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Heavy metal pollution and human biotoxic effects

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Some heavy metals have bio-importance as trace elements but, the biotoxic effects of many of them in human biochemistry are of great concern. Hence, there is the need for proper understanding of the conditions, such as the concentrations and oxidation states, which make them harmful, and how biotoxicity occurs. It is also important to know their sources, leaching processes, chemical conversions and their modes of deposition to pollute the environment, which essentially supports lives. Literature sources point to the fact that these metals are released into the environment by both natural and anthropogenic sources, especially mining and industrial activities, and automobile exhausts (for lead). They leach into underground waters, moving along water pathways and eventually depositing in the aquifer, or are washed away by run-off into surface waters thereby resulting in water and subsequently soil pollution. Poisoning and toxicity in animals occur frequently through exchange and co-ordination mechanisms. When ingested, they combine with the body's biomolecules, like proteins and enzymes to form stable biotoxic compounds, thereby mutilating their structures and hindering them from the bioreactions of their functions. This paper reviews certain heavy metals and their biotoxic effects on man and the mechanisms of their biochemical activities.

Keywords: Biochemical, biotoxic, environment, heavy metals, pollution.

INTRODUCTION

The term "heavy metals" refers to any metallic element that has a relatively high density and is toxic or poisonous even at low concentration (Lenntech, 2004). "Heavy metals" is a general collective term, which applies to the group of metals and metalloids with atomic density greater than 4 g/cm^3, or 5 times or more, greater than water (Huton and Symon, 1986; Battarbee et al., 1988; Nriagu and Pacyna 1988; Nriagu, 1989; Garbarino et al., 1995, Hawkes, 1997). However, being a heavy metal has little to do with density but concerns chemical properties. Heavy metals include lead (Pb), cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag) chromium (Cr), copper (Cu) iron (Fe), and the platinum group elements. Environment is defined as the totality of circumstances surrounding an organism or group of organisms especially, the combination of external physical conditions that affect and influence the growth, development and survival of organisms (Farlex, 2005). It consists of the flora, fauna and the abiotic, and includes the aquatic, terrestrial and atmospheric habitats. The environment is considered in terms of the most tangible aspects like air, water and food, and the less tangible, though no less important, the communities we live in (Gore, 1997). A pollutant is any substance in the environment, which causes objectionable effects, impairing the welfare of the environment, reducing the quality of life and may eventually cause death. Such a substance has to be present in the environment beyond a set or tolerance limit, which could be either a desirable or acceptable limit. Hence, environmental pollution is the presence of a pollutant in the environment; air, water and soil, which may be poisonous or toxic and will cause harm to living things in the polluted

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environment.

OCCURRENCE AND RECOVERY OF HEAVY METALS

Heavy metals occur as natural constituents of the earth crust, and are persistent environmental contaminants since they cannot be degraded or destroyed. To a small extent, they enter the body system through food, air, and water and bio-accumulate over a period of time. (Lenntech, 2004; UNEP/GPA, 2004). In rocks, they exist as their ores in different chemical forms, from which they are recovered as minerals. Heavy metal ores include sulphides, such as iron, arsenic, lead, lead-zinc, cobalt, gold-silver and nickel sulphides; oxides such as aluminium, manganese, gold, selenium and antimony. Some exist and can be recovered as both sulphide and oxide ores such as iron, copper and cobalt.

Ore minerals tend to occur in families whereby metals that exist naturally as sulphides would mostly occur together, likewise for oxides. Therefore, sulphides of lead, cadmium, arsenic and mercury would naturally be found occurring together with sulphides of iron (pyrite, FeS_2) and copper (chalcopyrite, $CuFeS_2$) as minors, which are obtained as by-products of various hydrometallurgical processes or as part of exhaust fumes in pyrometallurgical and other processes that follow after mining to recover them. During mining processes, some metals are left behind as tailings scattered in open and partially covered pits; some are transported through wind and flood, creating various environmental problems (Habashi, 1992). Heavy metals are basically recovered from their ores by mineral processing operations (Peplow, 1999; Lenntech, 2004; UNEP/GPA, 2004; United States Department of Labor (USDOL), 2004).

HEAVY METAL EMISSION

Heavy metals can be emitted into the environment by both natural and anthropogenic causes. The major causes of emission are the anthropogenic sources specifically mining operations (Hutton and Symon, 1986; Battarbee et al., 1988; Nriagu, 1989). In some cases, even long after mining activities have ceased, the emitted metals continue to persist in the environment. Peplow (1999) reported that hard rock mines operate from 5-15 years until the minerals are depleted, but metal contamination that occurs as a consequence of hard rock mining persist for hundreds of years after the cessation of mining operations. Apart from mining operations, mercury is introduced into the environment through cosmetic products as well as manufacturing processes like making of sodium hydroxide.

Heavy metals are emitted both in elemental and compound (organic and inorganic) forms. Anthropogenic sources of emission are the various industrial point sources including former and present mining sites, foundries and smelters, combustion by-products and traffics (UNEP / GPA, 2004). Cadmium is released as a by- product of zinc (and occasionally lead) refining; lead is emitted during its mining and smelting activities, from automobile exhausts (by combustion of petroleum fuels treated with tetraethyl lead antiknock) and from old lead paints; mercury is emitted by the degassing of the earth's crust. Generally, metals are emitted during their mining and processing activities (Lenntech, 2004).

Environmental pollution by heavy metals is very prominent in areas of mining and old mine sites and pollution reduces with increasing distance away from mining sites (Peplow, 1999). These metals are leached out and in sloppy areas, are carried by acid water downstream or run-off to the sea. Through mining activities, water bodies are most emphatically polluted (Garbarino et al., 1995; INECAR, 2000). The potential for contamination is increased when mining exposes metal-bearing ores rather than natural exposure of ore bodies through erosion (Garbarino et al., 1995), and when mined ores are dumped on the earth surfaces in manual dressing processes. Through rivers and streams, the metals are transported as either dissolved species in water or as an integral part of suspended sediments, (dissolved species in water have the greatest potential of causing the most deleterious effects). They may then be stored in river bed sediments or seep into the underground water thereby contaminating water from underground sources, particularly wells; and the extent of contamination will depend on the nearness of the well to the mining site. Wells located near mining sites have been reported to contain heavy metals at levels that exceed drinking water criteria (Garbarino et al., 1995; Peplow, 1999). The tolerance limits of some heavy metals are shown in Table 1.

CHEMISTRY OF HEAVY METAL POLLUTION

Mining activities and other geochemical processes often result in the generation of acid mine drainage (AMD), a phenomenon commonly associated with mining activities. It is generated when pyrite (FeS_2) and other sulphide minerals in the aquifer and present and former mining sites are exposed to air and water in the presence of oxidizing bacteria, such as *Thiobacillus ferrooxidans*, and oxidised to produce metal ions, sulphate and acidity (Ogwuegbu and Muhanga, 2005).

$$2FeS_2 + 7O_2 + 2H_2O \longrightarrow 2FeSO_4 + 2H_2SO_4$$

$$2FeSO_4 + 2H_2SO_4 \longrightarrow Fe_2(SO_4)_3 + SO_2 + 2H_2O$$

$$Fe_2(SO_4)_3 + 2FeAsS + {}^{9}/_{2}O_2 + 3H_2O \longrightarrow 2H_3AsO_4 + 4FeSO_4 + S$$

Table 1. United State Environmental Protection Agency (USEPA) maximum contamination levels for heavy metal concentration in air, soil and water.

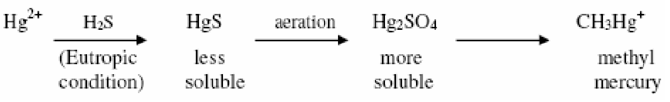
Heavy metal	Max conc. in air (mg/m^3)	Max. conc. in sludge (soil) (mg/ Kg or ppm)	Max. conc. in drinking water (mg/l)	Max conc. in H_20 supporting aquatic life (mg/l or ppm)
Cd	0.1-0.2	85	0.005	0.008^{δ}
Pb	- -	420	0.01^{π} (0.0)	0.0058^{δ}
Zn^2	1, 5*	7500	5.00	0.0766^{δ}
Hg	- -	<1	0.002	0.05
Ca	5	Tolerable	50	Tolerable >50
Ag	0.01	- -	0.0	0.1
As	- -	- -	0.01	- -

(Value in bracket is the desirable limit; $^{\pi}$ WHO ; ^{1}adapted from U.S. – OSHA; ^{2} EPA, July 1992; $^{\delta}$USEPA, 1987; Georgia Code, 1993; Florida Code, 1993; Washington Code, 1992; Texas Code, 1991; North Carolina, 1991; *1 for chloride fume, 5 for oxide fume; - - no guideline available).

Literature survey shows that heavy metals (M) at mining sites are leached and carried by acidic water downstream. They can be acted upon by bacterial and methyllated to yield organic forms, such as monomethylmercury and dimethylcadmium. This conversion is effected by bacteria in water, in the presence of organic matter, according to the following simplified equation.

$$\text{M + organic matter} \xrightarrow{H_2O,\ \text{bacteria}} CH_3\,M \text{ and } (CH_3)_2\,M$$

In the non-biological conversions, the following reactions have been identified for mercury:



These organic forms have been reported to be very toxic and adversely affect water qualities by seepage to pollute underground water sources. Low pH values do not need to be established for metals to be released from mine wastes at adverse concentrations because, near neutral pH (pH 6-7) have been established for some metals, such as Zn, Cd, and As (INECAR, 2000; Lenntech, 2004). Factors such as downstream distances from the mining sites, colloid loads, pH perturbations, and dilution ultimately control the quality of water sources.

HUMAN EXPOSURE THROUGH FOOD, AIR AND WATER

Heavy metal pollution of surface and underground water sources results in considerable soil pollution and pollution increases when mined ores are dumped on the ground surface for manual dressing (Garbarino et al., 1995; INECAR, 2000). Surface dumping exposes the metals to air and rain thereby generating much AMD. When agricultural soils are polluted, these metals are taken up by plants and consequently accumulate in their tissues (Trueby, 2003).Animals that graze on such contaminated plants and drink from polluted waters, as well as marine lives that breed in heavy metal polluted waters also accumulate such metals in their tissues, and milk, if lactating (Habashi, 1992; Garbarino et al., 1995; Horsfall and Spiff, 1999; Peplow, 1999). Humans are in turn exposed to heavy metals by consuming contaminated plants and animals, and this has been known to result in various biochemical disorders. In summary, all living organisms within a given ecosystem are variously contaminated along their cycles of food chain.

HUMAN EXPOSURE THROUGH INDUSTRIAL PRODUCTS

Industrial products that are used in homes, and which have been produced with heavy metals are sources of human exposure to such heavy metals. Mercury exposure is through disinfectants (like mercurochrome), antifungal agents, toiletries, creams and organo-metallics (McCluggage, 1991); cadmium exposure is through nickel/cadmium batteries and artist paints; lead exposure is through wine bottle wraps, mirror coatings, batteries, old paints and tiles and linolein amongst others. Infants are more susceptible to the endangering effects of exposure to heavy metals.

OCCUPATIONAL EXPOSURE

Heavy metal exposure occurs significantly by occupational exposure. Workers of the mining and production of cadmium, chromium, lead, mercury, gold and silver have been reported to be thus exposed; also inhabitants around industrial sites of heavy metal mining and processing, are exposed through air by suspended particulate matters (SPM) (Heyer, 1985; USDOL, 2004; Ogwuegbu and Muhanga, 2005).

Table 2. Recommended (Daily) Dietary Allowances (RDA) of The Food and Nutrition Board (Published by the National Academy of Science, Washington, DC, U.S.A).

	Age (Years)	Weight (kg)	Ca (mg)	Fe (mg)	Mg (mg)	Zn (mg)
Infants	0-$^{1}/_{2}$	6	360	10	60	3
	½-1	9	540	15	70	5
Children	1-3	13	800	15	150	10
	4-6	20	800	10	200	10
	7-10	30	800	10	250	10
Males	11-14	44	1200	18	350	15
	15-18	61	1200	18	400	15
	19+	67+	800	10	350	15
Females	11-18	44-54	1200	18	300	15
	19+	58	800	18(10)*	300	15
Pregnant			1200	18+**	450	20
Lactating			1200	15	450	25

*(10) for females above 50 years; ** figure cannot be met by ordinary diets. Therefore, use of supplemental iron is recommended.

Table 3. Guideline in drinking water by the World Health Organization (WHO) and National Agency for Food and Drugs Administration and Control (NAFDAC), Nigeria.

Heavy metal	Max. acceptable conc. (WHO)	Max. acceptable conc. (NAFDAC)
Zinc	5 mg/l	5 mg/l
Arsenic	0.01 mg/l	0.0 mg/l,
Magnesium	50 mg/l	30 mg/l
Calcium	50 mg/l	50 mg/l
Cadmium	0.003 mg/l	0.0 mg/l
Lead	0.01 mg/l	0.0 mg/l
Silver	0.0 mg/l	0.0 mg/l
Mercury	0.001 mg/l	0.0 mg/l

BIO-IMPORTANCE OF HEAVY METALS

Some heavy metals (like Fe, Zn, Ca and Mg) have been reported to be of bio-importance to man and their daily medicinal and dietary allowances had been recommended and is presented in Table 2. Their tolerance limits in drinking and potable waters have also been reported, and are indicated in Table 3. However, some others (like As, Cd, Pb, and methylated forms of Hg) have been reported to have no known bio-importance in human biochemistry and physiology and consumption even at very low concentrations can be toxic (Holum, 1983; Fosmire, 1990; McCluggage, 1991; Ferner, 2001; European Union, 2002; Nolan, 2003; Young, 2005). Even for those that have bio-importance, dietary intakes have to be maintained at regulatory limits, as excesses will result in poisoning or toxicity, which is evident by certain reported medical symptoms that are clinically diagnosable (Fosmire, 1990; Nolan, 2003; Young, 2005).

Zinc is a ‘masculine’ element that balances copper in the body, and is essential for male reproductive activity (Nolan, 2003). It serves as a co-factor for dehydrogenating enzymes and in carbonic anhydrase (Holum, 1983). Zinc deficiency causes anaemia and retardation of growth and development (McCluggage, 1991).

Calcium is a very vital element in human metabolism. It is the chief element in the production of very strong bones and teeth in mammals. Its tolerance limit is high relative to other bio-useful metals, that is, at 50 mg/l of drinking water as shown in Table 3. The daily dietary requirement of calcium soars at the highest across both sexes and all ages of humans as shown in Table 2, and it can be accommodated at higher doses in the body because its concentration in the blood is well regulated by thyrocalcitonin and parathormone hormones (Holum, 1983).

Magnesium is an important electrolytic constituent of the blood, present in the blood plasma and body fluids, viz; interstitial and cell fluids. Its daily dietary requirement increases from infants to adults and from males to females, with the highest daily requirements for pregnant and lactating women (Holum, 1983).

Arsenic has been reported to be a trace element of nutritional importance to humans but its functions in the biological system is not clear (Holum, 1983). Any level of concentration of silver in drinking water has been disallowed, both by the World Health Organization (WHO) and National Agency for Food and Drugs Administration and Control (NAFDAC), Nigeria. Lead, cadmium and mercury have been reported not to have any known function in human biochemistry or physiology, and do not occur naturally in living organisms (Lenntech, 2004). Hence dietary intakes of these metals, even at very low concentrations can be very harmful because they bioaccumulate.

HEAVY METAL POISONING AND BIOTOXICITY

The biotoxic effects of heavy metals refer to the harmful effects of heavy metals to the body when consumed above the bio-recommended limits. Although individual metals exhibit specific signs of their toxicity, the following have been reported as general signs associated with cadmium, lead, arsenic, mercury, zinc, copper and aluminium poisoning: gastrointestinal (GI) disorders, diarrhoea, stomatitis, tremor, hemoglobinuria causing a rust–red colour to stool, ataxia, paralysis, vomiting and convulsion, depression, and pneumonia when volatile vapours and fumes are inhaled (McCluggage, 1991). The nature of effects could be toxic (acute, chronic or sub-chronic), neurotoxic, carcinogenic, mutagenic or teratogenic.

Cadmium is toxic at extremely low levels. In humans, long term exposure results in renal dysfunction, characterized by tubular proteinuria. High exposure can lead to obstructive lung disease, cadmium pneumonitis, resulting from inhaled dusts and fumes. It is characterized by chest pain, cough with foamy and bloody sputum, and death of the lining of the lung tissues because of excessive accumulation of watery fluids. Cadmium is also associated with bone defects, viz; osteomalacia, osteoporosis and spontaneous fractures, increased blood pressure and myocardic dysfunctions. Depending on the severity of exposure, the symptoms of effects include nausea, vomiting, abdominal cramps, dyspnea and muscular weakness. Severe exposure may result in pulmonary odema and death. Pulmonary effects (emphysema, bronchiolitis and alveolitis) and renal effects may occur following subchronic inhalation exposure to cadmium and its compounds (McCluggage, 1991; INECAR, 2000; European Union, 2002; Young, 2005).

Lead is the most significant toxin of the heavy metals, and the inorganic forms are absorbed through ingestion by food and water, and inhalation (Ferner, 2001). A notably serious effect of lead toxicity is its teratogenic effect. Lead poisoning also causes inhibition of the synthesis of haemoglobin; dysfunctions in the kidneys, joints and reproductive systems, cardiovascular system and acute and chronic damage to the central nervous system (CNS) and peripheral nervous system (PNS) (Ogwuebgu and Muhanga, 2005). Other effects include damage to the gastrointestinal tract (GIT) and urinary tract resulting in bloody urine, neurological disorder and can cause severe and permanent brain damage. While inorganic forms of lead, typically affect the CNS, PNS, GIT and other biosystems, organic forms predominantly affect the CNS (McCluggage, 1991; INECAR, 2000; Ferner, 2001; Lenntech, 2004). Lead affects children by leading to the poor development of the grey matter of the brain, thereby resulting in poor intelligence quotient (IQ) (Udedi, 2003). Its absorption in the body is enhanced by Ca and Zn deficiencies. Acute and chronic effects of lead result in psychosis.

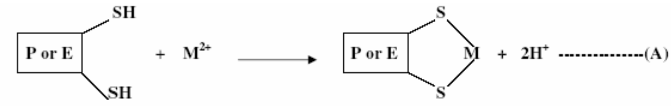
Zinc has been reported to cause the same signs of illness as does lead, and can easily be mistakenly diagnosed as lead poisoning (McCluggage, 1991). Zinc is considered to be relatively non-toxic, especially if taken orally. However, excess amount can cause system dysfunctions that result in impairment of growth and reproduction (INECAR, 2000; Nolan, 2003). The clinical signs of zinc toxicosis have been reported as vomiting, diarrhea, bloody urine, icterus (yellow mucus membrane), liver failure, kidney failure and anemia (Fosmire, 1990).

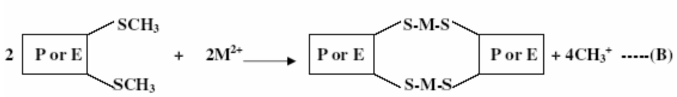
Mercury is toxic and has no known function in human biochemistry and physiology. Inorganic forms of mercury cause spontaneous abortion, congenital malformation and GI disorders (like corrosive esophagitis and hematochezia). Poisoning by its organic forms, which include monomethyl and dimenthylmecury presents with erethism (an abnormal irritation or sensitivity of an organ or body part to stimulation), acrodynia (Pink disease, which is characterized by rash and desquamation of the hands and feet), gingivitis, stomatitis, neurological disorders, total damage to the brain and CNS and are also associated with congenital malformation (Ferner, 2001; Lennetech, 2004).

As with lead and mercury, arsenic toxicity symptoms depend on the chemical form ingested (Holum, 1983; Ferner, 2001). Arsenic acts to coagulate protein, forms complexes with coenzymes and inhibits the production of adenosine triphosphate (ATP) during respiration (INECAR, 2000). It is possibly carcinogenic in com-pounds of all its oxidation states and high-level exposure can cause death (Ogwuebgu and Ijioma, 2003; USDOL, 2004). Arsenic toxicity also presents a disorder, which is similar to, and often confused with Guillain-Barre syndr-ome, an anti-immune disorder that occurs when the body's imm-une system mistakenly attacks part of the PNS, resulting in nerve inflammation that causes muscle weakness (Kantor, 2006; NINDS, 2007).

BIOCHEMISTRY OF TOXICITY

The poisoning effects of heavy metals are due to their interference with the normal body biochemistry in the normal metabolic processes. When ingested, in the acid medium of the stomach, they are converted to their stable oxidation states (Zn^{2+}, Pb^{2+}, Cd^{2+}, As^{2+}, As^{3+}, Hg^{2+} and Ag^{+}) and combine with the body's biomolecules such as proteins and enzymes to form strong and stable chemical bonds. The equations below show their reactions during bond formation with the sulphydryl groups (-SH) of cysteine and sulphur atoms of methionine ($-SCH_3$) (Ogwuegbu and Ijioma, 2003).





Where: (A) = Intramolecular bonding; (B) = Intermolecular bonding; P = Protein; E = Enzyme; M = Metal

The hydrogen atoms or the metal groups in the above case are replaced by the poisoning metal and the enzyme is thus inhibited from functioning, whereas the protein–metal compound acts as a substrate and reacts with a metabolic enzyme. In a scheme shown below (equation C), enzymes (E) react with substrates (S) in either the lock-and-key pattern or the induced-fit pattern. In both cases, a substrate fits into an enzyme in a highly specific fashion, due to enzyme chirality's, to form an enzyme–substrate complex (E-S*) as follows (Holum, 1983).

$$E + S \rightarrow E\text{-}S \rightarrow E - S^* \rightarrow E - P \rightarrow E + P$$ **-----(C)**

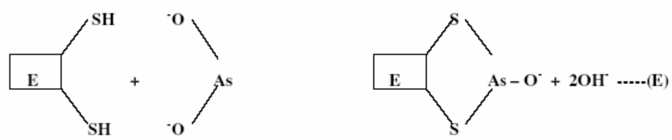
(E = Enzyme; S = Substrate; P = Product; * = Activated Complex)

While at the E-S, E–S* and E-P states, an enzyme cannot accommodate any other substrate until it is freed. Sometimes, the enzymes for an entire sequence coexist together in one multi-enzyme complex consisting of three or four enzymes. The product from one enzyme reacts with a second enzyme in a chain process, with the last enzyme yielding the final product as follows:

$$A \xrightarrow{E1} B \xrightarrow{E2} C \xrightarrow{E3} D \xrightarrow{E4} F$$ (E1 to E4 are enzymes) ----- **(D)**

The final product (F) goes back to react with the first enzyme thereby inhibiting further reaction since it is not the starting material for the process. Hence, the enzyme E1 becomes incapable of accommodating any other substrate until F leaves and F can only leave if the body utilizes it. If the body cannot utilize the product formed from the heavy metal – protein substrate, there will be a permanent blockage of the enzyme E1, which then cannot initiate any other bio-reaction of its function. Therefore, the metal remains embedded in the tissue, and will result in bio-dysfunctions of various gravities (Holum, 1983).

Furthermore, a metal ion in the body's metallo-enzyme can be conveniently replaced by another metal ion of similar size. Thus Cd^{2+} can replace Zn^{2+} in some dehydrogenating enzymes, leading to cadmium toxicity. In the process of inhibition, the structure of a protein molecule can be mutilated to a bio-inactive form, and in the case of an enzyme can be completely destroyed. For example, toxic As^{3+} occurs in herbicide, fungicides and insecticides, and can attack –SH groups in enzymes to inhibit their bioactivities as shown below (Ogwuegbu and Ijioma, 2003).



The most toxic forms of these metals in their ionic species are the most stable oxidation states. For example, Cd^{2+}, Pb^{2+}, Hg^{2+}, Ag^{+} and As^{3+}. In their most stable oxidation states, they form very stable biotoxic compounds with the body's bio-molecules, which become difficult to be dissociated, due to their bio-stabilities, during extraction from the body by medical detoxification therapy.

Conclusion

Heavy metals are important in many respects to man, especially in the manufacturing of certain important products of human use, such as accumulators (Pb), mercury-arch lamps and thermometers (Hg), utensils (Al) and a wide range of other products (Yaw, 1990; McCluggage, 1991). But the biotoxic effects, when unduly exposed to them could be potentially life threatening hence, cannot be neglected. While these metals are in many ways indispensable, good precaution and adequate occupational hygiene should be taken in handling them. Although heavy metal poisoning could be clinically diagn-osed and medically treated, the best option is to prevent heavy metal pollution and the subsequent human poisoning.

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