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Sustainable Exposure Prevention through Innovative Detection and Remediation Technologies from the NIEHS Superfund Research Program

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Abstract

Innovative devices and tools for exposure assessment and remediation play an integral role in preventing exposure to hazardous substances. New solutions for detecting and remediating organic, inorganic, and mixtures of contaminants can improve public health as a means of primary prevention. Using a public health prevention model, detection and remediation technologies contribute to primary prevention as tools to identify areas of high risk (e.g. contamination hotspots), to recognize hazards (bioassay tests), and to prevent exposure through contaminant cleanups. Primary prevention success is ultimately governed by the widespread acceptance of the prevention tool. And, in like fashion, detection and remediation technologies must convey technical and sustainability advantages to be adopted for use. Hence, sustainability - economic, environmental, and societal - drives innovation in detection and remediation technology. The National Institute of Health (NIH) National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program (SRP) is mandated to advance innovative detection, remediation, and toxicity screening technology development through grants to universities and small businesses. SRP recognizes the importance of fast, accurate, robust, and advanced detection technologies that allow for portable real-time, on-site characterization, monitoring, and assessment of contaminant concentration and/or toxicity. Advances in non-targeted screening, biological-based assays, passive sampling devices, sophisticated modeling approaches, and precision-based analytical tools are making it easier to quickly identify hazardous “hotspots” and, therefore, prevent exposures. Innovation in sustainable remediation uses a variety of approaches: in situ remediation; harnessing the natural catalytic properties of biological processes (such as bioremediation and phytotechnologies); and application of novel materials science (such as nanotechnology, advanced membranes, new carbon materials, and materials reuse). Collectively, the investment in new technologies shows promise to reduce the amount and toxicity of hazardous substances in the environment. This manuscript highlights SRP funded innovative devices and tools for exposure assessment and remediation of organic, inorganic, and mixtures of contaminants with a particular focus on sustainable technologies.

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Keywords

sustainability; primary prevention; environmental health; rapid detection technologies; bioremediation

Introduction

Innovative devices and tools for exposure assessment and remediation play an integral role in preventing exposure to hazardous substances and support the public health model of primary prevention (1). Using a public health model for prevention from the Centers for Disease Control and Prevention (CDC) (2), the connection between these engineering technologies and primary prevention strategies becomes clear (Figure 1). The public health approach to prevention begins by defining the problem – such as incidence of disease or dysfunction – followed by identifying risk and protective factors, and then developing and testing prevention strategies. Once the prevention strategies are validated, the next step is to ensure widespread adoption of that prevention or intervention activity. Accordingly, detection and remediation technologies are important tools for risk identification and exposure prevention. Generally, risk is a function of the hazard (e.g. toxicity) and the exposure (contact between the toxicant and a living system). First, detection technologies are critical to identify exposure by enabling public health professionals to delineate areas of high contamination (i.e., ‘hot spots’). Second, many detection devices utilize biological-based assays (i.e., bioassays). These assays provide feedback about the toxicity of contaminants in the environment, and therefore aid in determining whether or not there may be a hazard. Another feature gaining traction is for detection technologies to estimate the amount of the contaminant that is in a biologically available form (referred to here as “bioavailability”) to lend further detail to understanding the likelihood and the levels of exposure. Remediation efforts also fit within the primary prevention paradigm because they directly support exposure prevention. These technologies reduce the amount or toxicity of contaminants in the environment, leading to reduced exposures to toxicants. Hence, the public health goal of exposure prevention can be achieved through detection and remediation technologies.

Technical Benefits and Sustainability are Drivers

As mentioned previously, the public health benefits are realized when there is “widespread adoption” of an effective prevention or intervention strategy. For new technologies to enter the marketplace and gain wide acceptance, there must be a technical advantage, such as speed and accuracy, as well as robustness for that detection and remediation approach. Similarly, it must withstand complex environmental conditions (weather, humidity, etc), as well as maintain effectiveness in contaminant mixtures. As such, “technical advantage” is a governing principle that drives innovation in detection and remediation technologies – because it impacts whether or not a technology gains acceptance and use.

In addition, sustainability is a driver for improvements in detection and remediation technologies and is also a critical consideration for the successful adoption of these new technologies. Sustainable processes achieve net environmental, economic, and societal gains

(3). Environmentally sustainable tools, often labeled “green,” use less energy and are developed using non-harmful materials relative to existing technologies. In some cases, green solutions reuse materials that would otherwise become a part of the waste stream. To achieve successful market entry, new technologies must have a cost advantage; however, that is not the only criterion of economic sustainability. Economic sustainability also includes the infrastructural capacity needed to maintain/operate the technology. As such, there is an advantage and need for technologies that are easy to use and that do not require sophisticated infrastructure to operate. This broadens the chances of applicability, and operability, allowing the chance—in some cases—for citizens to actively participate in site monitoring or cleanup. Lastly, it is critical that these technologies lead to a net gain for society – i.e., they must be effective at protecting health. Remediation approaches should aim to reduce and/or eliminate toxicity, and attention should be given to minimizing the creation of byproducts that might be as or more toxic than the parent compounds driving the remediation. Furthermore, environmental clean-ups should be equitable: they should not benefit one sector of society to the detriment of another sector of society. For example, remediation efforts that can treat hazardous substances in place may be more consistent with societal sustainability than remediation approaches that transfer toxicants from one neighborhood and move them to another neighborhood where they may continue to impact health. Rather, remediation efforts should uphold the principles of environmental justice, meaning all people enjoy the same protection from environmental and health hazards (4).

The National Institutes of Health (NIH) National Institute of Environmental Health Sciences (NIEHS) Superfund Research Program (SRP) invests in innovative detection, remediation, and toxicity screening technology development. The SRP has a multidisciplinary research portfolio of university and small business grants spanning from basic toxicology and epidemiology to applied engineer and tool development. Out of the full suite of approximately 150 research projects, approximately a third of the research investment goes toward remediation and detection technologies at stages from basic to field-ready. This paper highlights examples of SRP-funded innovative detection and remediation technologies that can be used as part of primary prevention, highlighting technical advantages and sustainability of these approaches.

Detection and Toxicity Testing

Fast, accurate, robust, portable, real-time, cost effective, on-site characterization technologies make it easier to quickly identify hazardous hotspots and, therefore, prevent exposures. Several projects under way by SRP-funded small businesses demonstrate the direction of innovative technologies applied for detection (Table 1). One example is a small business developing a gold nanoparticle-based plasmonic mercury sensor for on-site measurement of mercury in soil, sediment, and water at contaminated sites (Table 1A) (5). Their device weighs less than 20 pounds and requires low power, replacing time-consuming and costly lab methods. While the target of this device is mercury, such innovative plasmonic sensing platforms are a burgeoning field and have potential to improve detection of a variety of chemical and biological toxicants and or contaminants Researchers are also developing technologies to measure harmful vapors entering buildings from underlying contaminated sources (vapor intrusion). One approach uses a mobile sampling platform for

real-time trace trichloroethylene (TCE) detection. This vapor sensor uses a combination of cavity ring-down spectroscopy (CRDS) and diffusion time-of-flight (DiTOF) incorporating stationary phases. The CRDS provides extremely sensitive detection while diffusion with stationary phase provides specificity (Table 1B). Another small business is developing a portable technology which provides an improved means for measurement of harmful compounds using a miniature, cartridge-based sample collection method that pre-concentrates volatile organic compounds (VOCs) with high selectivity (Table 1C). Their technology uses advances in solid phase extraction and novel selective coatings for optical detection, to detect volatile and semi-volatile toxic chemicals. The approach needs minimal user expertise and operates without reagents, solvents or carrier gas. The sample collection method is being integrated with existing portable spectrometers, thereby providing a means to unambiguously identify VOCs at low concentrations in a highly portable format. These approaches are just a few examples of SRP-supported technologies that emphasize ease of use and portability.

Sampling as an early gauge of remediation success

Passive sampling devices (PSDs) are a type of detection tool that is left in the environment for a defined time period as it comes into equilibrium with the target contaminants in air, water, sediments, or porewater (water between sediments). PSDs are used for chemical characterization and can also aid in hazard identification to inform management actions. PSDs are being developed and tested for polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and some metals. In most cases, the deployment of PSDs in the environment is fairly simple, and the materials used to adsorb contaminants are economical. PSDs are gaining attention for their ability to estimate the bioavailable fraction of contaminants, as opposed to the total contamination; therefore, providing a more nuanced look at the nature of contamination at a particular site.

Some PSDs utilize accessible materials, making them practical to estimate the bioavailable fraction of persistent bioaccumulative contaminants in sediments. Typically, these PSDs are made of polyethylene (PE) (e.g. painters drop cloth); polyoxymethylene (POM) (e.g. acetate); or polydimethyl-siloxane (PDMS) solid phase microextraction (SPME) (e.g. fiber-optic threads). After a period of equilibrium, the PSDs are removed from the field, extracted, and measured using standard analytical chemical methodologies. Several SRP researchers are using PSDs as a means to test remediation success. One researcher uses a POM PSD to predict changes in uptake in PCBs in fish after remediation (carbon-based “sedimite”) of aquatic environment (Table 1D). The use of PSDs, validated by mathematical models to correspond to freely dissolved PCB concentrations, can predict bioavailability of PCBs in sediment. The PSD levels also correspond to fish uptake of PCBs. Ultimately, they show that these devices can help predict the reduction of bioavailable PCBs during remediation efforts and, therefore, give an early indication whether remediation efforts have been successful in reducing fish PCB uptake (6).

Another innovative approach for PSDs is to preload SPME fibers with stable isotopes, such as ^{13}C -labeled or deuterated dichlorodiphenyltrichloroethane (DDT) (Table 1E). This

methodology estimates the degree of equilibrium achieved in much less time than to wait for the device to come into full equilibrium (9 hours with isotope vs. 9 days for full equilibrium) (7). This approach yields a strong correlation between the derived equilibrium concentrations on the SPME fiber and bioaccumulation (lipid-normalized tissue residues) for DDTs in worms, showing that this method can rapidly measure reductions in bioavailable contaminants. Related work on PBDEs shows how this methodology can assess remediation effectiveness (8).

Passive sampling methods are also being used to show not only the presence of contaminants but also the risks of the contamination. Researchers use PE collection for air, sediment, and water. Passive sampling methods have also been used to predict PAH concentrations in crayfish—a simple model that could be adapted to predict risks of eating other shellfish in contaminated environments (Table 1F) (9). For other studies, researchers use a large quantity of PE not only for chemical analysis, but also for toxicity testing with an embryonic zebrafish developmental toxicity bioassay (10). This way, the PSD application facilitates detection of both the fraction of contamination present and the overall toxicity of the contamination as well. This is important because sometimes the unregulated byproducts of persistent compounds have differing toxicity than the parent regulated compounds.

PSDs have been used not only in toxicity testing, but also in epidemiology studies. Grantees have employed polyurethane foam (PUF) passive air samplers (PAS) to collect semi-volatile PCB compounds (Table 1G). After accounting for covariates impacting adsorption (11), the team used the PAS as part of studies looking at the impact of dredging on PCB signatures in mothers and children in two communities in the United States (12). The advantage of using PAS for these studies is that it predicts the complex mixture of PCB congeners in air of peoples' homes and their schools and may help identify sources.

Non-targeted sampling

Thus far, the sampling devices described have targeted particular classes of contaminants. However, some researchers are developing devices that target much wider suite of contaminants by utilizing a broader spectrum adsorbent materials. These are sometimes referred to as “non-targeted” sampling devices. Such devices are often used when one does not know what type of contamination is present, as is the case in some disasters or in following the totality of chemicals to which a person may be exposed.

For instance, a device is under development to be used for an epidemiology study evaluating the correlation between contaminants in drinking water (well-water and tap water) and the high preterm birth (PTB) rate in Puerto Rico (Table 1H). Although the team of researchers is specifically looking at phthalates and TCE exposure as a factor in PTB, it is not known which toxicants are present in the environment nor which ones best correlate to the PTB incidence. Hence, a research team is developing a patented sampling device called a “Porous Extraction Paddle” (PEP) that rapidly concentrates hundreds of contaminants and stores them in a compact tea bag-like object. The PEP is practical for a researcher or medical team to use during epidemiological studies. For example, the PEP can be placed into urine or drinking water and then easily be transported to a laboratory for chemical analysis. Though

the chemical analysis will initially focus on the suspected agents (phthalates and TCE), the team will have the capability to resample the PEP should they discover other toxicants associated with the PTB incidence. Hence, this test meets the needs of the epidemiological researcher to track exposure; it is packaged for ease of use; and it reduces the amount of material that has to go back to the laboratory for analysis and storage (13, 14).

Personal exposure monitoring

Other non-targeted sampling devices are meant to measure personal exposures, facilitating citizen science. For example, grantees have developed a silicone wristband and extraction method that tests approximately 1,200 air-borne chemicals of personal exposure (Table 1I). These PSDs are packaged in the form of a wristband which absorbs chemicals from the air, water, and even the skin. The chemicals remain in the silicone wristband, mimicking the body's absorption process (15).

Similarly, several researchers are developing environmental monitoring interfaces for smart phones. The advantage of using smart phones in detection monitoring is that it allows citizens to actively participate in personal exposure monitoring. SRP researchers have developed a tool to monitor one's personal air quality using a phone-enabled interface (Table 1J). It utilizes PM_{2.5}, PM₁₀, and ozone air pollutant data integrated with models for the state of Oregon (15). The predicted pollutant concentrations are displayed on phones as interactive maps and graphs. Another device under development is a low-cost portable smart phone-enabled device to detect the presence and concentrations of the flame retardant BDE-47 (Table 1K). The device uses a lab-on-a-chip (LOC) platform to perform microscale enzyme-linked immunosorbent assays (ELISA) (16).

Biological-based assays used for detection

Biological-based assays can be used as detection technologies because they indicate where contamination confers a toxic biological response. These assays are a form of toxicological testing, but have been tailored for use in environmental screening – that is, to identify hot spots of toxicity. Researchers have developed the chemically-activated luciferase expression (CALUX) cell bioassay to detect and measure chemicals in a variety of sources including water. The bioassay uses mouse hepatoma cells plated into a 96-well microplate (Table 1L). Chemicals of interest (or the extractants) are added to each well and incubated for 24 hours. Finally, wells are processed and luciferase activity is measured with a luminometer. The assay is tailored to light up according to the amount of a certain chemical in a sample, such as dioxins and hormonal mimics and has been converted to a USEPA SW-846 Method 4435 for Halogenated Aromatic Hydrocarbon analysis. In addition, a sensitive, competitive enzyme linked immunosorbent assay (ELISA) is being developed for the detection of the antimicrobial triclosan (Table 1M). This bioassay is a rapid and convenient tool to screen for human and environmental exposure (17). Lastly, an innovative assay to map protein targets of environmental chemicals is another approach for rapid toxicity screening (Table 1N). Using a chemoproteomic platform, the assay is reactivity-based and mines for distinct sets of proteins throughout the proteome that may be particularly sensitive to environmental

chemicals. The assay is a comprehensive screen to determine how molecules interact in the body (18).

Sustainable Remediation

As mentioned previously, environmental cleanup is also a form of primary prevention because sustainable remediation technologies reduce the amount or toxicity of contaminants in the environment, leading to reduced exposures. SRP remediation research is summarized in Table 2.

In terms of sustainability, remediation technologies that are applied “*in situ*,” meaning “in place,” can be advantageous because it avoids the expensive practice of contaminant removal. Furthermore, it means the contaminants are not being transferred from one community to become a burden to another community. Biological-based remediation (bioremediation) approaches stabilize, reduce, or destroy contaminants by harnessing the natural processes of microorganisms, fungi, plants, and ecological communities. These approaches tend to be sustainable due to a low energy footprint; however, optimizing these biological systems is an important research goal in order to achieve fast and effective contaminant remediation. Researchers are also developing and utilizing novel materials such as nanotechnology, advanced engineered membranes, and new carbon materials to improve the speed and efficacy of environmental remediation. These advanced materials are highly efficient, are often reusable, and therefore tend to minimize the amount of chemicals, reagents, and waste materials associated with environmental cleanups. Finally, novel reuse of waste materials/industrial byproducts as part of a remediation effort is another way that technology developers advance the goals of sustainability in cleanups.

Several SRP grantees are working on biological-based remediation technologies, many of which are applied *in situ*. These technologies stabilize, reduce, or destroy contaminants by harnessing the natural catalytic properties of biological processes of microorganisms, fungi, plants, and ecological communities. Researchers are developing sustainable plant-based remediation strategies to address widespread mine-waste contamination in semi-arid environments using a process called “phytostabilization” (Table 2A). Using the Iron King Mine Superfund site as a test location, researchers developed several examples of best practices for using phytostabilization in these challenging environments. The team identified native plants that sequester metals in the root zone, rather than into their above-ground biomass, preventing metals from entering the food chain. Pilot tests were run on mine tailings to optimize plant growth under increasing composting conditions (19). These research findings are impactful because sustainable management of mining wastes is a global challenge.

Several other researchers are developing plant-based remediation technologies including a team of university and small business investigators piloting a project using poplar trees to assist degradation of PCBs in a wastewater lagoon in a small town in Virginia (Table 2B). Their preliminary results show removal of PCBs in soil by plants and their associated microbes in the root zone (20–23). These results are promising, given that this approach is an inexpensive alternative for PCB removal. Research on endophyte assisted

phytoremediation method to remove arsenic and mercury has resulted in the identification of fern plants that can reduce levels of soil arsenic. (Table 2C) Other research on the horizon includes an innovative methodology to extract cadmium using certain plant's natural process of trichome secretion (Table D). These plant-based remedies are an example of technologies that require a low energy footprint and, in many cases, are easily maintained.

Another *in situ* approach under development is a strategy to reduce lead mobility in soils using microbial-induced calcite precipitation by indigenous soil bacteria. This patented approach would provide a low-cost and safe alternative to the widespread issue of soils contaminated with lead as well as, potentially, other metals (Table 2E) (24). Another patented device uses a microbial nanowire to precipitate uranium from water and has been tested at Oak Ridge National Laboratory (Table 2F) (25). A green remediation technology for *in situ* TCE remediation, currently under development, is powered by solar energy, converting groundwater TCE into safe byproducts (Table 2G). These solar panels apply low direct electric currents through electrodes in wells to manipulate groundwater chemistry by electrolysis. One of the potential applications of this technology is for remediation of contaminated karst (i.e. cave) aquifers, an extremely challenging scenario due to the complexity of the subsurface (26, 27).

Novel materials

Novel materials (e.g., nanotechnology, advanced membranes, and new carbon materials) provide promising solutions for remediation. Researchers have developed functionalized zero valent iron/palladium membrane filters to rapidly degrade PCBs and TCE, completely eliminating their toxic byproducts (Table 2H). Also under development is a magnetic nanocomposite platform that allows for the selective capture of PCB congeners with a range of affinities and levels of selectivity (Table 2I). In another example, researchers coupled microorganism degradation processes with zero valent iron (ZVI) and titanium dioxide (TiO₂) nanomaterials for contaminant degradation of brominated flame retardants (Table 2J). They also work on a natural product system using cellulose nanomaterials in environmental cleanup technologies (28). Other work in novel materials includes the use of functionalized graphene sheets as a novel vapor barrier; and the development of membrane-enhancement technologies to purify water without fouling (Table 2K–L).

Finally, a small business is developing an on-site mercury capture system by using activated fly ash (Table 2M). Their product, “X-FA” shows promise to capture mercury from coal-fired boiler/power facilities at a fraction of current costs. X-FA sorbents use an innovative coating technology that deposits a thin mercury oxidizing activator layer around the fly ash particles. Once in contact with mercury vapor, the activator coated powder chemically binds and captures mercury. An added benefit of this approach – besides reuse of waste materials – is that they are developing production capabilities so that they can reuse and activate fly ash at the site of the power plant.

Summary and Challenges

In summary, this paper provides several examples of SRP-funded research focused on developing detection and remediation technologies for sustainable exposure prevention from hazardous environmental substances. These research teams are utilizing sustainable principles to develop technologies that are technically advantageous, but also confer a net benefit in terms of the overall environmental, economic, and societal impacts. While it is not expected that every detection and remediation technology meet all of these criteria, it is evident that these goals are important drivers of innovation.

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Figure 1.
Role of Remediation and Detection Technologies in Public Health Model of Prevention and Intervention (Adapted from CDC <http://www.cdc.gov/violenceprevention/overview/publichealthapproach.html>).

Table 1.

Examples of Detection and Toxicity Testing Technologies Supported by the SRP.

Text Reference	Technology	Grantee	Grant numbers	Applications	Contaminant	Benefits
A	Gold nanoparticle-based plasmonic mercury sensor	J. James, Picoyne	R44ES023729	On-site measurement of mercury in soil, sediment, and water	Mercury	Ease of use and portability
B	Cavity ring-down spectroscopy and diffusion time-of-flight incorporating stationary phases called "AROMA"	B. Richman, Entanglement Technologies	R44ES022538	Real-time trace trichloroethylene vapor sensor	Trichloroethylene (TCE)	Mobile, sensitive detection plus specificity
C	Advances in solid phase extraction and novel selection coatings for optical detection	B. Vaidya, Lynntech, Inc.	R43ES021625	Vapor intrusion modeling, detection of volatile and semi-volatile toxic chemicals.	Volatile and semi-volatile toxic chemicals	Ease of use and portability, high selectivity
D	Polyoxymethylene (POM) passive sampling device	U. Ghosh, University of Maryland	R01ES020941	Predict changes in uptake of PCBs in fish after remediation	Polychlorinated biphenyls (PCBs)	Early indication of remediation success
E	Passive sampling device made of SPME fiber preloaded with stable isotopes	J. Gay and D. Schlenk, University of California-Riverside	R01ES02092	Measure bioaccumulation of several classes of contaminants in sediments	Dichlorodiphenyltrichloroethanes (DDTs), PCBs, environmental pollution	Fast results, early indication of remediation success
F	Polyethylene passive (PE) passive sampling device	Kim Anderson, Oregon State University	P42ES016465	Sampling of air, sediment, and water	Polycyclic aromatic hydrocarbons (PAHs)	Can predict PAH concentrations in crayfish; extractants used in zebrafish toxicity test
G	Polyurethane foam passive air samplers	K. Hornbuckle, P. Thome, University of Iowa	P42ES013661	Measure airborne contaminants from dredging	Semi-volatile PCBs	Predicts complex mixture of chemicals in air, may help identify sources
H	Porous Extraction Paddle (PEP) – a tea bag-like non-targeted passive sampling device	R. Giese, Northeastern University	P42ES171980	Rapid collection of contaminants in urine and drinking water; compatible to use by nurses during in-home interviews	Phthalates, trichloroethylenes, other toxicants	Ease of use, reduces material to go to lab for analysis and storage
I	Silicone wristband and extraction method	K. Anderson, Oregon State University	P42ES016465	Personal exposure monitoring	1,200 airborne chemicals	Mimics the body's absorption process
J	Interface for smartphone uses pollutant data integrated with geographical models	W. Bair and D. Williams, Oregon State University	P42ES016465	Personal air quality monitoring	Particulate matter, ozone	Approachable for citizen science or personal monitoring
K	Smartphone-enabled device uses lab-on-a-chip platform to perform microscale enzyme-linked immunosorbent assays	T. Pan, University of California - Davis	P42ES004699	Personal exposure monitoring	Flame retardant BDE-47	Low cost, approachable for citizen science or personal monitoring

Text Reference	Technology	Grantee	Grant numbers	Applications	Contaminant	Benefits
L	Chemically activated luciferase expression cell bioassay	M. Denison, University California-Davis	P42ES004699	Measure chemicals in a variety of sources, including water	Dioxins, hormonal mimics	Identifies a hotspot of toxicity
M	Sensitive, competitive enzyme-linked immunosorbent assay	S. Gee, University of California-Davis	P42ES004699	Screen for human and environmental exposure	Triclosan	Rapid, convenient; identifies a hotspot of toxicity
N	Assay uses a chemoproteomic platform to map protein targets of environmental chemicals	D. Nomura, University of California-Berkeley	P42ES004705	Comprehensive screen to determine how molecules interact in the body	Multiple environmental chemicals	Identifies a hotspot of toxicity
N/A	Surface-enhanced Raman spectroscopy	M. Benhabib, Ondavia, Inc.	R43ES025083 R43ES026513	Environmental remediation of halogenated solvents, coal-fired power plant waste water monitoring; oil refinery process control.	Halogenated solvents	Ease of use and portability
N/A	Simple colorimeter using green technology avoids use of mercury, commonly used in arsenic samplers	B. Vaidya, Lynntech, Inc.	R43ES025466	Rapid detection of chemicals in water	Arsenic	Ease of use and portability, green chemistry
N/A	Passive sampling device; mixed-polymer sorptive phase within a non-selective and highly porous membrane	D. Shea, NC State University	P42ES005948	Detection and determination of bioavailability in water and sediment	Over 400 chemicals	Non-targeted sampling of disaster site (coal ash spill)

Table 2.

Examples of Remediation Technologies Supported by the SRP.

Text Reference	Technology	Grantee	Grant numbers	Applications	Contaminant	Benefits
A	Phytostabilization-- plants that accumulate metals in the root zone	R. Maier, University of Arizona	P42ES004940	Prevents metals from entering the food chain	Metals	Sustainable management of mining wastes
B	Poplar trees to remove chemicals from soil	J. Schmoor, University of Iowa	P42ES013661	Remediation of wastewater	PCBs	Inexpensive, low energy footprint, easily maintained
C	Endophyte assisted phytoremediation	Edenspace Systems, Inc	R43ES025483 R44ES020099	Contaminated soil (As); groundwater remediation	Arsenic and organic contaminants	Inexpensive, low energy footprint, easily maintained
D	Phytoextraction of cadmium from plant trichomes expressing a stabilized antibody	Phyllotech, LLC	R43ES021682	Contaminated soil	Cadmium	Inexpensive, low energy footprint, easily maintained
E	Microbial-induced calcite precipitation by indigenous soil bacteria	BioCement Technologies		Reduce lead mobility in soils	Lead, other metals	Low-cost, novel <i>in situ</i> technology
F	Microbial nanowire device	G. Reguera, Michigan State University	R01ES017052	Uranium removal from water	Uranium	Based on metal reduction by <i>Geobacter</i> bacteria
G	Solar panels apply low direct electric currents through electrodes in wells to manipulate groundwater chemistry by electrolysis	A. Alshawabkeh, Northeastern University	P42ES017198	Remediation of contaminated karst (i.e. cave) aquifers	TCE	Green technology, <i>in situ</i> remediation
H	Functionalized zero valent iron / palladium membrane filters	D. Bhattacharyya, University of Kentucky	P42ES007380	Novel materials for remediation	PCBs, TCE	Green, cost effective, remediation without toxic byproducts
I	Magnetic nanocomposite platform	Z. Hilt, University of Kentucky	P42ES007380	Novel materials for remediation	PCB congeners	Green, cost effective
J	Microorganism degradation processes coupled with nanomaterials	M. Weisner, Duke University	P42ES010356	Remediation in sediments and water	Brominated flame retardants	Understanding of interactions between nanoparticle and microbial remediation processes
K	Graphene-based environmental barriers	R. Hurt, Brown University	P42ES013660	Prevents release and transport of vapor toxicants	TCE, Hg	Low cost, pliable geometry for ease of space-filling
L	Membrane-enhancement technologies	Lynntech, Inc.	R4ES024625	Treatment and recycling of wastewaters generated by industry	Many environmental chemicals in the form of dissolved solids	Reduces membrane fouling, reduces system maintenance
M	Activated fly ash with an innovating coating technology	Pollution Control Technologies	R43ES024620	Capture mercury from coal-fired boiler/power facilities	Mercury	Low cost, reuses waste materials (fly ash) on site at power plant
N/A	Dual biofilm reactive barrier; granular activated carbon coated with	E. Bouwer, Johns Hopkins University	R01ES024279	Bioremediation of groundwater and sediments	Chlorobenzenes, benzenes	Novel <i>in situ</i> technology

Text Reference	Technology	Grantee	Grant numbers	Applications	Contaminant	Benefits
	anaerobic and aerobic microorganisms					
N/A	High-throughput quantitative polymerase chain reaction tool	F. Loeffler; University of Tennessee, Knoxville	R01ES024294	Groundwater bioremediation	Solvents such as TCE, tetrachloroethene	Identify conditions that may impede remediation by chloroflexi bacteria
N/A	Oxalic acid injection into groundwater to form mineral formations to trap dissolved arsenic	S. Chillrud, Columbia University	P42ES010349	Remediation of arsenic in groundwater	Arsenic	Safe, inexpensive compound, could be a sustainable approach
N/A	In situ chemical oxidation using persulfate and hydrogen peroxide	D. Sedlak and F. Doyle	P42ES004705	Aquifer remediation	Solvents, benzene, perfluorooctanoic acid	Relatively inexpensive, in situ
N/A	Oxidant-paraffin candles with pneumatic circulators	Airlift Environmental, Inc.	R42ES022530	Aquifer remediation	Chlorinated solvents such as TCE	May improve remediation of hard-to-treat aquifers
N/A	Biocatalyst composite with a novel monoculture	Microvi Biotechnologies	R43/ R44ES022123	Water resource remediation	1,4-dioxane and chlorinated co-contaminants	Less costly, no secondary waste stream
N/A	Patented technology for profitable dilute metal recovery	Blue Planet Strategies, LLC	R43ES020096	Recover and reuse metal ore to clean up acid mines	Metals such as iron	Reuses materials, treats waste as a resource