Phytoremediation, Bioremediation, and Mycoremediation - using life to remediate contaminated sites

In the last few hundred years, humans have discovered and created a wide range of dangerous substances. And through industry, accidents, and poor waste management, we've contaminated land and water all over the earth with them. Cleaning up these sites is challenging and expensive, involving chemical washes, tremendous heat, or eternal storage of contaminated material in a landfill. And for the contaminated habitats, the cure is often almost as bad as the disease, with huge swaths of land clearcut, the soil excavated and replaced, and the old growth forests replaced with fields of fresh seedlings. But there is a surprisingly-recent field of study around using certain plants, fungi, and microorganisms with special capabilities to extract, contain, or even destroy the contaminants without otherwise disturbing the habitat. When this works, it's not just easier on the land but cheaper too. This is a quite new field, with new breakthroughs every year, and there's a sense that many otherwise-familiar organisms have special abilities we just haven't discovered yet. But the gist is already pretty clear: phytoremediation, bioremediation, and mycoremediation are powerful toolkits for eliminating some of the worst poisons humanity has ever produced. Most of what we need to remediate these contaminants already exists - in the right circumstances plants, bacteria, and fungi can eliminate things we've already written off as forever chemicals in a matter of weeks. Learning how to work with them, what species to match with what job and how to produce those right circumstances seems to be the work ahead of us.

This page is an attempt to gather up a broad strokes introduction to a quite new and technical field. The info here should introduce the contaminants, the present-day standards for remediation, the various bioremediation methods, and my own system for narrowing down your options and finding a plant/fungus/bacteria that fits your setting and situation.

Unfortunately, while I'd absolutely love to put together a catalogue of all known/potential phytoremediation/bioremediation/mycoremediation species, the contaminants they help with (and how they do it), and their ranges and invasive status, the scope of that project would be worthy of its own full time academic research. That said, the guide towards the end has helped me with my own research while trying to find options that fit my region, so perhaps it'll help you too!

One last thing: I want to note up-front that though I've done my best to get this information correct, I'm in no ways an expert on phytoremediation, bioremediation, mycoremediation, environmental restoration, chemistry, botany, or biology. The topics covered here involve a wide range of hazardous substances and practices for cleaning them up, and done incorrectly this stuff can kill you fast or slow! Please do not treat this writing research as real-life cleanup advice without vetting it with someone who actually knows what they're talking about. Don't die because you got your bioremediaton advice from a guy who's highest mark in biology was a 'C' in high school.

Contaminants

Defining Contaminated Sites

Contaminated sites are places where the soil, water, air, plants, or some combination contain a hazardous substance at a level considered harmful to humans or the wider ecosystem.

Sites can be contaminated intentionally/negligently, through accidents like truck wrecks, or through natural disasters such as hurricanes or floods. Sources of contaminants include manufacturing, transportation, mining, agriculture, waste management, energy production, military activities, and even naturally occurring sources (after all, lead, arsenic and asbestos are all mined from the ground). Many contaminants are harmful at a certain level, so and some (like certain metals) are beneficial or even necessary at a low dose. Others are bad at any dose because they're so harmful, because they accumulate in the body, or both.

Exposure Pathways

https://www.epa.gov/ecobox/epa-ecobox-tools-exposure-pathways-exposure-pathways-era

One consideration which is included in assessing sites today is what will be harmed and how. In some countries, a pathway to human harm is part of the legal definition of a contaminated site. An exposure pathway defines the process by which a contaminant may come in contact with receptors (such as people, animals, farmland, fish, or the general environment but definitions vary). A pathway could be people eating contaminated food, or chemicals in the soil entering the groundwater and poisoning nearby wells. This could even include the risk posed by people riding dirt bikes in a former lead mine and kicking up dust, or children playing on heavy-metal-rich slag heaps in a factory town.

Some contaminated sites are considered lower priority because they pose little risk to human health and the environment because the level of contamination is low or the chance of exposure to toxics is low.

Other contaminated sites can pose greater risks to human health and the environment because the chemicals at these sites may exist in the environment for long periods of time or move easily through the environment. These sites must be carefully managed through containment, institutional controls such as access restriction, and/or cleanup to prevent harm to humans, wildlife, or the surrounding environment both on- and offsite.

Specifics are obviously going to vary based on where your story is set - different legal systems, unions, nations, provinces, states, even municipalities will have their own lists of which contaminants they track, the levels they consider concerning vs safe, and proper response procedures.

Its possible that a solarpunk society would track and remediate far more contaminants than our current societies do, or would have stricter standards on acceptable levels. They might also be less human-centric in their risk assessments, tracking and remediating harm to the environment and species we share our world with, even if no human appears to be endangered by a particular site.

https://www.epa.gov/superfund/contaminants-superfund-sites

Types of Contaminants and Where They Come From

One thing I've realized while working on these projects: there are no neat lists of every dangerous substance. Even the lists of what this or that country or organization tracks are frequently asterisk'ed with entries including entire families of thousands of related chemicals, definitional nuances, and notes on how the dose makes the poison - and those lists are often incomplete themselves!

Nonetheless, and with the confidence of the layman, I've attempted to break the most common and dangerous contaminants into the following broad categories:

Heavy Metals / Toxic Metals

A heavy metal is a metal-like element noted for its potential toxicity, such as cadmium, lead, and mercury. While trying to find a full list of heavy metals for this page, I learned that there's some disagreement on the terminology around 'heavy metals' as being misleading or meaningless (not all heavy metals are toxic and some toxic metals are not elementally heavy), and that some people prefer 'toxic metals' which probably does the job better. That said, I've been reading papers on phytoremediation and environmental restoration for two years now without noticing the dispute, so 'heavy metal' still seems to be a good search term in this context.

It's also worth noting that some of these metals are nutritionally essential for animal or plant life but are considered toxic in high doses or other forms.

Entries with * are from the EPA Clean Water Act's list of Priority Pollutants. Entries with a ^ are RCRA-8 (Resource Conservation and Recovery Act) metals.

- **Aluminum (Al)** - Aluminum is the second most-produced metal after iron. It is used in vehicles, packaging, building and construction, in conductor alloys, motors, and generators, transformers, capacitors, and in a variety of household items. Aluminium is generally used because of its corrosion resistance, non-pyrophoricity, and mechanical strength. High levels of aluminium occur near mining sites; small amounts of aluminium are released to the environment at coal-fired power plants or incinerators. In water, aluminium acts as a toxic agent on gill-breathing animals such as fish when the water is acidic, in which aluminium may precipitate on gills, which causes loss of plasma- and hemolymph ions leading to osmoregulatory failure. Aluminium is primary among the factors that reduce plant growth on acidic soils. Although it is generally harmless to plant growth in pH-neutral soils, in acid soils the concentration of toxic Al^{3+} cations increases and disturbs root growth and function.
- **Antimony (Sb)** * - The most common applications for metallic antimony are in alloys with lead and tin, which have improved properties for solders, bullets, and plain bearings. It improves the rigidity of lead-alloy plates in lead–acid batteries. Antimony trioxide is also used in halogen-containing flame retardants and as a dopant in semiconductor devices. Because Antimony is used as a co-active fire retardant and as an additive or catalyst in plastics products, it can be found in polymeric, consumable, and daily-use products, including plastics and plastic fragments, rubber, fabrics, fibers, and foams. Antimony is introduced into soils, sediments, and aquatic environments from various sources such as weathering of sulfide ores, leaching of mining wastes, and anthropogenic activities. High Sb concentrations are toxic to ecosystems and potentially to public health via the accumulation in food chain. Although Sb is poisonous and carcinogenic to humans, the exact mechanisms causing toxicity still remain unclear.
- **Arsenic (As)** *^ - Arsenic is a notoriously toxic metalloid. It has had many uses: in alloys of lead (for example, in car batteries and ammunition), as a common n-type dopant in semiconductor electronic devices, and a component of the III–V compound semiconductor gallium arsenide. Arsenic and its compounds, especially the trioxide, are used in the production of pesticides, treated wood products, herbicides, and insecticides. The United States Agency for Toxic Substances and Disease Registry ranked arsenic number 1 in its 2001 prioritized list of hazardous substances at Superfund sites. Arsenic is classified as a group-A carcinogen.

- **Barium (Ba)** ^ - Barium is used in various industrial applications, including oil and gas drilling, drill bits, medical imaging, fireworks, and in the production of fluorescent lighting and ceramic tiles. In its pure form, Barium is toxic and can be hazardous to human health if ingested or inhaled, leading to gastrointestinal, cardiovascular, respiratory, and muscular issues. It can produce toxic or corrosive fumes when heated. The US EPA considers it unlikely that barium is carcinogenic when consumed orally. Inhaled dust containing insoluble barium compounds can accumulate in the lungs, causing a benign condition called baritosis.
- **Beryllium (Be)** * - Beryllium is a relatively rare element and occurs naturally in the Earth's crust, in coal, and in various minerals. Beryllium is used as an alloy with other metals in aerospace, electronics and mechanical industries. The major emission sources to the atmosphere are the combustion of coal and fossil fuels and the incineration of municipal solid waste. The general public is exposed to Be through inhalation of air and the consumption of Be-contaminated food and drinking water.
- **Cadmium (Cd)** *^ - Cadmium is a naturally occurring toxic metal with common exposure in industrial workplaces, plant soils, and from smoking. It occurs as a minor component in most zinc ores and is a byproduct of zinc production. It was used in the 1900s as a corrosion-resistant plating on steel, and cadmium compounds are used as red, orange, and yellow pigments, to color glass, and to stabilize plastic. Cadmium's use is generally decreasing because it is toxic, and nickel–cadmium batteries have been replaced. One of its few new uses is in cadmium telluride solar panels. Cadmium is considered an environmental pollutant hazardous to living organisms.
- **Chromium (Cr)** *^ - Chromium is valued for its high corrosion resistance and hardness. Metallic chromium can be added to steel to form stainless steel, which is highly resistant to corrosion and discoloration. Stainless steel and chrome plating (electroplating with chromium) together comprise 85% of the commercial use though chromates are also used to manufacture leather products, paints, cement, mortar and anti-corrosives. While chromium metal and Cr(III) ions are considered non-toxic, chromate and its derivatives, often called “hexavalent chromium”, is toxic and carcinogenic. According to the European Chemicals Agency (ECHA), chromium trioxide that is used in industrial electroplating processes is a “substance of very high concern” (SVHC). The acute toxicity of chromium(VI) is due to its strong oxidant properties. After it reaches the blood stream, it damages the kidneys, the liver and blood cells through oxidation reactions. Hemolysis, renal, and liver failure result. Contact with products containing chromates can lead to allergic contact dermatitis and irritant dermatitis, resulting in ulceration of the skin, sometimes referred to as “chrome ulcers”.
- **Cobalt (Co)** - Cobalt is primarily used in lithium-ion batteries, and in the manufacture of magnetic, wear-resistant and high-strength alloys. The compounds cobalt silicate and cobalt(II) aluminate (CoAl2O4, cobalt blue) give a distinctive deep blue color to glass, ceramics, inks, paints and varnishes. Cobalt is also used in the petroleum industry as a catalyst when refining crude oil to purge it of sulfur. Cobalt consumption can be fatal and chronic cobalt ingestion has caused serious health problems at doses far less than the lethal dose. It causes respiratory problems when inhaled and causes skin problems when touched; cobalt is a major cause of contact dermatitis. It is also suspected of causing cancer by the the International Agency for Research on Cancer (IARC).
- **Copper (Cu)** * - Copper is a soft, malleable, and ductile metal with very high thermal and electrical conductivity (you've likely seen it in electrical wiring and cooking tools alike). Copper is one of the few native metals, meaning metals that occur naturally in a directly usable, unalloyed metallic form. It is an essential trace element in plants and animals but as with most metals it has an upper dose, which can be easy to reach around smelting and other industrial sites. The major sources of releases to water are mining operations, agriculture, sludge from publicly owned treatment works (POTWs), and municipal and industrial solid waste. Mining and milling contribute the most waste. Loss of biodiversity has been reported in environments

contaminated with copper.

- **Iron (Fe)** - Iron is a common metal which is important both to human civilization and to our biology. Iron alloys, such as steel, stainless steel, cast iron and special steels, are by far the most common industrial metals, due to their mechanical properties and low cost. Fe plays an essential role in the metabolism, but prolonged overload may lead to significant health risks and adverse effects on human health. Overdoses of ingested iron can cause damage to DNA, proteins, lipids, and other cellular components. Damage to the cells of the gastrointestinal tract can also prevent them from regulating iron absorption, leading to further increases in blood levels. Iron typically damages cells in the heart, liver and elsewhere, causing adverse effects that include coma, metabolic acidosis, shock, liver failure, coagulopathy, long-term organ damage, and even death. An overabundance of iron in marine environments can also harm fish and aquatic plants.
- **Lead (Pb)** *^ - Lead is one of the big ones you'll find on every list of contaminants people worry about. Its chemical and physical characteristics, such as its malleability, low melting point and resistance to corrosion, make it useful in all sorts of things including paint, ceramics, pipes and plumbing materials, solders, gasoline, batteries, ammunition and cosmetics. Lead is also highly toxic to humans and the environment. It is a cumulative toxicant particularly hazardous to young children and pregnant women - the growing bodies of babies and children absorb more lead than adults do and their brains and nervous systems are more sensitive to the damaging effects. No safe level of lead exposure has been established. Once taken into the body, lead can cause permanent damage to the neurological and cardiovascular systems.
- **Manganese (Mn)** - Manganese is a transition metal with many industrial alloy uses, particularly in stainless steels. Manganese oxide is used as an oxidising agent, as a rubber additive, and in glass making, fertilizers, and ceramics. Manganese sulfate can be used as a fungicide.Methylcyclopentadienyl manganese tricarbonyl (MMT) is an additive developed to replace lead compounds for gasolines to improve the octane rating. Manganese is essential for human health, albeit in milligram amounts. Manganese overexposure is most frequently associated with a Parkinsonism-like neurological disorder called manganism. It is also known to bioaccumulate in and harm marine organisms including fish, crustaceans, mollusks, and echinoderms.
- **Mercury (Hg)** *^ - this is another big one. Mercury is used in thermometers, barometers, manometers, sphygmomanometers, float valves, mercury switches, mercury relays, fluorescent lamps and other devices, though the safety hazards have limited its use in recent years. Exposure to mercury and mercury-containing organic compounds is toxic to the nervous system, immune system and kidneys of humans and other animals; mercury poisoning can result from exposure to water-soluble forms of mercury either directly or through mechanisms of biomagnification.
- **Molybdenum (Mo)** - Molybdenum can withstand extreme temperatures without significantly expanding or softening, making it useful in environments of intense heat, including military armor, aircraft parts, electrical contacts, industrial motors, and supports for filaments in light bulbs. Molybdenum dusts and fumes, generated by mining or metalworking, can be toxic, especially if ingested (including dust trapped in the sinuses and later swallowed). Chronic exposure to 60 to 600 mg/m3 can cause symptoms including fatigue, headaches and joint pains.At levels of 5000 mg/m3, molybdenum is immediately dangerous to life and health.
- **Nickel (Ni)** * - Nickel is a hard and ductile transition metal. It is mostly used in the production of stainless steel and other alloys. The small remainder is in a wide range of other applications such as in rechargeable batteries,including those in electric vehicles (EVs), in coins, as a catalyst for hydrogenation, in cathodes for rechargeable batteries, in pigments, and in metal surface treatments. Nickel is not a cumulative poison, but larger doses or chronic inhalation exposure may be toxic, even carcinogenic, and constitute an occupational hazard.
- **Selenium (Se)** *^ - Currently the largest commercial use of selenium, accounting for about

50% of consumption, is for the production of glass, where it produces a red color. It used to be common in a wide range of uses in electronics, including in photocells and batteries, but has mostly been replaced. It was used in very old solar panels and has reappeared in very modern ones. Selenium is used with bismuth in brasses to replace lead, which is more toxic. Although trace amounts of selenium are necessary for cellular function in many animals, including humans, both elemental selenium and (especially) selenium salts are toxic in even small doses, causing selenosis. Selenium is bioaccumulated in aquatic habitats, which results in higher concentrations in organisms than the surrounding water. Selenium poisoning of water systems may result whenever new agricultural run-off courses through dry lands. Selenium pollution of waterways also occurs when selenium is leached from coal flue ash, mining and metal smelting, crude oil processing, and landfills. High selenium levels in waterways were found to cause congenital disorders in oviparous species, including wetland birds and fish.

- **Silver (Ag)** *^ - The major use of silver besides coinage throughout most of history was in the manufacture of jewellery and other general-use items, such as table silver for cutlery, for which silver is highly suited due to its antibacterial properties. In the modern day it sees use in medicine, where silver is incorporated into wound dressings and used as an antibiotic coating in medical devices, and in electronics, where it is used as a conductor and in the manufacture of semiconductor devices, circuits, and their components. Silver compounds have low toxicity compared to those of most other heavy metals, as they are poorly absorbed by the human body when ingested, but it is still a priority pollutant and considered toxic to soil microorganisms and avian and mammalian species. Its adverse impacts include reduced growth and reproduction and increased mortality.
- **Thallium (Ti)** * - The odorless and tasteless thallium sulfate was once widely used as rat poison and ant killer. Thallium(I) bromide and thallium(I) iodide crystals have been used as infrared optical materials, because they are harder than other common infrared optics, and because they have transmission at significantly longer wavelengths. It is part of alloys which are used in thermometers and low-temperature switches, and in electronics like photoresistors and bolometers. Thallium and its compounds are extremely toxic, with numerous recorded cases of fatal thallium poisoning. Contact with skin is dangerous, and adequate ventilation is necessary when melting this metal. Thallium(I) compounds have a high aqueous solubility and are readily absorbed through the skin, and care should be taken to avoid this route of exposure, as cutaneous absorption can exceed the absorbed dose received by inhalation at the permissible exposure limit (PEL).
- **Zinc (Zn)** * - Zinc is most commonly used as an anti-corrosion agent, and galvanization (coating of iron or steel) is its most familiar form. It also plays an important role in batteries and various alloys, in varistors and photocopying products, as a white pigment in paints and as a catalyst in the manufacture of rubber to disperse heat. Zinc chloride is often added to lumber as a fire retardant and sometimes as a wood preservative. Zinc sulfide (ZnS) is used in luminescent pigments such as on the hands of clocks, X-ray and television screens, and luminous paints. Although Zinc is an essential trace element for humans, animals, plants and for microorganisms and is necessary for both prenatal and postnatal development, excess zinc can be harmful. Excessive absorption of zinc suppresses copper and iron absorption and the free zinc ion in solution is highly toxic to plants, invertebrates, and even vertebrate fish. Zinc in excess of 500 ppm in soil interferes with the plant absorption of other essential metals, such as iron and manganese

Persistent Organic Pollutants (POPs)

POPs are a broad category of organic compounds that are toxic, adversely affecting human health or the environment. They are persistent in the environment and able to last for years before breaking down. They're both very able to spread far from their source, and to bioaccumulate in fatty tissue in humans and other animals.

You can find a good deal of information on them at this page which is (at time of writing, Feb 2026) still maintained by the EPA. This similar writeup by the UN provides more information on the Caribbean.

Put simply, POPs are a long list of chemicals produced for various industrial and household practices, or by accident as other chemicals broke down or interacted in the environment. They are tracked by the United Nations Environment Programme (UNEP) Stockholm Convention - the original 12 POPs are often called the Dirty Dozen but more have been added since. They include the following, though it's worth noting that some of these are basically entire categories or broad suites of similar chemicals themselves:

- **Aldrin** - an insecticide used in soils to kill termites, grasshoppers, Western corn rootworm, and others, is also known to kill birds, fish, and humans. Humans are primarily exposed to aldrin through dairy products and animal meats.
- **Chlordane** - an insecticide used to control termites and on a range of agricultural crops including small grains, potatoes, sugarcane, sugar beets, fruits, nuts, citrus, and cotton. Used on home lawn and garden pests. Also used extensively to control termites. It is known to be lethal in various species of birds, including mallard ducks, bobwhite quail, and pink shrimp; it is a chemical that remains in the soil with a reported half-life of one year. Chlordane has been postulated to affect the human immune system and is classified as a possible human carcinogen. Chlordane air pollution is believed the primary route of human exposure.
- **DDT (Dichlorodiphenyltrichloroethane)** - possibly the most infamous POP. It was widely used as insecticide during WWII to protect against malaria and typhus. After the war, DDT was used as an agricultural insecticide. In 1962, the American biologist Rachel Carson published Silent Spring, describing the impact of DDT spraying on the US environment and human health. DDT's persistence in the soil for up to 10–15 years after application has resulted in widespread and persistent DDT residues throughout the world including the arctic, even though it has been banned or severely restricted in most of the world. DDT is toxic to many organisms including birds where it is detrimental to reproduction due to eggshell thinning. DDT can be detected in foods from all over the world and food-borne DDT remains the greatest source of human exposure. Short-term acute effects of DDT on humans are limited, however long-term exposure has been associated with chronic health effects including increased risk of cancer and diabetes, reduced reproductive success, and neurological disease.
- **Dieldrin** - a pesticide used to control termites, textile pests, insect-borne diseases and insects living in agricultural soils. In soil and insects, aldrin can be oxidized, resulting in rapid conversion to dieldrin. Dieldrin's half-life is approximately five years. Dieldrin is highly toxic to fish and other aquatic animals, particularly frogs, whose embryos can develop spinal deformities after exposure to low levels. Dieldrin has been linked to Parkinson's disease, breast cancer, and classified as immunotoxic, neurotoxic, with endocrine disrupting capacity. Dieldrin residues have been found in air, water, soil, fish, birds, and mammals. Human exposure to dieldrin primarily derives from food.
- **Dioxins and furans** - Unintentionally produced during most forms of combustion, including burning of municipal and medical wastes, backyard burning of trash, and industrial processes. Also can be found as trace contaminants in certain herbicides (including Agent Orange), wood preservatives, and in PCB mixtures. Dioxins are typically emitted from the burning of hospital waste, municipal waste, and hazardous waste, along with automobile emissions, peat, coal, and wood. Dioxins have been associated with several adverse effects in humans, including immune and enzyme disorders, chloracne, and are classified as a possible human carcinogen. In

laboratory studies of dioxin effects an increase in birth defects and stillbirths, and lethal exposure have been associated with the substances. Food, particularly from animals, is the principal source of human exposure to dioxins.

- **Endrin** - an insecticide sprayed on the leaves of crops, and used to control rodents. Endrin is highly toxic to aquatic animals and humans as a neurotoxin. Human exposure results primarily through food. The chemical has a long half-life in soil for up to 12 years. This one is a bit unusual in that Animals can metabolize endrin, so fatty tissue accumulation is not an issue.
- **Heptachlor** - a pesticide primarily used to kill soil insects and termites, along with cotton insects, grasshoppers, other crop pests, and malaria-carrying mosquitoes. Heptachlor, even at very low doses has been associated with the decline of several wild bird populations – Canada geese and American kestrels. In laboratory tests have shown high-dose heptachlor as lethal, with adverse behavioral changes and reduced reproductive success at low-doses, and is classified as a possible human carcinogen. Human exposure primarily results from food.
- **Hexachlorobenzene** - Fungicide used for seed treatment. Also an industrial chemical used to make fireworks, ammunition, synthetic rubber, and other substances. Also unintentionally produced during combustion and the manufacture of certain chemicals. Also an impurity in certain pesticides. HCB-treated seed grain consumption is associated with photosensitive skin lesions, colic, debilitation, and a metabolic disorder called *porphyria turcica*, which can be lethal. Mothers can pass HCB to their infants through the placenta and breast milk, causing reproductive difficulty and infant death. Human exposure is primarily from food.
- **Mirex**- “Insecticide used to combat fire ants, termites, and mealybugs. Also used as a fire retardant in plastics, rubber, and electrical products. Mirex is one of the most stable and persistent pesticides, with a half-life of up to 10 years. Mirex is toxic to several plant, fish and crustacean species, with suggested carcinogenic capacity in humans. Humans are exposed primarily through animal meat, fish, and wild game.
- **Toxaphene** - an insecticide used on cotton, cereal, grain, fruits, nuts, and vegetables, for tick and mite control in livestock, and the EPA website says 'to kill unwanted fish in lakes'. Widespread toxaphene use in the US and chemical persistence, with a half-life of up to 12 years in soil, results in residual toxaphene in the environment. Toxaphene is highly toxic to fish, inducing dramatic weight loss and reduced egg viability. Human exposure primarily results from food. While human toxicity to direct toxaphene exposure is low, the compound is classified as a possible human carcinogen.
- **PCBs (Polychlorinated biphenyls)** - Used for a variety of industrial processes and purposes, including in electrical transformers and capacitors, as heat exchange fluids, as paint additives, in carbonless copy paper, and in plastics. Also unintentionally produced during combustion. Persistence varies with degree of halogenation, with an estimated half-life of 10 years. PCBs are toxic to fish at high doses, and associated with spawning failure at low doses. Human exposure occurs through food, and is associated with reproductive failure and immune suppression. Immediate effects of PCB exposure include pigmentation of nails and mucous membranes and swelling of the eyelids, along with fatigue, nausea, and vomiting. Effects are transgenerational, as the chemical can persist in a mother's body for up to 7 years, resulting in developmental delays and behavioral problems in her children. Food contamination has led to large scale PCB exposure.

The Stockholm Convention site and Wikipedia both have full lists of the POPs which have been added since 2001. As many of them are pesticides (and many of the above are pesticides) I thought I'd limit the ones I include here to other sources just to show the range of sources.

- **Decabromodiphenyl ether** - a flame retardant, commonly sold as decaBDE, which is added to polymers, textiles, adhesives, coatings and more. In addition to bioaccumulation potential, the Stockholm convention identified decaBDE as affecting human endocrine, reproductive, and

nervous systems.
- **Dechlorane plus** - a flame retardant structurally similar to Mirex. Added to the Stockholm Convention in 2023, research into human toxicology is ongoing.
- **Hexabromodiphenyl** - a flame retardant and possible human carcinogen. Like the related chemicals hexaBDE, heptaBDE, and octaBDE (see below), hexabromodiphenyl is an endocrine disruptor.
- **Hexabromodiphenyl** - a flame retardant and possible human carcinogen. Like the related chemicals hexaBDE, heptaBDE, and octaBDE (see below), hexabromodiphenyl is an endocrine disruptor.
- **Hexabromocyclododecane** - a flame retardant predominately used in foams and textiles that is highly toxic to aquatic organisms. Human toxicology studies are ongoing, but it shows neuroendocrine disruption and developmental toxicity in animal studies.
- **Hexabromodiphenyl ether (hexaBDE) and heptabromodiphenyl ether (heptaBDE)** - these are main components of the flame retardant octabromodiphenyl ether (octaBDE). Commercial octaBDE is highly persistent in the environment, whose only degradation pathway is through debromination and the production of bromodiphenyl ethers, which themselves can be toxic.
- **Hexachlorobutadiene (HCBD)** - is a byproduct of the production of other chlorinated compounds. HCBD is a possible human carcinogen and causes renal damage
- **Pentachlorobenzene (PeCB)** - a pesticide and unintentional byproduct. PeCB has also been used in PCB products, dyestuff carriers, as a fungicide, a flame retardant, and a chemical intermediate. This compound is moderately toxic to humans, whilst being highly toxic to aquatic organisms.
- **Perfluorooctanesulfonic acid (PFOS)** - These and related compounds are extremely persistent and readily biomagnify.
- **Tetrabromodiphenyl ether (tetraBDE) and pentabromodiphenyl ether (pentaBDE)** - these are industrial chemicals and the main components of commercial pentabromodiphenyl ether (pentaBDE). This pair of molecules have been detected in humans in all regions of the world.

PFAS (Per- and poly-fluoroalkyl substances)

PFAS are another broad category of manufactured chemicals that have been used in industry and consumer products since the 1940s. I often see them mentioned separately from POPs but many of them (such as PFOS and PFOA) are also persistent organic pollutants. There are thousands of different PFAS, some of which have been more widely used and studied than others. PFAS have been used in a wide variety of products including waterproof fabrics, nonstick pans, athletic clothing, carpets, shampoo, mobile phones, paint, furniture, adhesives, food packaging, firefighting foam, electrical insulation, and cosmetics.

Often called “forever chemicals”, PFAS move through soils and bioaccumulate in fish and wildlife, which are then eaten by humans. Residues are now commonly found in soil, rain, drinking water, and wastewater. Due to the large number of PFAS, it is challenging to assess the potential human health and environmental risks but some are known to be carcinogens or endocrine disruptors, and exposure to them has been linked to diseases and health conditions including cancers, ulcerative colitis, thyroid disease, suboptimal antibody response or decreased immunit.

This page by the EPA is still an excellent resource at time of writing. The wikipedia page is also quite useful.

Organophosphate Esters (OPEs)

OPEs are a functional group of similar chemicals found in Pesticides, Flame retardants, Plasticisers, Metal extractants, Surfactants, Nerve agents, Hydraulic fluids and lubricant additives. These compounds are highly toxic, show environmental persistence and accumulation, and contribute to numerous cases of poisoning and death each year. Like PFAS and phthalates, human exposure to OPEs appears widespread, originating from numerous products, the environment, and food. Their environmental persistence and toxicity raise serious concerns and their wide-scale dissemination as agricultural products has led to environmental accumulation and toxification of soil and water across the globe. They have been detected in the air as far away as Antarctica.

Depending on the nature of the exposure and the specific compound in question, OPEs have been linked to potentially adverse impacts on multiple human organ systems, including the respiratory, gastrointestinal, central nervous system, cardiovascular, and renal systems.

This category may overlap with some of the above, I'm not sure. At one time OPEs were considered to be a good alternative for the widely used polybrominated diphenyl ethers (PBDEs), which were listed as persistent organic pollutants (POPs) by the Stockholm Convention.

Volatile Organic Compounds (VOCs)

Many VOCs are human-made chemicals that are used and produced in the manufacture of paints, pharmaceuticals, and refrigerants. VOCs typically are industrial solvents, such as trichloroethylene; fuel oxygenates, such as methyl tert-butyl ether (MTBE); or by-products produced by chlorination in water treatment, such as chloroform. VOCs are often components of petroleum fuels, hydraulic fluids, paint thinners, and dry cleaning agents. VOCs are common ground-water contaminants.

VOCs are emitted by a wide array of products numbering in the thousands. Examples include: paints and lacquers, paint strippers, cleaning supplies, pesticides, building materials and furnishings, office equipment such as copiers and printers, correction fluids and carbonless copy paper, graphics and craft materials including glues and adhesives, permanent markers, and photographic solutions. Organic chemicals are widely used as ingredients in household products. Paints, varnishes, and wax all contain organic solvents, as do many cleaning, disinfecting, cosmetic, degreasing, and hobby products. Fuels are made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored.

Concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors.

VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. The ability of organic chemicals to cause health effects varies greatly from those that are highly toxic to those with no known health effects. As with other pollutants, the extent and nature of the health effect will depend on many factors including level of exposure and length of time exposed. Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment are among the immediate symptoms that some people have experienced soon after exposure to some organics.

Health effects include eye, nose, and throat irritation; headaches, loss of coordination, nausea, hearing disorders and damage to the liver, kidney, and central nervous system. Some VOCs are suspected or known to cause cancer in humans. Key signs or symptoms associated with exposure to VOCs include conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnea, declines in serum cholinesterase levels, nausea, vomiting, nose bleeding, fatigue, dizziness.

Asbestos

Asbestos is a group of naturally occurring, toxic and carcinogenic, fibrous silicate minerals, used for thousands of years for their fire-resistant and insulating properties. The visible fibers are themselves each composed of millions of microscopic “fibrils” that can be released by abrasion and other processes. Sometimes called the Miracle Mineral, Asbestos' ability to form a fireproof fabric made it useful in a variety of applications. These included thousands of materials in the construction industry such as fire-retardant coatings, concrete, bricks, pipes and fireplace cement, heat-, fire-, and acid-resistant gaskets, pipe insulation, ceiling insulation, fireproof drywall, flooring, roofing, sprayed coatings, pipe insulation, and Asbestos Insulating Board (AIB), and drywall joint compound. It also saw use in friction products such as automobile clutch, brake, and transmission parts. As well as general use in heat-resistant fabrics, packaging, gaskets, and coatings, even lawn furniture.

Some applications are considered to be more dangerous than others due to the amount of asbestos in the product and the material's friable nature.

Exposure to asbestos increases your risk of developing lung disease, such as lung cancer, mesothelioma, a rare form of cancer that is found in the thin lining of the lung, chest and the abdomen and heart, and asbestosis, a serious progressive, long-term, non-cancer disease of the lungs.

Compared to the impact on humans, the environmental pollution potential of asbestos products is often overlooked. Asbestos fibers are diverse in their physicochemical properties, and this diversity has a significant influence on their behavior in the environment. Recent research has confirmed that asbestos can be transported by water and spread to other parts of the environment.

Radioactive Contamination

Humans have been tinkering with radioactive substances for over a hundred years, often following insufficient safety practices. Sites can and have been contaminated through the mining, transportation, and refinement of materials for nuclear power, by the production of nuclear weapons, by the disposal of medical equipment and treatment solutions, and even by civilian factories which used radioactive materials, including radium and tritium, in manufacturing commercial products. Depending on the type of facility and the type of radiation released, contamination could be found in air, soil, liquids, or on equipment.

The following US EPA resource is still quite helpful if you need more information: https://www.epa.gov/radtown/radioactively-contaminated-sites

Existing Site Remediation Procedures

When it comes to cleaning up contaminated sites, phytoremediation is one of several options, each with its own advantages and disadvantages. Many of these practices are more invasive and expensive, but they're likely not going away, even if phytoremediation continues to improve. For sites which are badly contaminated, or which have multiple co-contaminants in one place, or where the cleanup is urgent to prevent further spread or to protect human communities, the most straightforward solution is going to remain digging out it out and remediating it elsewhere, under controlled conditions.

Physical Methods:

- **Soil excavation and removal**: This involves testing to find the extent of the contamination and digging out all or some of the contaminated soil. This can be really harsh on the site, often involving both clearcut logging and deep excavation. The site crew then brings in fresh fill (possibly after laying down a barrier if they weren't able to remove contaminants under a certain depth for cost reasons), and plant new trees to help the site recover. The end result often isn't as pretty, but it's much safer and will heal with time. This is a common but logistically complex solution, - excavation, transportation, and storage can all pose some health risks and have to be done a certain way, and finding a suitable site for long-term storage of the contaminated soil can be expensive.
    - **Disposal in a regulated landfill** Once the soil has been removed, it may be transported to a per-arranged site. This long term storage will usually involve dumping it into a lined and capped pit. Essentially we seal the dangerous stuff in giant tupperware and leave it there.
    - **Soil washing** Alternatively, after the soil is removed, it may instead be transported to a facility where it is mixed with a solvent or surfactant to remove contaminants, which are then separated from the soil. This can be more complex but reduces the amount of 'waste' the project needs to store.
    - **Soil thermal treatment**: Similar to soil washing, heat is applied to the soil to volatilize or destroy contaminants.
- **Soil vapor extraction (SVE):** This method is used to remove volatile organic compounds (VOCs) from the soil by drawing them into the atmosphere.
    - This would be useful on newer sites, or ones that have been previously capped in some way blocking volitlisation.
- **Soil flushing:** Water or a chemical solution is injected into the soil to flush out contaminants. This is done when the area is well above the water table.

Chemical Methods:

- **Chemical oxidation**: Oxidizing agents are added to the soil to break down contaminants into less harmful substances.
- **Chemical reduction**: Reducing agents are used to convert contaminants into less harmful forms.
- **In-situ chemical stabilization:** Chemicals are added to the soil to immobilize contaminants and prevent their leaching.

Safety note: It's important to remember that working on contaminated sites is dangerous and requires appropriate precautions. Depending on the contamination and state of the site, just walking around can be dangerous, and the remediations outlined above generally involve disturbing the site by digging up soil, which will lead to airborne dust and other increased risks of exposure. Dust control, PPE such as masks, even hazmat suits and self-contained air supplies can be necessary onsite.

Phytoremediation

Phytoremediation is the practice of using living plants to clean soil, air and water by absorbing, containing, or breaking down hazardous substances (including heavy metals and organic compounds like pesticides, explosives, and oil). Many plants have an ability to tolerate one or more environmental pollutant(s) - and the mechanisms they use to protect themselves can be very useful with trapping or even destroying that contaminant. Sometimes this ability is easily mapped to their origin (if their native range has high natural soil concentrations of a certain heavy metal for example) sometimes it's less obvious.

We'll go into these mechanisms in more detail in the next section, but at its core, phytoremediation is about identifying plants with a suitable ability and matching them to a site or circumstance.

There are a few advantages here:

- Phytoremediation tends to be cheaper than traditional environmental restoration techniques. Compared to logging the site, excavating soil, cleaning that soil with heat or chemical washes etc or else landfilling it, purchasing new clean fill, and replanting the site, planting some trees and monitoring their health long-term can be appealing.
- Phytoremediation is generally easier on the existing habitat. Some contaminated sites look fine to the naked eye, as the toxins are less harmful to shorter-lived animals or the existing plants than they are to humans. Phytoremediation (and myco- and bioremediation) tend to be much lower-impact than traditional alternatives.

There are also some disadvantages:

- Phytoremediation isn't as fast as 'traditional' environmental restoration techniques. If the site in your story is badly contaminated with high concentrations of the pollutant, or multiple contaminants of concern, or if the cleanup is otherwise urgent (perhaps it's near a major human settlement, near a freshwater aquifer, reservoir, etc), then physically digging out the poison and remediating it elsewhere might make the most sense. Phytoremediation etc may still be a good fit for the long-term 'polish' stage of the cleanup which will follow.
- Even with well-adapted plants, high concentrations of a contaminant may limit plant growth or even kill the phytoremediation plants. Similarly, a site which is contaminated with one hazardous material is often contaminated with others (particularly industrial sites and dumping grounds). These co-contaminants can stunt or prevent plant growth, as even plants which are adapted to one poison may be harmed by others.

Other things to note upfront:

- Plants can also help prevent wind, rain, and groundwater flow from carrying contaminants away from the site to surrounding areas or deeper underground.
- These solutions can be implemented in combination - some sites have seen excellent success combining phyto- and bioremediation by inoculating trees with symbiotic bacteria.

One theme I've noticed is that if you want to remediate heavy metals, microbes *might* be able to oxidize them down into a less harmful state but generally, plants seem to be your best option for containment and removal. (Organic compounds like POPs seem to be more of an even split between plants, fungi, and microbes, leaning towards fungi and microbes.)

Types of Phytoremediation

Phytoaccumulation/Phytoextraction

Phytoaccumulation involves the absorption of contaminants by plant roots followed by translocation of absorbed contaminants to shoots and deposition at vacuole, cell wall, cell membrane, and other metabolically inactive parts in plant tissues. Over time, these plants tend to concentrate higher amounts of contaminant in their tissues than exist in the ground/water.

The ideal Phytoaccumulation plants are known as Hyperaccumulators. These plants extract contaminants from the soil at a higher rate, transfer it more quickly to their shoots, and store large amounts in leaves and roots. In most papers I've read, the focus in phytoaccumulation/hyperaccumulation research is in the remediation of heavy metals, but plants can also bioaccumulate other substances, like PFAS. (This can be a good or bad thing - if the plants are part of a phytoremediation project, it's a benefit, otherwise this process might transfer the contamination to your local herbivors and up the food chain from there. Bioaccumulation of PFAS in agricultural plants is a particular concern).

Generally the goal here is to introduce plants which accumulate the contaminant of concern in harvestable plant biomass, such as shoots or leaves, but with some crops (such as sunflowers, hemp, or mustard plants) this could mean pulling the entire plant, roots and all. Because the plants are generally trapping this stuff to protect themselves from it, the highest concentrations are often in the roots.

In some ways this is one of the more intuitive ways to clean up a site. Why dig out all the contaminated soil, transport it, and extract the contaminant, when you can grow plants that will extract the contaminant and then simply remove part or all of the plant?

Wikipedia's list of known hyperaccumulators can be a great starting point, but just know it's incomplete and you may be able to find a better fit for your region/contaminant looking through academic papers.

Phytomining

Phytomining, also known as Agromining, is another quite new field, looking to obtain various metals for industrial purposes using plants. It is currently the subject of several research studies and startups, including ones attempting to genetically modify more effective plants, and it seems like its overall viability is still undetermined at this time.

It is included in this list because the harvested hyperaccumulators need to be sent somewhere for containment, and it's possible that any industrial experience gleaned in commercial phytomining work will be useful in separating the contaminants from the plant matter. This would be ideal because reducing the mass of organic matter needing long-term storage will reduce both waste and cost. It may even be able to turn a waste product into a useful input in industry as many heavy metals have manufacturing uses. This could mean that in a solarpunk setting, phytomining operations receive some of all of their inputs from partner organizations doing site remediation and environmental restoration.

Phytovolatilization

Some plants take up contaminants from the soil and release them into the atmosphere - this is known as Phytovolatilization. This can be a good thing, such as when the contaminant is something like Dioxane which can be photodegraded and has a half-life measured in hours to days when exposed to sunlight but it can also be a problem, like when the contaminant is a heavy metal. Aerosolized mercury or PFAS may be enough of a hazard to rule out some phytoremediation candidates if they're known for phytovolatilizing contaminants along with transpirated water. So far it seems like most of the time when I see phytovolatilization mentioned in a phytoremediation paper the authors are treating a low phytovolatilization rate as being a good thing but it definitely varies by contaminant.

Rhizofiltration

Rhizofiltration is a form of phytoremediation that involves filtering contaminated groundwater, surface water and wastewater through a mass of roots to remove toxic substances or excess nutrients. The contaminant is stored in the root tissues or adsorbed onto the root surface.

It seems like the encompasses both plants grown in soil and in water (including dedicated wastewater treatment systems with plants growing in a substrate, in which case the plants are harvested and replaced with new ones once their roots are saturated with toxins).

From what I've seen, the focus here seems to be on heavy metal contamination - a few resources have stated that rhizofiltration is effective for treating large volumes of water with low concentrations of metals, such as the runoff from e-waste sites.

Phytodegradation

Out of all these options, this is probably the closest fit to “remediation” in “phytoremediation.” Phytodegradation is a process where plants absorb organic pollutants and break them down into less harmful substances through metabolic processes or by releasing enzymes. It's not possible for every contaminant (for example, most? all? heavy metals) but for organic ones like Dioxins or VOCs, it can be a pretty miraculous. We'll talk more about bioremediation through fungus and bacteria in the next sections, it seems like they may be even better for this work.

Rhizodegradation

Rhizodegradation refers to the degradation of contaminants into other forms within the rhizosphere. This microorganism-rich soil zone around the roots plays a crucial role in degrading synthetic organic contaminants by releasing enzymes such as laccases, peroxidases, cytochrome P450, dehalogenases, and monooxygenases, contributing to soil decontamination.

This seems more focused on organic compounds and seems to involve bioremediation and mycoremediation all working together. I've noticed a pretty consistent theme that most of these organisms work better as a team than alone - whether that's bacterial strains working more efficiently when part of a larger group, or trees and fungi or bacteria working symbiotically to remediate contamination.

Phytostabilization

This title seems to encompass two different processes with similar results. The first is when plants change the soil's physical and chemical properties, making it less suitable for contaminant leaching.

This might be the biological equivalent to adding a chemical binding/fixing agent to the soil. The second is when the plants take up contaminants but trap them in their roots to protect themselves. This has overlap with phytoaccumulation but in the case of trees, it would make it challenging to remove the contaminated plant matter from the site. Just the same, it does have the effect of stopping the contaminant from spreading or migrating underground.

Hydraulic Control

There are other ways to utilize plants in environmental remediation. One of the big challenges of restoring contaminated land is managing the flow of groundwater below (and out of) the site - many contaminants are quite stable underground, meaning they'll persist and remain dangerous for a very long time, and they can often spread and migrate with the groundwater flow. This plume can eventually contaminate wells and underground aquifers people rely on for drinking water and emerge from springs into surface water bodies.

Certain plants, such as poplar trees, can be used as natural water pumps, operating so well during their growing season that they can actually reverse the flow of groundwater.

This was used to interesting effect in this project, which used biochar to trap PFAS in groundwater, and used poplar trees to draw groundwater into that 'trap'.

It's important to note that the efficacy of these projects varies by site and it can be hard to tell why the trees seem serve as an excellent barrier in one case, and have minimal impact in others.

Mycoremediation

Mycoremediation is a set of remediation methods which use fungi to decontaminate the environment. The linked wikipedia article is honestly very good and covers this topic in more depth than I'll probably be able to.

The short version is that fungi are an effective way to remove a wide array of contaminants from damaged environments or wastewater. They can bioaccumulate heavy metals in their fruiting bodies for harvest and removal and break down organic pollutants, textile dyes, leather tanning chemicals and wastewater, petroleum fuels, polycyclic aromatic hydrocarbons, pharmaceuticals, personal care products, pesticides, herbicides, X-ray contrast agents, and even explosives such as 2,4,6-trinitrotoluene.

Wikipedia states that the byproducts of this remediation can be valuable materials themselves, such as enzymes (like laccase), or edible or medicinal mushrooms but the bioaccumulation factor means that this option will definitely vary by site/contaminant, and it may be *very* important to keep people and animals away from these mushrooms. For example, oyster mushrooms are effective at breaking down all kinds of stuff (we'll get into specifics in the next section), including PFAS - but they also bioacumulate PFAS in their tissues. This means a mycoremediation crew could accelerate the removal of PFAS from a contaminated site by harvesting the mushrooms and sending them for safe destruction, but if they're eaten by animals, the PFAS would accumulate in their tissues and move up the food chain (if those animals get eaten by predators) or otherwise persist in the environment.

So how do they work?

Chemical Breakdown

Fungi play an important role in decomposing almost everything else, and they've developed some incredibly effective, non-specific enzymes to do that work.

For example, liginolytic fungi evolved to digest tree lignin, one of the complex, tough organic polymers used by trees to make strong wood. Lignin is a long-chain organic (carbon-based) compound and unusually hard to break down, and the chain of tools (ex assorted extracellular enzymes) some of the fungi developed is so powerful it is general purpose, enabling them to break down many structurally similar organic pollutants (like dioxins).

It's worth noting that mushrooms may be a precursor to subsequent microbial activity rather than individually effective in the removal of pollutants. All of these things work together, see also: arbuscular mycorrhizal fungi

Metal Absorption

Many fungi are hyperaccumulators, therefore they are able to concentrate toxins in their fruiting bodies for later removal. This is usually true for populations that have been exposed to contaminants for a long time, and have developed a high tolerance. Hyperaccumulation occurs via biosorption on the cellular surface, where the metals enter the mycelium passively with very little intracellular uptake. A variety of fungi, such as *Pleurotus*, *Aspergillus*, and *Trichoderma*, have proven to be effective in the removal of lead, cadmium, nickel, chromium, mercury, arsenic, copper, boron, iron and zinc in marine environments, wastewater and on land.

In some overlap with our page on Landfill Mining, it seems they've also been used to recover precious metals from ewaste.

A few resources mention that their hyperacumulation traits are more distinct in fungi which have been exposed to a contaminated site for a long time, so transferring a contaminant-adapted strain of a native fungi to an new site might speed up the remediation process.

Bioremediation

The term Bioremediation seems to apply both to the general practice of using living things to clean up contaminated sites, and specifically to using microorganisms to break down contaminants into less harmful substances. But from what I've seen so far, it seems the second use-case is more common. At the very least “bioremediation <contaminant name>” has been a very useful search when I need to find research on cleaning a particular poison using bacteria.

This is an entire massive field of study with some remarkable successes to its credit. It probably deserves its own page at some point, but for now we're going to consolidate it here.

Bioremediation can be done in situ or ex situ. It seems like bioremediation is often used in situations where liquid medium has been contaminated, such as with industrial oil spills or other organic pollutants, or where a contaminant plume is spreading through groundwater.

As with plants, these microorganisms exist in and thrive in complex network of symbiosis we don't fully understand, and their performance in a given cleanup will depend strongly on whether they have the right tools to do their job. Some are provided by other bacteria, others can be provided as chemical inputs, added via the same liquid medium the bacteria is introduced through.

From what I've found, bioremediation seems to be an excellent option if you're looking for a way to clean up organic compounds like POPs, fuels, especially when the contaminant is in groundwater.

If you're planning to write about bioremediation, there's two terms which are good to know:

Biostimulation

As an in-situ bioremediation technology, biostimulation involves implanting nutrients in the subsurface that stimulate the microorganisms in the reduction of the contaminant of concern. There's a lot of chemistry in figuring out the right substrate to use to provide whatever normally-scarce resources the bioremediation bacteria need to thrive, such as electron donors. Basically you periodically give the bacteria the tools they need to do their job and let them get on with it.

Bioaugmentation

Depending on the contaminant of concern, the presence of suitable native microorganisms capable of breaking it down may not be guaranteed. Or their levels may be so low as to be insufficient if biostimulation is used alone. In these situations, bioaugmentation can be considered as a possible option, either as a means of initiation or as a backup. Pre-grown bioremediation microorganisms are added to contaminated sites in order to improve their ability to degrade contaminants. I've found examples of these added bacteria being tilled into contaminated soil or added to aquifers or contaminated groundwater via injection wells.

This paper provides a detailed description and diagrams of the process of introducing bioremediation bacteria to contaminated aquifers. It includes details on the arrangement of wells for testing and remediation. The paper is about dechlorinators but it seems likely that other groundwater bioremediation projects might follow similar steps.

This site provides some similar hands-on details for bioaugmentation in aquifers using injected oxygen or other gases to enable aerobic bacteria in what would otherwise be an anerobic environment.

So an example bioremediation project might look like this:

1. Test the groundwater to determine the level of contamination and extent of the plume
2. Test for the presence of suitable bioremediation bacteria (and the symbiotic bacteria which enable them). Using native bacteria already present in the groundwater is much preferred. Bacteria can also be invasive.
    - If they are present, test to determine what, if any, chemical nutrients/additives/remediation would help them to thrive and work quickly
    - Biostimulation - pump the necessary solution into the aquifer
3. If the concentration of contaminants is too high, or the right mix of bacteria aren’t present, they would try bioaugmentation - injecting pre-grown cultures along with the necessary substrate.

This older report provides some similar information.

Bacterial bioremediation can also be used in combination with phytoextraction, such as in this example where poplar trees were used almost like biological pumps to draw in groundwater and transpirate it into the atmosphere. The trees had been inoculated with specific strains of symbiotic bacteria, known as endophytes, that would eliminate the TCE the trees absorbed from the soil and would help protect them from the toxin while doing so. The bacteria thrive on eating TCE and similar compounds, consuming the molecule’s carbon backbone and exuding chloride ions that end up as a harmless by-product in adjacent soil. The trees were soaked in a solution containing the endophyte bacterial inoculum as bare root cuttings, before being brought onsite and planted.

Microbes play pivotal roles in enhancing plant tolerance to heavy metal stress through metal solubilization, immobilization, and detoxification. Specific groups of microbes, including plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and metal-resistant bacteria, are discussed for their beneficial effects in remediation processes.
https://link.springer.com/chapter/10.1007/978-981-96-4253-3_11

https://www.sciencedirect.com/science/article/pii/S0301479724038970

https://www.tandfonline.com/doi/full/10.1080/15226514.2025.2539429#d1e304
https://www.sciencedirect.com/science/article/pii/S2352186423002067#sec3
https://biosearchambiente.it/en/portfolio/ethylene-glycol/#1455640520643-eb3f1774-23c2
https://www.atsdr.cdc.gov/toxprofiles/tp96-c6.pdf
https://www.sciencedirect.com/science/article/pii/S2666821122001193

Finding Phytoremediation Options That Fit Your Story and Setting

Bioremediation/Phytoremediation are very new fields, with tons of ongoing research. Unless you go in with very specific requirements already in mind, you'll likely notice that there's an almost overwhelming number of options and variables to consider - there are hundreds of contaminants of concern, far more species that may work on them, and complex relationships where some species work on some contaminants but will be poisoned by others, or work best when supported by other species. Add to that concerns about accidentally importing invasive species and it can become quite a tangle. This isn't helped by the density of academic research language and the fact that these reports are often short on the sort of details which help when planning/writing depictions of remediation work in the field.

My workflow for finding suitable plants while not going insane

Start with the contaminant of concern. Pick your poison, then look up which plants can be used to remediate, accumulate, or stabilize it.

Wikipedia's list of known hyperaccumulators can be a start but it may also be incomplete or out of date and it focuses mostly on heavy metals. For each contaminant you can often find a review paper such as this one which will provide lists of phytoremediation species which have been tested for suitability in other studies.

You don't need to read up on how these plants work yet - some contaminants have dozens or hundreds of suitable plants so you need to narrow it down. First check each one to see if they’re native or naturalized in the region where your story is set (or decide if they’re an invasive that’s already present that might also be tolerated as part of the cleanup). Introducing an invasive or potentially-invasive species is generally a really bad idea, which makes it a hard sell in an environmental justice related story. (If your list is especially short or you really need a particular plant, consider whether its range may have moved with climate change.)

The academic papers will generally use the plants scientific name so just search for that in your search engine of choice with the word 'range' tacked on the end. Wikipedia or a plant database like Plants of the World Online will generally have a listing complete with a map. If it's listed as 'introduced' in my story's setting, I like to then search ”<plant name> invasive“ and see if it has a listing in my relevant invasive species databases (in my case https://www.naisn.org/ and https://www.invasiveplantatlas.org).

Make a shortlist of any relevant plants that seem to be effective in some way, and are native/naturalized in your region, then look more into how they work, and use that to shape the scene/setting in your story. This is a good time to look into specific scientific studies on phytoremediation with that one plant and to try to parse them as best you can.

Some plants are hyperaccumulators, meaning they take up an outsized portion of the poison into their tissues and trap it there. This is great in the short term, but they’re not destroying it, just extracting/containing it, so humans will need to remove the plants at some point. For small plants this might mean pulling them up stem and root and bagging them, while for bigger trees it could mean collecting the leaves that fall annually or even cutting them down or pollarding/coppicing them routinely to capture and remove some of the contaminant they’ve contained. It will depend on the type of plant and how they store the contaminant.

Other plants actually remediate the poison by breaking it down, or by expiating it into the air where it is exposed to sunlight and broken down, or through other biochemical processes. These are more of a set-it-and-forget-it solution.

Still others only stabilize it, holding it in place inside their roots or causing it to bind chemically to other elements and become less bioavailable. This doesn’t remove it exactly, but it might keep it contained or stop a plume of contaminant spreading underground. There are also plants like poplars which both accumulate a range of contaminants, but also drink up so much water that they can actually redirect groundwater movement.

There are so many plants, contaminants of concerns, and varying ways the two interact that it really does need some review

Other Resources

General details which might be useful

Bioremediation -

Useful Links

- Wikipedia's list of known hyperaccumulators
- This document is an open source attempt to collect options for the bioremediation of dioxin, vinyl chloride and related toxins.
- The following documents provide decent lists of likely contaminants produced by internal

combustion engine automobiles (such as you might find in a scrapyard, salvage operation, or car graveyard).
    - https://www.epa.gov/sites/default/files/2015-10/documents/sector_m_autosalvage.pdf
    - https://web.archive.org/web/20230309211038/https://eeuroparts.com/blog/how-toxic-are-the-chemicals-in-your-car/
- This paper has some details on deep rooting poplar trees.
- A decent list of candidates for zinc https://www.sciencedirect.com/science/article/pii/S2352554121001777#sec3
- Some options for bioremediation of PFAS https://www.sciencedirect.com/science/article/pii/S2949919424000694#sec1 https://www.nature.com/articles/s41467-022-31881-5 https://stud.epsilon.slu.se/9787/1/gobelius_l_161108.pdf
- A summary of current progress in bioremediation of 1,4-Dioxane https://www.researchgate.net/publication/380607199_Advances_in_Remediation_Solutions_New_Developments_and_Opportunities_in_14-Dioxane_Biological_Treatment#pfc

Other concerns

Many invasive species are strong phytoremediators since they can tolerate and take in nonessential metals, as well as handle poor growing medium and climate conditions. Therefore extensive knowledge of the plant selected within the site-climate must be known

Related concepts

This paper suggests using biofuel crops to slowly extract some amount of heavy metals from a site, until bioavailable metals in the soil are low enough for a second phase. The idea is that even if these crops don't qualify as hyperaccumulators, as long as they take up some amount of the contaminant of concern, their commercial use would make the effort profitable enough to be worth continuing. One of the main challenges with remediation efforts in the real world is cost - there's usually no profit in remediating contaminated sites for anyone other than contractor companies doing the digging and transportation. Phytoremediation is often cheaper than the alternative, but it may still require ongoing labor such as soil and water testing, site assessments, or the harvesting of contaminated plant material. This may be of less concern in a solarpunk society where this work is better prioritized, or even where basic needs are met through systems like universal basic income, and people are more free to pursue their callings, including cleaning up damaged sites.

Detection Dogs

We've covered plants, fungi, and microbes, but what about animals? Dogs have an amazing ability to detect scents and can be very effective partners in finding contamination.

https://www.washington.edu/boundless/conservation-canines/

https://aegisenvironmentalinc.com/commercial/site-investigation-scent-dog/

https://www.wsp.com/en-us/insights/meet-louie-wsps-newest-four-legged-pollution-detective#:~:text=They%20are%20trained%20to%20identify,glues%2C%20and%20dry%20cleaning%20applications