy Communities and Successful Land Reuse. 2010. http://www.atsdr.cdc.gov/sites/brownfields/docs/ATSDR_LandReuse.pdf

Balouet JC, Burken JG, Karg F, Vroblesky DA, Balouet JC, Smith KT, Grudd H, Rindby R, Beaujard F, Chalot M. Dendrochemistry of Multiple Releases of Chlorinated Solvents at a Former Industrial Site. Environmental Science and Technology. 2012; 46(17):9541–9547. [PubMed: 22856596]

Balouet JC, Smith KT, Vroblesky D, Oudijk G. Use of dendrochronology and dendrochemistry in environmental forensics: Does it meet the Daubert criteria? Environ. Forensics. 2009; 10(4):268–276.

Baumgardner D, Varela S, Escobedo FJ, Chacalo A, Ochoa C. The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis. Environ. Poll. 2012; 163:174–183.

Beebe, A.; Liu, J.; Zhai, G.; Meggo, R.; Bircher, S.; Anderson, T.; Flannigan, M.; Van Aken, B.; Schnoor, J. Reducing Human Exposure to Toxicants from Air, Soil, and Water using Phytoremediation. Poster Abstract B9. 7th International Conference on Phytotechnologies, Phytotechnologies in the 21st Century: Remediation-Energy-Health-Sustainability; University of Parma, Italy. 26–29 September; 2010.

Bennett DH, McKone TE, Evans JS, Nazaroff WW, Margni MD, Jolliet O, Smith KR. Defining Intake Fraction. Environmental Science & Technology. 2002; 36(9):206A–211A.

Brown KH, Jameton AL. Public Health Implications of Urban Agriculture. Journal of Public Health Policy. 2000; 21:20–39. [PubMed: 10754796]

Burken JG, Vroblesky DA, Balouet JC. Phytoforensics, Dendrochemistry, and Phytoscreening: New Green Tools for Delineating Contaminants from Past and Present. Environmental Science and Technology. 2011; 45(15):6218–6226. [PubMed: 21749088]

Carey A-M, Norton GJ, Deacon C, Scheckel KG, Lombi E, Punshon T, Guerinot ML, Lanzirotti A, Newville M, Choi Y, Price AH, Meharg AA. Phloem transport of arsenic species from flag leaf to grain during grain filling. New Phytologist. 2011; Volume 192(Issue 1):87–98. http://onlinelibrary.wiley.com/doi/10.1111/j.1469-8137.2011.03789.x/full. [PubMed: 21658183]

Cengage G. Breslow L. Primary Prevention. Encyclopedia of Public Health. 2002; Vol. 3

Chen B, Li Y, Guo Y, Zhu L, Schnoor JL. Role of the Extractable Lipids and Polymeric Lipids in Sorption of Organic Contaminants onto Plant Cuticles. Environmental Science and Technology. 2008; 42(5):1517–1523. [PubMed: 18441797]

Csavina J, Landazuri A, Wonaschutz A, Rine K, Rheinheimer P, Barbaris B, Conant W, Saez AE, Betterton EA. Metal and metalloid contaminants in atmospheric aerosols from mining operations. Water Air Soil Pollut. 2011; 221:145–157. [PubMed: 23441050]

Denyes MJ, Langlois VS, Rutter A, Zeeb BA. The use of biochar to reduce soil PCB bioavailability to Cucurbita pepo and Eisenia fetida. Science of the Total Environment. 2012; Volume 437:15. October 2012, Pages 76–82.

Environmental Protection Agency. EPA's Vapor Intrusion Database: Preliminary Evaluation of Attenuation Factors. Washington (DC): EPA; 2008.

Environmental Protection Agency. Phytotechnologies for Site cleanup. EPA 542-F-10-009. 2010 September 2010. www.cluin.org/download/remed/phytotechnologies-factsheet.pdf.

Environmental Protection Agency. Reusing Potentially Contaminated Landscapes: Growing Gardens in Urban Soils. EPA 542/F-10/011. 2011 , Spring 2011, www.clu-in.org/ecotools/urbangardens.cfm.

Grahn P, Stigsdotter U. Landscape planning and stress. Urban Forestry & Urban Greening. 2003; 1:1–18.

Hartley W, Lepp NW. Effect of in situ soil amendments on arsenic uptake in successive harvests of ryegrass (Lolium perenne cv Elka) grown in amended as-polluted soils. Environ. Pollut. 2008; 156:1030–1040. [PubMed: 18524441]

Holzman, DC. Accounting for Nature's Benefits: The Dollar Value of Ecosystem Services. Environ Health Perspect. 2012; 120(4):a152–a157. April; [PubMed: 22469778]

Institute of Medicine. Executive Summary: The Future of the Public's Health in the 21st Century Committee on Assuring the Health of the Public in the 21st Century. 2002

Isleyen M, Sevim P, White JC. Accumulation of weathered p,p′-DDTs in hybridized Cucurbita pepo cultivars. Environ. Toxicol. Chem. 2012; 3:1699–1704. [PubMed: 22610730]

Interstate Technology & Regulatory Council. Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. PHYTO-3. Washington, D.C.: Interstate Technology & Regulatory Council, Phytotechnologies Team, Tech Reg Update; 2009.

Kozul-Horvath CD, Zandbergen F, Jackson BP, Enelow RI, Hamilton JW. Effects of Low- Dose Drinking Water Arsenic on Mouse Fetal and Postnatal Growth and Development. PLoS One. 2012; 7(5):e38249. [PubMed: 22693606]

Kumpiene J, Ore S, Renella G, Mench M, Lagerkvist A, Maurice C. Assessment of zerovalent iron for stabilization of chromium, copper, and arsenic in soil. Environ. Pollut. 2006; 144:62–69. [PubMed: 16517035]

Jorgensen J. PCB leak that hits Staten Island student leads to removal of light fixtures at PS 41. Staten Island Advance. 2012 Tuesday, September 11.

Limmer MA, Balouet JC, Karg F, Vroblesky DA, Balouet JC. Phyto screening for Chlorinated Solvents Using Rapid In-Vitro SPME Sampling: Application to Urban Plume in Verl, Germany. Environmental Science and Technology. 2011; 45(19):827–882. [PubMed: 21142001]

Marmiroli, N. Phytotechnologies in the 21st Century: Challenges After Copenhagen 2009. Remediation-Energy-Health-Sustainability. International Journal of Phytoremediation; Conference Review-7th International Phytotechnologies Conference; September 26–29, 2010; Parma, Italy. 2012. p. 303-304.

Mench M, Vangronsveld J, Beckx C, Ruttens A. Progress in assisted natural remediation of an arsenic contaminated agricultural soil. Environ. Pollut. 2006; 144:51–61. [PubMed: 16522348]

Mendez MO, Maier RM. Phytostabilization of mine tailings in arid and semiarid environments – an emerging remediation technology. Environ. Health Perspec. 2008; 116:278–283.

Navarro, M. Parents Seek More Action on PCBs in Schools. New York Times; 2011. Published: February 3, 2011

Ryan JA, Scheckel KG, Berti WR, Brown SL, Casteel SW, Chaney RL, Hallfrisch J, Doolan M, Grevatt P, Maddaloni M, Mosby D. Reducing children's risk from lead in soil. Environ Sci Technol. 2004; 38(1):18A–24A. Jan 1.

Sanchez-Soria P, Broka D, Monks SL, Camenisch TD. Chronic low-level arsenite exposure through drinking water increases blood pressure and promotes concentric left ventricular hypertrophy in female mice. Toxicol Pathol. 2012; 40(3):504–512. Apr; Epub Jan 3. [PubMed: 22215511]

Sandermann H Jr. Higher plant metabolism of xenobiotics: the 'green liver' concept. Pharmacogenetics. 1994; 4(5):225–241. Oct; [PubMed: 7894495]

Saumel I, Kotsyuk I, Hölscher M, Lenkereit C, Weber F, Kowarik I. How healthy is urban horticulture in high traffic areas? Trace metal concentrations in vegetable crops from plantings within inner city neighbourhoods in Berlin, Germany. Environmental Pollution. 2012; 165:124–132. [PubMed: 22445920]

Schröder P, Navarro-Aviñó J, Azaizeh H, Golan Goldhirsh A, DiGregorio S, Komives T, Langergraber G, Lenz A, Maestri E, Memon AR, Ranalli A, Sebastiani L, Smrcek S, Vanek T, Vuilleumier S, Wissing T. Using Phytoremediation Technologies to Upgrade Waste Water Treatment in Europe Environmental Science and Pollution Research. 2007; Volume 14(Number 7):490–497. http://www.springerlink.com/content/t7780214p7gu43m6/.

Solís-Dominguez F, White SA, Borrillo Hutter T, Amistadi MK, Root RA, Chorover J, Maier RM. Response of key soil parameters during phytostabilization in extremely acidic tailings: effect of plant species. Environ. Sci. Technol. 2012; 46:1019–1027. [PubMed: 22191663]

Struckhoff G, Burken JG, Schumacher JG. Phytoremediation of Vadose Zone VOCs. Environmental Science and Technology. 2005; 39(6):1563–1568. [PubMed: 15819210]

Suk WA, Davis EA. Strategies for addressing global environmental health concerns. Ann NY Acad Sci. 2008; 1140:40–44. Oct; [PubMed: 18991900]

Toccalino PL, Norman JE, Hitt KJ. Quality of source water from public-supply wells in the United States. 1993–2007: U.S. Geological Survey Scientific Investigations Report 2010-5024. 2010:206.

Vroblesky DA, Nietch CT, Morris JT. Chlorinated ethenes from groundwater in tree trunks. Environ. Sci. Technol. 1999; 33(3):510–515.

White JC. Inheritance of *p,p'*-DDE Phytoextraction Ability in Hybridized *Cucurbita pepo* Cultivars. Environ. Sci. Technol. 2010; 44:5164–5169.

Wolff MS, Brittona JA, Boguski L, Hochman S, Maloney N, Serra N, Liu Z, Berkowitz G, Larson S, Forman J. Environmental exposures and puberty in inner-city girls. Environmental Research. 2008; Volume 107(Issue 3):393–400. July, [PubMed: 18479682]

World Health Organization (WHO). Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference; New York. 19–22 June, 1946; 1948. signed on 22 July 1946 by the representatives of 61 States (Official Records of the World Health Organization, no. 2, p. 100) and entered into force on 7 April 1948.

Zhai G, Hu D, Lehmler H-J, Schnoor JL. Enantioselective biotransformation of chiral PCBs in whole poplar plants. Environmental Science and Technology. Volume 45(Issue 6):2308–2316. 15 March, http://pubs.acs.org/doi/full/10.1021/es1033662.

Zhai G, Lehmler HJ, Schnoor JL. Hydroxylated Metabolites of 4-Monochlorobiphenyl and Its Metabolic Pathway in Whole Poplar Plants. Environ. Sci. Technol. 2010; 44(10):3901–3907. http://pubs.acs.org/doi/abs/10.1021/es100230m. [PubMed: 20402517]

Table 1

Summary of the advantages of phytotechnology, with a particular focus on public health and community (adapted from ITRC, 2009)

Technical Advantages
• passive and *in situ* • inherently controls erosion, runoff, infiltration, and fugitive dust emissions • applicable to remote locations, potentially without utility access (in some cases requires a supplemental source of irrigation, but this can be solar or wind powered) • can be used to supplement other remediation approaches or as a polishing step • can be installed as a preventative measure, possibly as a leak detection system • can be used to identify and map contamination
Community benefits/capacity building
• favorable public perception provides a community educational opportunity • improves aesthetics, reduces noise • creates habitat (can be a disadvantage—attractive nuisance) • provides restoration and land reclamation during cleanup and upon completion • can be cost-competitive • has the potential for capacity building through involvement of community in maintenance, stewardship, etc.
Pollution Reduction and Resource Conservation
• lower maintenance, resilient, and self-repairing • considered a green technology and sustainable • wind- and solar-powered • improves air quality and sequesters greenhouse gases • minimal air emissions, water discharge, and secondary waste generation

Table 2

Common Sources of Contamination in Urban Soils based on prior land use (EPA, 2011).

General Source	Specific Contaminants
Paint (before 1978)	Lead
Deposition from vehicle exhaust	Lead, zinc, polycyclic aromatic hydrocarbons (PAHs), asbestos
Treated Lumber	Arsenic, chromium, copper
Deposition from burned buildings	PAHs, dioxins
Coal ash	Molybdenum, sulfur, particulates
Sewage sludge	Cadmium, copper, zinc, lead, persistent bioaccumulative toxins (PBTs)
Petroleum spills	PAHs, benzene, toluene, xylene, ethyl benzene
Commercial/industrial site use	PAHs, petroleum products, solvents, lead, other heavy metals (such as arsenic, cadmium, chromium, lead, mercury and zinc)
Pesticides	Lead, arsenic, mercury (historical use), chlordane and other chlorinated pesticides
Dry cleaners	Trichloroethylene (TCE), perchloroethylene (PCE), Stoddard solvent, and tetrachloroethene (PERC))
Metal finishing operations	Metals and cyanides