



WHITE PAPER

Biological Soil Remediation

What the Science Documents and How We Put It to Work

Elm Dirt Remediation

October 2026

1. Executive summary

Soil already holds the organisms that break down many of the contaminants people worry about most. Bacteria and fungi feed on petroleum hydrocarbons, many PAHs and a range of pesticides. Others change the chemical form of metals, bind metals to their cells, or help plants draw them out of the ground. Carbon-rich materials such as biochar hold organic contaminants in place while that biology works. EPA has described bioremediation to the public for years as microbes that "use contaminants as a source of food and energy" [1].

Elm Dirt makes organic biological soil products in Kansas City, Missouri. Independent DNA sequencing by Biome Makers identified **291 microbial species** (223 bacteria and 68 fungi) in our Plant Juice [2]. This paper lists which of those species peer-reviewed research has studied against which contaminants, with the citation for each. The largest groups cover petroleum hydrocarbons, PAHs, organophosphate and phenoxy pesticides, and the binding and chemical conversion of metals.

The limits get equal space in this paper. Research on a species is not a test of a product, and several of the best-studied capabilities belong to specific strains, while our lab report identifies species. Metals are never destroyed, highly chlorinated dioxins resist microbial attack, and microbial PFAS breakdown is emerging research. Biology is also slow, with results taking months to a year or more and verified by lab testing.

So we assess the site, test before and after, apply living biology with biochar where binding is part of the plan, and monitor over time with independent laboratories. Elm Dirt has product in the ground in East Palestine, Ohio, as part of an ongoing soil-restoration pilot run on those terms.

2. The problem with dig-and-haul alone

Excavation is the default response to contaminated soil, and often the right one. It is fast and certain, and in an emergency speed comes first.

Excavation also relocates the contamination, since the soil goes by truck to a licensed landfill or incinerator and clean fill comes back, and that has three consequences.

First, the contaminant still exists: unless the receiving facility treats it, the material is now contained somewhere else. Superfund law directs EPA to prefer remedies in which treatment "permanently and significantly reduces the volume, toxicity or mobility" of hazardous substances over remedies without such treatment [3].

Second, the restored ground is biologically empty, because backfill and imported topsoil carry little organic matter or living structure. A site can pass its confirmation samples and still fail to grow grass, hold a slope or soak up a storm, because soil structure depends on biology: fungal networks and microbial byproducts bind particles into stable aggregates [4].

Third, some contamination is too thin or too deep to dig. Low-level residue spread over large areas, contamination under structures or in wetlands, and sediments are poor candidates for excavation. For contaminated sediments, in-place treatment is generally less disturbing and cheaper than dredging or capping, and in-place sorbent treatment has been carried out at pilot or full scale at more than 25 field sites [5].

Biological treatment works where the soil sits. EPA's guide notes it treats soil on site "without having to dig, pump, and transport" it, can take less equipment, labor and energy, and cuts truck traffic [1], though the price is time.

3. How biological remediation works

Five mechanisms do the work, and most real sites involve more than one.

3.1 Degradation

Microbes break contaminant molecules apart, ideally all the way to carbon dioxide and water. Some organisms grow on the contaminant as food. Others break it down incidentally while feeding on something else, a process called cometabolism.

Petroleum hydrocarbons are the classic case, since many soil bacteria carry alkane hydroxylase enzymes that attack the straight-chain hydrocarbons in diesel and fuel oil [6]. In a 365-day field study of diesel-contaminated soil, adding a bacterial consortium gave the highest cleanup efficiency of the treatments tested [7].

A wide range of bacteria and fungi degrade PAHs, starting with dioxygenase enzymes that open the aromatic ring [8]. Lighter PAHs such as naphthalene and phenanthrene go fastest. Five- and six-ring PAHs such as benzo[a]pyrene are slower and often need bacteria and fungi working together [9].

Some chlorinated solvents degrade cometabolically with oxygen present. *Pseudomonas putida* strain F1 degrades trichloroethylene using toluene dioxygenase [10].

Aerobic bacteria in the genera *Sphingomonas*, *Pseudomonas* and *Burkholderia* can degrade lower-chlorinated dioxins. Higher-chlorinated dioxins are reductively dechlorinated, slowly, in anaerobic sediments, with *Dehalococcoides* implicated [11].

3.2 Transformation

Some contaminants, metals above all, are converted to a less toxic or less mobile form instead of being broken down. Bacteria can reduce hexavalent chromium, Cr(VI), to the far less toxic and less mobile Cr(III), and soluble uranium(VI) to insoluble uranium(IV) [12][13]. Others oxidize arsenite, As(III), to arsenate, As(V), which moves less and is less toxic [14].

These conversions are real and useful, though they can reverse when pH, oxygen or organic matter shifts.

3.3 Biosorption and precipitation

Microbial cell walls carry chemical groups that bind metal ions. Yeast cell walls bind lead, cadmium and uranium [15]. Living cells of the fungus *Penicillium simplicissimum* removed chromium, lead, copper, cadmium and zinc from solution by surface binding and uptake [16]. *Cupriavidus metallidurans* pumps metal ions out of the cell, where its surface polysaccharides act as nucleation sites and the metals crystallize as carbonates. It has been used in engineered systems to remove metals from contaminated water [17].

3.4 Sequestration with biochar

Biochar is a stable, porous carbon made by heating biomass with little oxygen, and it binds organic contaminants. The idea is best developed for contaminated sediments, where in-place activated carbon sequesters hydrophobic organic compounds, lowers their concentration in pore water and cuts uptake by organisms [18][5]. Biochar works on the same principle. In soil studies, biochar reduced the water-soluble fraction and bioavailability of phenanthrene, most of all in soils low in organic carbon [19]. Biochars and other carbon-rich materials also sorb PFAS, more strongly as the fluorinated chain gets longer [20].

Sequestration lowers how much of a contaminant can move or be taken up, while the total measured by a standard lab extraction stays the same, so monitoring has to include bioavailability methods alongside totals. Biochar can also carry PAH residue from its own production, so the biochar used on a site needs its own analysis [21].

3.5 Plant-assisted remediation

Roots feed microbes, open the soil to air and water, and take up some contaminants. Microbes in turn help plants survive stressed ground. Some bacteria make an enzyme, ACC deaminase, that intercepts the stress-ethylene signal that shuts down plant growth on contaminated soil [22]. In cadmium-contaminated soil, a consortium built around such a bacterium more than doubled plant biomass [23]. Fungi help as well, and *Mucor circinelloides* paired with a lead-accumulating plant removed 58.6 percent of the lead from contaminated soil, more than either alone [24]. In a field experiment on cadmium- and arsenic-contaminated soil, *Trichoderma harzianum* with biochar lowered total soil cadmium and arsenic and raised soil nitrogen, phosphorus and organic matter [25]. *T. harzianum* has been identified in Elm Dirt's Bloom Juice by independent lab analysis (Biome Makers lab profile) [26].

Plant-assisted work is measured in growing seasons. Often its biggest contribution is stabilization: living cover that holds contaminated soil in place and keeps people and water off it.

4. The Elm Dirt microbial profile

What was measured

Biome Makers, an independent soil-microbiome laboratory, analyzed a sample of Elm Dirt's Plant Juice by next-generation sequencing of bacterial (16S) and fungal (ITS) marker genes, with a synthetic spike-in standard for absolute quantification. The analysis, dated May 29, 2024, identifies **291 microbial species: 223 bacteria and 68 fungi** [2]. A separate Biome Makers lab profile identifies 192 species in Bloom Juice [26].

Plant Juice is CDFA Certified Organic, and Ancient Soil, the solid product we pair with it in the field, is a Class A certified compost made from worm castings.

How the profile is used

The profile shows **which organisms are present**, identified by DNA. Every species discussed in Section 5 appears in the Biome Makers lab profile of Plant Juice, subject to three qualifications.

1. Remediation research often concerns one named strain, and degradative genes frequently sit on plasmids or other mobile elements that vary between strains of a species. The carbon tetrachloride activity of *Pseudomonas stutzeri* strain KC, for example, is carried on a mobile genetic element [27]. Sequencing identifies the species, and the table in Section 5 marks where the published work is strain-specific.

2. Sequencing detects organisms, while their activity in soil, and the field degradation rates that follow from it, come from testing on site.
3. Product performance is a separate question, and the Biome Makers report itself says its results are "an interpretation of the potential function or potential impact of tested sample in the soil based on the characterization of the sample microbiome." Performance on a given site is measured on that site, before and after, by independent laboratories, which is what our field program is for.

Within those limits the profile is useful. Our products deliver a diverse community that includes many species that peer-reviewed research shows can degrade, convert or bind contaminants, along with organic matter and nutrients that support soil biology generally.

5. Microbe × contaminant evidence

Every species below was identified in Elm Dirt's Plant Juice by independent lab analysis (Biome Makers), and peer-reviewed research shows it can act on the listed contaminant. Citations are numbered to the reference list.

The **Match** column describes how closely the organism in the published work matches what the lab found: *Species* means the work applies to the species broadly, *Strain* means the capability belongs to a named strain, and *Genus only* means the published organism was identified to genus.

Species (Plant Juice)	Contaminant	Mechanism	Match	Refs
<i>Pseudomonas putida</i>	Diesel, n-alkanes	Alkane hydroxylase degradation	Species (field consortium)	[7][6]
<i>Pseudomonas putida</i>	Trichloroethylene	Cometabolic oxidation (toluene dioxygenase)	Strain F1	[10]
<i>Pseudomonas putida</i>	Chlorpyrifos	Hydrolysis and catabolism	Species	[28] [29]
<i>Pseudomonas putida</i>	2-Butoxyethanol	Oxidation and ether cleavage	Strain BOE100	[30]
<i>Pseudomonas putida</i>	Mercury	Hg(II) reduction	Strain SP1	[31]
<i>Pseudomonas stutzeri</i>	Carbon tetrachloride	Cometabolic degradation; 98–99.9% removal sustained 4 years at full field scale	Strain KC	[32] [27]
<i>Pseudomonas stutzeri</i>	Naphthalene	Naphthalene degradation pathway	Strain AN10	[33]
<i>Pseudomonas stutzeri</i>	Cr(VI), Hg, Cd, Pb, As	Chromium reduction; metal precipitation	Strain KC	[34]
<i>Pseudomonas fluorescens</i>	Naphthalene, PAHs	Naphthalene catabolism; 2-year contained field release	Strain HK44	[35] [7]
<i>Pseudomonas oleovorans</i>	Medium-chain alkanes	Alkane hydroxylase oxidation	Species	[6]
<i>Pseudomonas mendocina</i>	Trichloroethylene, chloroform	Cometabolic oxidation (toluene-4-monooxygenase)	Strain KR1	[36] [37]
<i>Acinetobacter calcoaceticus</i>	Diesel-range alkanes	Alkane oxidation; 82–92% of C12–C18 in 28 days	Strain CA16	[38]
<i>Comamonas testosteroni</i>	PAHs in soil	Ring-cleaving dioxygenases; phenanthrene 81%, benzo[a]pyrene 38% in 25 days	Species	[39]
<i>Comamonas testosteroni</i>	Dibenzofuran, dibenzo-p-dioxin	Biphenyl dioxygenase oxygenates both ring systems	Strain B-356	[57]
<i>Pseudomonas putida</i>	Dibenzofuran	Cometabolic degradation on biphenyl	Strain B6-2	[58]
<i>Comamonas testosteroni</i>	Selenite, antimony	Se(IV) reduction; Sb oxidation and efflux	Species	[40] [41]
<i>Nocardioides</i> sp.	Vinyl chloride	Alkene monooxygenase pathway	Genus only	[42] [43]
<i>Hydrogenophaga</i> sp.	2-Butoxyethanol	Oxidation and ether cleavage	Genus only	[30]
<i>Cupriavidus metallidurans</i>	Cd, Zn, Cu, Pb, Hg, Ni	Efflux and carbonate precipitation; used in engineered systems	Species (CH34)	[17] [44]
<i>Cupriavidus necator</i>	2,4-D and phenoxy herbicides	<i>tfd</i> degradation pathway	Strain JMP134	[45] [46]

Species (Plant Juice)	Contaminant	Mechanism	Match	Refs
<i>Ensifer adhaerens</i>	Arsenite, Cr(VI)	As(III) oxidation and Cr(VI) reduction	Strain M8	[14]
<i>Pseudarthrobacter oxydans</i>	Cr(VI)	Cr(VI) reduction	Species	[47]
<i>Desulfovibrio vulgaris</i>	Cr(VI), U(VI)	Anaerobic reduction and precipitation	Species	[12] [13]
<i>Variovorax paradoxus</i>	Cadmium (plant-assisted)	ACC deaminase supports plant growth	Strain 5C-2	[22] [23]
<i>Brevundimonas diminuta</i>	Organophosphate insecticides	Organophosphate hydrolase	Species	[48]
<i>Delftia</i> sp.	2,4-D	<i>tfd</i> degradation pathway	Genus only	[49]
<i>Penicillium simplicissimum</i>	Cr, Pb, Cu, Cd, Zn; U	Biosorption, bioaccumulation, biomineralization	Species	[16] [50]
<i>Mucor circinelloides</i>	Pb (plant-assisted), Cd, As	Biosorption; enhanced plant uptake	Species	[24] [51]
<i>Saccharomyces cerevisiae</i>	Pb, Cd, U and other metals	Cell-wall biosorption	Species	[15]

Reading the table by contaminant

Petroleum hydrocarbons have the deepest record, including field scale, and *P. putida* and *P. fluorescens* were both in the consortium in the 365-day diesel field study [7].

For PAHs there are soil studies on several species, and for the heaviest PAHs the published pattern is bacteria and fungi degrading them together [9], and our products carry both.

On chlorinated solvents, the organisms in our profile act aerobically and mostly cometabolically. Complete reductive dechlorination of chlorinated ethenes is done by specialized anaerobes [52], so solvent plumes in groundwater need an engineered design.

For dioxins and furans, aerobic degradation is reported mainly for the lower-chlorinated congeners [11]. Research shows *Comamonas testosteroni* and *Pseudomonas putida*, both in our profile, can act on the dioxin and furan ring structure [57][58]. Our dioxin approach pairs that biology with sequestration in biochar and carbon amendments, plus long-term independent monitoring (Sections 3.4 and 6).

Microbial breakdown of PFAS is emerging research, and for field work today the established tool is sorption to carbon, and performance depends on the material [20]. We pair biochar with soil biology and measure leaching and concentrations over time.

Metals research covers chromium, arsenic, cadmium, lead and uranium, with field results for chromium and cadmium in plant-assisted systems. Every one of these mechanisms changes where a metal is or what form it takes, and none destroys it.

Pesticides have species-level research for organophosphates (*B. diminuta*, *P. putida*) and phenoxy herbicides (*C. necator*).

6. Field approach

Every project runs in four stages, and the order counts for more than any single product.

Assess

Start with the site's history, the contaminants of concern, soil type, regulatory setting and goal. Restoring soil health on clean backfill takes a different plan from a petroleum hot spot or a dioxin-impacted yard. Identify who approves the work, since under a regulatory cleanup, biological work happens inside an approved work plan.

Test

Before anything goes down, composite samples from several cores per area, taken at a consistent depth and sent to the same independent laboratory using standard EPA methods, give a baseline that later samples can be compared with. Single grab samples vary too much spot to spot to support conclusions. Where binding is part of the plan, add bioavailability measures (passive samplers, mild extractions or leachate tests) alongside totals, since sequestration lowers availability without lowering totals, and measure soil biology too. Untreated control areas make the results interpretable, and where the decision warrants it, a bench test in the site's own soil comes before field scale.

Apply

A typical application has four parts:

- **Aeration or decompaction**, because most hydrocarbon and PAH degradation needs oxygen
- **Biochar**, where sequestration is part of the plan, with a certificate of analysis that includes its own PAH content [21]
- **Plant Juice**, the liquid carrying the 291-species community
- **Ancient Soil**, the Class A worm-casting compost that adds organic matter and biology

Moisture management and living plant cover keep the system going, and rates are set per site. We work directly with applicators and can be on site. Production capacity is 18,000 gallons of liquid biologicals and 35,000 pounds of Ancient Soil per week, and it scales.

Monitor

Resample over a year or more, typically at three, six and twelve months, with the same lab, methods and sampling pattern as the baseline. Report totals, bioavailability and biology together. Where a community is involved, it sees the results first.

7. Where this fits and where it doesn't

Situation	Fit	What to expect
Soil-health restoration after excavation, fire, flooding or construction	Strongest	Structure, cover and biology measured over growing seasons
Petroleum hydrocarbons	Strong, established practice	Months to more than a year, depending on product type and age
PAHs	Species-level research in soil	Lighter PAHs over months; heavier PAHs slower
Organophosphate and phenoxy pesticides	Species-level research	Site-specific; test before and after
Metals	Binding, chemical conversion and plant-assisted only	Reduced mobility or uptake; reversible; never destruction
Chlorinated solvents in groundwater	Limited; needs engineered design	Our organisms act aerobically and cometabolically
Dioxins and furans	Sequestration-led; degradation slow	Long-term monitoring; no claims on highly chlorinated congeners
PFAS	Sorption-led with carbon amendments; microbial breakdown is emerging research	Leaching and concentration monitoring over time

EPA's guide puts bioremediation at "a few months or even several years," longer where concentrations are high, contamination is trapped in dense soil, or the area is large or deep [1]. We plan the same way, and a promise of results in weeks should be treated with suspicion.

Biology does not replace emergency response, debris removal, engineered containment or ordered cleanups, and it works alongside and after them.

As a regulatory matter, Elm Dirt products support natural biological soil processes. They are not a chemical treatment, and no biological approach can guarantee contaminant removal. Performance depends on site conditions, management practices and integration with appropriate remediation protocols, and our products do not replace engineered remediation where it is required.

Oxygen, moisture, temperature, pH, salinity, contaminant age and organic matter decide the outcome, which is why we test before and after on every site.

8. Current field work: East Palestine, Ohio

On February 3, 2023, a Norfolk Southern freight train derailed in East Palestine, Ohio, near the Pennsylvania line. Thirty-eight cars derailed, eleven of them hazardous-materials tank cars, and five vinyl chloride cars were vented and burned on February 6 [53]. EPA directed the response, which it now describes as in a monitoring, maintenance and reporting phase [54]. Independent researchers have published soil measurements of dioxins and furans near the site [55], and a study of local creek sediments found native microbial communities able to break down vinyl chloride and butyl acrylate [56].

Elm Dirt has product in the ground in East Palestine as part of an ongoing soil-restoration pilot, with independent lab monitoring, working alongside community environmental advocates. The pilot targets dioxins and furans, PAHs and other SVOCs, and PFAS. Treatment combines aeration, biochar, Plant Juice and Ancient Soil, applied as in Section 6.

We are not publishing pilot results yet. Biology needs months to a year or more, and early samples cannot show whether treatment is working. For the next phase we recommend untreated controls, composite sampling at intervals over a year, and bioavailability measurements alongside totals. The community will see results before anyone else.

We do not comment on the federal cleanup or the legal proceedings. Our work is soil health and the data from it.

9. Conclusion

Every soil already has biology at work. Published research shows what many of the organisms in our products can do: break down fuels, PAHs and pesticides, convert and bind metals, and help plants hold contaminated ground. Biochar adds a well-studied way to keep contaminants in

place while that happens.

On any given site, the results come from design and measurement: assess, test, apply, monitor, and report what the lab finds. If you have a site in mind, [talk with us](#).

References

1. U.S. EPA (2012). *A Citizen's Guide to Bioremediation*. EPA 542-F-12-003. semspub.epa.gov/work/01/580734.pdf
2. Biome Makers / BeCrop. *Independent lab analysis (Biome Makers lab profile), Elm Dirt Plant Juice*, May 29, 2024. 16S and ITS next-generation sequencing with synthetic spike-in quantification. Unpublished laboratory report; available on request.
3. Congressional Research Service. *Comprehensive Environmental Response, Compensation, and Liability Act: A Summary of Superfund Cleanup Authorities and Related Provisions of the Act (R41039)*. congress.gov
4. Rillig MC, Mummey DL (2006). Mycorrhizas and soil structure. *New Phytologist* 171(1):41–53. doi:10.1111/j.1469-8137.2006.01750.x
5. Patmont CR, Ghosh U, LaRosa P, et al. (2015). In situ sediment treatment using activated carbon: a demonstrated sediment cleanup technology. *Integrated Environmental Assessment and Management* 11(2):195–207. doi:10.1002/ieam.1589
6. van Beilen JB, Neuenschwander M, Smits TH, et al. (2002). Rubredoxins involved in alkane oxidation. *Journal of Bacteriology* 184(6):1722–1732. doi:10.1128/JB.184.6.1722-1732.2002
7. Szulc A, Ambrożewicz D, Sydow M, et al. (2014). The influence of bioaugmentation and biosurfactant addition on bioremediation efficiency of diesel-oil contaminated soil: feasibility during field studies. *Journal of Environmental Management* 132:121–128. doi:10.1016/j.jenvman.2013.11.006
8. Haritash AK, Kaushik CP (2009). Biodegradation aspects of polycyclic aromatic hydrocarbons (PAHs): a review. *Journal of Hazardous Materials* 169(1–3):1–15. doi:10.1016/j.jhazmat.2009.03.137
9. Boonchan S, Britz ML, Stanley GA (2000). Degradation and mineralization of high-molecular-weight polycyclic aromatic hydrocarbons by defined fungal-bacterial cocultures. *Applied and Environmental Microbiology* 66(3):1007–1019. doi:10.1128/AEM.66.3.1007-1019.2000
10. Wackett LP, Gibson DT (1988). Degradation of trichloroethylene by toluene dioxygenase in whole-cell studies with *Pseudomonas putida* F1. *Applied and Environmental Microbiology* 54(7):1703–1708. doi:10.1128/aem.54.7.1703-1708.1988
11. Field JA, Sierra-Alvarez R (2008). Microbial degradation of chlorinated dioxins. *Chemosphere* 71(6):1005–1018. doi:10.1016/j.chemosphere.2007.10.039
12. Lovley DR, Phillips EJ (1994). Reduction of chromate by *Desulfovibrio vulgaris* and its c3 cytochrome. *Applied and Environmental Microbiology* 60(2):726–728. doi:10.1128/aem.60.2.726-728.1994
13. Lovley DR, Widman PK, Woodward JC, Phillips EJ (1993). Reduction of uranium by cytochrome c3 of *Desulfovibrio vulgaris*. *Applied and Environmental Microbiology* 59(11):3572–3576. doi:10.1128/aem.59.11.3572-3576.1993
14. Li X, Li J, Zhao Q, et al. (2023). Physiological, biochemical, and genomic elucidation of the *Ensifer adhaerens* M8 strain with simultaneous arsenic oxidation and chromium reduction. *Journal of Hazardous Materials* 441:129862. doi:10.1016/j.jhazmat.2022.129862
15. Wang J, Chen C (2006). Biosorption of heavy metals by *Saccharomyces cerevisiae*: a review. *Biotechnology Advances* 24(5):427–451. doi:10.1016/j.biotechadv.2006.03.001
16. Chen SH, Cheow YL, Ng SL, Ting ASY (2019). Mechanisms for metal removal established via electron microscopy and spectroscopy: a case study on metal tolerant fungi *Penicillium simplicissimum*. *Journal of Hazardous Materials* 362:394–402. doi:10.1016/j.jhazmat.2018.08.077

17. Diels L, Van Roy S, Taghavi S, Van Houdt R (2009). From industrial sites to environmental applications with *Cupriavidus metallidurans*. *Antonie van Leeuwenhoek* 96(2):247–258. doi:10.1007/s10482-009-9361-4
18. Ghosh U, Luthy RG, Cornelissen G, et al. (2011). In-situ sorbent amendments: a new direction in contaminated sediment management. *Environmental Science & Technology* 45(4):1163–1168. doi:10.1021/es102694h
19. Moreno Jiménez E, Aceña-Heras S, Frišták V, et al. (2018). The effect of biochar amendments on phenanthrene sorption, desorption and mineralisation in different soils. *PeerJ* 6:e5074. doi:10.7717/peerj.5074
20. Fabregat-Palau J, Vidal M, Rigol A (2022). Examining sorption of perfluoroalkyl substances (PFAS) in biochars and other carbon-rich materials. *Chemosphere* 302:134733. doi:10.1016/j.chemosphere.2022.134733
21. Hilber I, Blum F, Leifeld J, et al. (2012). Quantitative determination of PAHs in biochar: a prerequisite to ensure its quality and safe application. *Journal of Agricultural and Food Chemistry* 60(12):3042–3050. doi:10.1021/jf205278v
22. Belimov AA, Safronova VI, Sergeyeva TA, et al. (2001). Characterization of plant growth promoting rhizobacteria isolated from polluted soils and containing 1-aminocyclopropane-1-carboxylate deaminase. *Canadian Journal of Microbiology* 47(7):642–652. doi:10.1139/w01-062
23. Belimov AA, Shaposhnikov AI, Azarova TS, et al. (2020). Microbial consortium of PGPR, rhizobia and arbuscular mycorrhizal fungus makes pea mutant SGEcd(t) comparable with Indian mustard in cadmium tolerance and accumulation. *Plants* 9(8):975. doi:10.3390/plants9080975
24. Sun L, Cao X, Li M, et al. (2017). Enhanced bioremediation of lead-contaminated soil by *Solanum nigrum* L. with *Mucor circinelloides*. *Environmental Science and Pollution Research* 24(10):9681–9689. doi:10.1007/s11356-017-8637-x
25. Yao S, Zhou B, Duan M, et al. (2023). Combination of biochar and *Trichoderma harzianum* can improve the phytoremediation efficiency of *Brassica juncea* and the rhizosphere micro-ecology in cadmium and arsenic contaminated soil. *Plants* 12(16):2939. doi:10.3390/plants12162939
26. Biome Makers / BeCrop. *Independent lab analysis (Biome Makers lab profile), Elm Dirt Bloom Juice*. Unpublished laboratory report; available on request.
27. Sewell HL, Criddle CS, Woo SG, et al. (2024). *Pseudomonas stutzeri* KC carries the *pdt* genes for carbon tetrachloride degradation on an integrative and conjugative element. *Microbial Physiology* 34(1). doi:10.1159/000538783
28. Pradeep V, Subbaiah UM (2015). Repeated batch and continuous degradation of chlorpyrifos by *Pseudomonas putida*. *Journal of Environmental Science and Health, Part B* 50(4):346–360. doi:10.1080/03601234.2015.1000180
29. Gilani RA, Rafique M, Rehman A, et al. (2016). Biodegradation of chlorpyrifos by bacterial genus *Pseudomonas*. *Journal of Basic Microbiology* 56(2):105–119. doi:10.1002/jobm.201500336
30. Woiski C, Dobslaw D, Engesser KH (2020). Isolation and characterization of 2-butoxyethanol degrading bacterial strains. *Biodegradation* 31(3):153–169. doi:10.1007/s10532-020-09900-3
31. Zhang W, Chen L, Liu D (2012). Characterization of a marine-isolated mercury-resistant *Pseudomonas putida* strain SP1 and its potential application in marine mercury reduction. *Applied Microbiology and Biotechnology* 93(3):1305–1314. doi:10.1007/s00253-011-3454-5
32. Dybas MJ, Hyndman DW, Heine R, et al. (2002). Development, operation, and long-term performance of a full-scale biocurtain utilizing bioaugmentation. *Environmental Science & Technology* 36(16):3635–3644.

doi:10.1021/es0114557

33. Bosch R, García-Valdés E, Moore ER (1999). Genetic characterization and evolutionary implications of a chromosomally encoded naphthalene-degradation upper pathway from *Pseudomonas stutzeri* AN10. *Gene* 236(1):149–157. doi:10.1016/s0378-1119(99)00241-3
34. Zawadzka AM, Crawford RL, Paszczynski AJ (2007). Pyridine-2,6-bis(thiocarboxylic acid) produced by *Pseudomonas stutzeri* KC reduces chromium(VI) and precipitates mercury, cadmium, lead and arsenic. *BioMetals* 20(2):145–158. doi:10.1007/s10534-006-9022-2
35. Ripp S, Nivens DE, Werner C, Sayler GS (2000). Bioluminescent most-probable-number monitoring of a genetically engineered bacterium during a long-term contained field release. *Applied Microbiology and Biotechnology* 53(6):736–741. doi:10.1007/s002530000343
36. Yen KM, Karl MR, Blatt LM, et al. (1991). Cloning and characterization of a *Pseudomonas mendocina* KR1 gene cluster encoding toluene-4-monooxygenase. *Journal of Bacteriology* 173(17):5315–5327. doi:10.1128/jb.173.17.5315-5327.1991
37. McClay K, Fox BG, Steffan RJ (1996). Chloroform mineralization by toluene-oxidizing bacteria. *Applied and Environmental Microbiology* 62(8):2716–2722. doi:10.1128/aem.62.8.2716-2722.1996
38. Ho MT, Li MSM, McDowell T, et al. (2020). Characterization and genomic analysis of a diesel-degrading bacterium, *Acinetobacter calcoaceticus* CA16, isolated from Canadian soil. *BMC Biotechnology* 20(1):39. doi:10.1186/s12896-020-00632-z
39. Lu Q, Sun X, Jiang Z, et al. (2022). Effects of *Comamonas testosteroni* on dissipation of polycyclic aromatic hydrocarbons and the response of endogenous bacteria for soil bioremediation. *Environmental Science and Pollution Research* 29(54):82351–82364. doi:10.1007/s11356-022-21497-z
40. Zheng S, Su J, Wang L, et al. (2014). Selenite reduction by the obligate aerobic bacterium *Comamonas testosteroni* S44 isolated from a metal-contaminated soil. *BMC Microbiology* 14:204. doi:10.1186/s12866-014-0204-8
41. Luo X, Guo J, Lan Y, et al. (2023). Toxic response of antimony in the *Comamonas testosteroni* and its application in soil antimony bioremediation. *Environment International* 177:108040. doi:10.1016/j.envint.2023.108040
42. Coleman NV, Mattes TE, Gossett JM, Spain JC (2002). Phylogenetic and kinetic diversity of aerobic vinyl chloride-assimilating bacteria from contaminated sites. *Applied and Environmental Microbiology* 68(12):6162–6171. doi:10.1128/AEM.68.12.6162-6171.2002
43. Mattes TE, Coleman NV, Spain JC, Gossett JM (2005). Physiological and molecular genetic analyses of vinyl chloride and ethene biodegradation in *Nocardioides* sp. strain JS614. *Archives of Microbiology* 183(2):95–106. doi:10.1007/s00203-004-0749-2
44. Mergeay M, Monchy S, Vallaëys T, et al. (2003). *Ralstonia metallidurans*, a bacterium specifically adapted to toxic metals: towards a catalogue of metal-responsive genes. *FEMS Microbiology Reviews* 27(2–3):385–410. doi:10.1016/S0168-6445(03)00045-7
45. Lerch TZ, Dignac MF, Barriuso E, et al. (2007). Tracing 2,4-D metabolism in *Cupriavidus necator* JMP134 with ¹³C-labelling technique and fatty acid profiling. *Journal of Microbiological Methods* 71(2):162–174. doi:10.1016/j.mimet.2007.08.003
46. Kumar A, Trefault N, Olaniran AO (2016). Microbial degradation of 2,4-dichlorophenoxyacetic acid: insight into the enzymes and catabolic genes involved, their regulation and biotechnological implications. *Critical Reviews in Microbiology* 42(2):194–208. doi:10.3109/1040841X.2014.917068

47. Asatiani NV, Abuladze MK, Kartvelishvili TM, et al. (2004). Effect of chromium(VI) action on *Arthrobacter oxydans*. *Current Microbiology* 49(5):321–326. doi:10.1007/s00284-004-4351-2
48. Parthasarathy S, Parapatla H, Nandavaram A, et al. (2016). Organophosphate hydrolase is a lipoprotein and interacts with Pi-specific transport system to facilitate growth of *Brevundimonas diminuta* using OP insecticide as source of phosphate. *Journal of Biological Chemistry* 291(14):7774–7785. doi:10.1074/jbc.M116.715110
49. Hoffmann D, Kleinstaub S, Müller RH, Babel W (2003). A transposon encoding the complete 2,4-dichlorophenoxyacetic acid degradation pathway in the alkali-tolerant strain *Delftia acidovorans* P4a. *Microbiology* 149(9):2545–2556. doi:10.1099/mic.0.26260-0
50. Schaefer S, Steudtner R, Hübner R, et al. (2021). Effect of temperature and cell viability on uranium biomineralization by the uranium mine isolate *Penicillium simplicissimum*. *Frontiers in Microbiology* 12:802926. doi:10.3389/fmicb.2021.802926
51. Li X, Lan X, Feng X, et al. (2021). Biosorption capacity of *Mucor circinelloides* bioaugmented with *Solanum nigrum* L. for the cleanup of lead, cadmium and arsenic. *Ecotoxicology and Environmental Safety* 212:112014. doi:10.1016/j.ecoenv.2021.112014
52. Maymó-Gatell X, Chien Y, Gossett JM, Zinder SH (1997). Isolation of a bacterium that reductively dechlorinates tetrachloroethene to ethene. *Science* 276(5318):1568–1571. doi:10.1126/science.276.5318.1568
53. National Transportation Safety Board (2024). "Failed Wheel Bearing Caused Norfolk Southern Train Derailment in East Palestine, Ohio." Press release, June 25, 2024. [ntsb.gov](https://www.ntsb.gov)
54. U.S. EPA. East Palestine, Ohio Train Derailment: Operational Updates. [epa.gov](https://www.epa.gov)
55. Lard ML, Eichler SE, Gao P, et al. (2025). Soil contamination by environmentally persistent free radicals and dioxins following train derailment in East Palestine, OH. *Environmental Science: Processes & Impacts* 27(3):729–740. doi:10.1039/d4em00609g
56. Chen G, Rosolina S, Padilla-Crespo E, et al. (2024). Natural attenuation potential of vinyl chloride and butyl acrylate released in the East Palestine, Ohio train derailment accident. *Environmental Science & Technology* 58(40):17743–17755. doi:10.1021/acs.est.4c04198
57. L'Abbée JB, Barriault D, Sylvestre M (2005). Metabolism of dibenzofuran and dibenzo-p-dioxin by the biphenyl dioxygenase of *Burkholderia xenovorans* LB400 and *Comamonas testosteroni* B-356. *Applied Microbiology and Biotechnology* 67(4):506–514. doi:10.1007/s00253-004-1791-3
58. Li Q, Wang X, Yin G, et al. (2009). New metabolites in dibenzofuran cometabolic degradation by a biphenyl-cultivated *Pseudomonas putida* strain B6-2. *Environmental Science & Technology* 43(22):8635–8642. doi:10.1021/es901991d