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Application of Phytoremediation in Restoring Sustainable Development to the Environment: Economic and Soil Conditions

Abstract

The objective of this article is a presentation of priority questions and relations involving economic and soil conditions for the application of phytoremediation technology in restoring sustainable development to the environment. The analysis looks at the justifiability of the application of phytoremediation in restoring a balanced environment as an alternative method to costly land recultivation aimed at eliminating pollutants—a solution that is impossible in the case of large areas. The cost effectiveness of the use of phytoremediation in the recovery of trace element in the soil through the process of phytoremediation was demonstrated.

The quality of soils as found in the Voivodeship of Łódź was analyzed from the point of view of potential application of the phytoremediation method, taking into account subdivision by heavy metals found in the soils as well as their origins and properties. Grades of soil purity are presented and border values of heavy metal content were identified.

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1. Introduction

Most problems linked with environmental pollution may be solved with the involvement of plants. Possibilities for utilizing plants to transfer, accumulate, and remove pollutants from the environment, or at least decrease their mobility, have been a topic of discussion for over twenty years. Such an approach may also be used to eliminate both inorganic and organic xenobiotics, including pollutants present in the soil, water, and air. A major objective is the prevention of pollutant migration that might cause a greater threat to public health. Phytoremediation is a promising and dynamically developing technique for cleaning the environment. The technology involves the applications of plants that are potentially capable of growing in polluted soils that influence biological, chemical, and physical processes so as to eliminate xenobiotics from the environment. The range of pollutants that can be the object of phytoremediation is very broad. It encompasses inorganic fertilizer, pesticides, heavy metals trace elements and radionuclides, explosives, petroleum and other leaked liquid fuel, and even compounds used in chemical weapons. Substances disrupting the hormone economy (endocrine disrupting compounds – EDCs) such as tributyltin, bisphenol A, and nonylphenol are also objects of interest as are the very difficult to decompose polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). Plants often use pathways and enzymes similar to those present in mammals. This is behind the emergence of the concept of a “green liver.” However, plants are phototrophic organism and are not capable of achieving the complete mineralization of organic particles. They do not use essential compounds in the carbon and energy metabolism and as a consequence the lack the normal catabolic enzymes vital in this process. In practice, this means that plants are not capable of metabolizing organic compounds into basic products such as CO_2 and H_2O (Singh et al. 2009)

The mechanical removal of pollutants and chemical engineering are very expensive, difficult, and simultaneously destroy the structure of the soil and lower its fertility (Shi and Cai, 2009). Utilization of plant systems to eliminate toxic components from the soil seems to be more effective and, in many aspects, better solution. Phytoremediation is cost effective, environmentally friendly, and may be applied to extremely large areas. The method also has its disadvantages because the process proceeds slowly, usually requiring several years or even decades in certain cases to decrease heavy metal pollutants by one–half. Moreover, methods for utilizing or applying biomass enriched with heavy metals are insufficiently developed (Shi and Cai 2009). The only solution that allows for the complete cleaning of the soil from heavy metals while simultaneously eliminating the disadvantages of phytoremediation is growing plants for energy purposes. Such a combination may generate profits and serve as a method for cleaning that are areas many hectares in size.

The goal of this article is the presentation of justification for the application of phytoremediation in restoring a sustainable environment as an alternative to the costly mechanical removal of pollutants, which is impossible in the case of large areas of soil.

2. The cost effectiveness of phytoremediation in recovering trace elements from the soil

Something of a discourse has been underway in the scientific community as to what plant types are best suited for phytoextraction—hyperaccumulators or plants with very large biomass (Dickinson et al. 2009; Chaney et al. 1997; Ebbs et al. 1997; Kayser et al. 2000). In many cases, the quantity of accumulated trace elements in the plant is, in the final analysis, the same—i.e. hyperaccumulators can accumulate significantly more trace elements per unit mass, but at the same time the biomass harvested is significantly lower. There is also the question of the tolerance of the plant to the presents of trace elements in the soil. In the case of major contamination, hyperaccumulators work better. As a rule, they are more resistant to pollutants. Hyperaccumulators also hold the advantage when the goal of phytoextraction is the recycling of a specific trace element. The operation involving the growing of plants accumulating a given element or group of elements that have a large concentration in the soil followed by their recovery from ashes resulting from the burning of the plants is called *phytomining*. It differs from phytoremediation in that it is also applicable to elements such as gold or platinum with a very limited presence in the surface soil. The cost effectiveness of this method depends on many factors, including the level of accumulation of the metals in the soil, the plants, and the biomass harvest. However, the most important economic factor is the value of the recovered metal. This may range from approximately PLN 172.000 per kg^{-1} in the case of gold to somewhat more than PLN 6 per kg^{-1} for lead. The phytomining method has been deemed cost effective for gold, thallium, cobalt, and nickel, where only the last is a true problem for the environment. The costs of extraction of other trace elements, such as zinc, using the discussed method are not favorable (Chaney et al. 2007; Vangronsveld et al. 2009; Sheorana et al. 2009). The phytoextraction market for trace elements is growing and is estimated to have increased in value from USD 15–25 million in the year 2000 to USD 70–100 million in the year 2005 (Glass 2000). Small plants with a capacity for hyperaccumulation of elements and a significant tolerance to their high concentration in the soil are used in phytomining. Thus, cost effectiveness is mainly dependent on the price of the extracted element. Calculating the profitability of application of phytoextraction using energy plants is significantly more difficult. The trace element content may have an impact on the volume of the plant harvest. The biomass of energy plants is many times greater as compared to hyperaccumulators, but their pollutant content per kilogram of dry matter will be lower. This may be a significant impediment to recycling. Applying the principles of the multiple land use (MLU) system, both biophysical and economic aspects should be examined. This means that in the first phase what is taken into account is the number of tons of soil protected against erosion and the number of species of plants to be placed in the habitat. In the second, profits from specific ways of management are calculated. It is estimated that Europe and the United States have several hundred thousand hectares of soil polluted by heavy metals. The phytoremediation market is estimated at approximately USD 36–54 billion, of which USD 1.2–1.4 billion involves the spontaneous removal of heavy metals from the soil (Glass 1999). Current estimates regarding the size of the area polluted by heavy metals requiring new ways of development may be significantly greater if stricter European Commission (EC 2002) requirements as to soils designated for the growing of plants for consumption are taken into account. The application of phytoremediation using the willow, taking into account MLU principles, is cost effective in the case of farmers and local authorities. Among other things, cost effectiveness is dependent on the value of product that may be produced on the soil following its cleaning through the process of phytoremediation, the time needed for its production, and the costs of investments incurred to date on the polluted area (e.g. an irrigation system). The analysis also takes into account the time needed to lower the heavy metal content to a safe level as well as revenues from the sale of biomass and subsidies, growing costs, and the costs of managing the polluted wastes derived from burning. Calculated benefits from applying phytoremediation are also dependent on the methodology used for estimates (Lewandowski et al. 2006).

Improved phytoextraction is becoming an economically viable and potentially broadly applicable technology for cleaning large areas of land of heavy metals on which decreasing the quantity of pollutants using mechanical methods known to date is impossible. Depending on the level and type of pollution as well as geographical location, the most efficient plant species may be used. The use of plants generating large amounts of biomass that may be utilized for energy purposes has opened up completely new possibilities and significantly improves the cost effectiveness of such a venture. This solution is especially beneficial for Poland and other countries of the European Union that are striving to limit carbon dioxide emissions by the power industry.

Unfortunately, modern methods of phytoremediation have, to date, not been applied on a large scale, where the bulk of cases use traditional methods for removing pollutants from the soil, which does not involve significant areas (Witters et al. 2009, 2012).

3. The quality of soils in the voivodeship of łódź in terms of potential for the application of the phytoremediation method

The development of civilization (industry, agriculture, transportation, mining, and urbanization) has a direct and indirect impact on changes to the chemistry of soil, water, the air, and food products. To a significant degree, these factors determine the health of the population. Especially dangerous is the process of accumulating trace cation elements, customarily called **heavy metals**. In Poland as well as the rest of the world, the most frequently observed complaints in humans are caused by the accumulation of lead (Pb), cadmium (Cd), and mercury (Hg) as well as to a lesser degree ten other trace elements, including copper (Cu), nickel (Ni), chromium (Cr), arsenic (As), fluoride (F), and beryllium (Be) (Kabata–Pendias et al., 1995). The order and proportions of passing through specific **ecosystems and food chains** may be established for all elements, especially the metallic ones. Most of these elements show a tendency for biological accumulation. Living organisms have biological barriers protecting them against excessive concentrations of chemical elements. When the operation of these barriers weakens, there is a concentration resulting in the accumulation of heavy metals in the last link of the food chain—**Man**. This occurs through the consumption of contaminated plant and animal products. It is for this reason that it is so important to take action aimed at limiting to a minimum the content of harmful elements in plant designated for eating. The most effective way is the exclusion of the production of plants designated for food on polluted arable soils and the development of the potential of such land by growing **energy crops**. Such efforts are in line with the assumptions behind Poland's energy policy up to the year 2025 according to which biomass utilization shall continue to be a basic direction of renewable energy source development.

Heavy metals occurring in the soil may be subdivided into their derivatives and sources as well as properties giving three groups (Kabata–Pendias et al. 1995):

- Lithogenic (bedrock–related material),
- Pedogenic (which can originate from various sources, but the form of their occurrence undergoes transformations as a result of soil formation processes), and
- Anthropogenic (introduced into the soil as a result of human activity and remaining in initial forms as introduced).

The bedrock of the **soils of the Voivodeship of Łódź** mainly consists of Quaternary deposits—dumped sands and clays, fluvial–glacial sands and gravel, river gravel and sand, Eolithic gravel and particulate matter as well as residual silt and clay. It is only in the southern part of the Voivodeship that bedrock consists of limestone, marl, claystone, and sandstone—Mesozoic deposits. As a result, the soils of the area have little variability with a dominance of podsolic soils (approximately 85% of the surface area of the Voivodeship). The remaining part consists of wetland and peat, brown, and black soils as well as alluvial soils (Ochal 2009).

Soils undergo degradation through a worsening of their chemical and physical properties as well as a fall in biological activity. This causes a decrease in the quantity and quality of plant biomass that can be derived from them. The total loss of useable soil value is called devastation. For the most part, land where there is a problem of significant degradation or devastation of the soil remains outside the area of productive agricultural land—withdrawn from agricultural use. The main factors posing a threat to soil quality are erosion, a fall in organic matter content, local and distributed pollution, sealing and compaction, a fall in biodiversity, and salting (COM(2006)231). The main direct and indirect anthropogenic sources of heavy metal soil pollution are the chemical industry, artificial fertilizers, and the cellulose and paper, electro–technical, coke, glassmaking, ceramic, cement and asbestos industries, and steel mills as well as coal power plants and petroleum refineries.

The use of traffic routes is an important source of soil pollution, especially lead and zinc. Among pollutants emitted by internal combustion engine drive vehicles, apart from lead and zinc, are chromium, cadmium, and platinum (Indeka and Karczun 1999, 2000). Heavy metals find their way into the environment as a result of the abrasion of tires and other vehicle parts. Moreover, lubricants used in motor vehicles can be a source of cadmium pollution along roads (Antonkiewicz and Macuda 2005; Baran et al. 2007).

Meteorological phenomena, including precipitation, have a major impact on the circulation of heavy metals in nature. Pollution, heavy metal acidic compounds, and salts cumulate in the atmosphere and are carried by it to be dumped on soil surfaces or on water. To a great extent, the concentration of these pollutants depends on the season of the year and quantity of precipitation.

Most substances (sulfates, nitrates, Kieldahl nitrogen, total phosphorus, potassium, magnesium, calcium, copper, lead, and manganese) are deposited in the soil and water during May and June precipitation. For their part, chlorides, sodium, and high concentrations of the remaining heavy metals are accumulated in winter and late autumn precipitation. Table No. 1 presents the annual surface load for the Voivodeship of Łódź by pollutants brought in through atmospheric precipitation.

Table 1. Annual pollutant surface load for the voivodeship of łódź through precipitation

	Precipitation (kg ha^{-1} $year^{-1}$)	**Total precipitation** (t)
Zinc	0.542	987.5
Copper	0.0364	66.3
Lead	0.0110	20.04
Cadmium	0.00123	2.241
Nickel	0.0045	8.20
Chromium	0.0022	4.008
Manganese	0.0316	57.57

Source: based on Institute of Meteorology and Water Management (2008), Report of the Department of Ecology of the of the Wrocław Branch Institute of Meteorology and Water Management, “Monitoring chemizmu opadów atmosferycznych i ocena depozycji zanieczyszczeń do podłoża. Wyniki badań monitoringowych w województwie łódzkim w 2008 roku (Monitoring the chemistry of atmospheric precipitation and assessing the depositing of pollutants to the surface: Monitoring research results for the Voivodeship of Łódź for the year 2008).

Conditions for agricultural production in the Voivodeship of Łódź are less favorable than the average for Poland. In spite of this, 57.2% of the surface area of the Voivodeship is occupied by arable land and orchards. Primary problems are acidity and soil conditions. Table No. 2 presents agricultural land use in the Voivodeship of Łódź.

Table 2. Land area of poland by land use: łódź and adjacent voivodeships

		Poland	VOIVODESHIP						
			Łódzkie	Kujawsko–pomorskie	Mazowieckie	Świętokrzyskie	Śląskie	Opolskie	Wielkopolskie
Agricultural land (ha)	Total	18869891	1297955	1176826	2437791	754466	638497	603216	1944707
	Arable land	13921466	1008897	994963	1723540	547925	460844	491663	1575063
	Orchards	294836	31091	15498	84054	31493	8146	3446	16971
	Permanent Meadowland	2286565	116666	84714	280052	95353	90299	68248	206259
	Permanent Pastureland	1627438	86987	47860	248780	43942	49481	18282	80669
	Agricultural: built–up	531895	41390	23571	79068	28292	19177	13136	43087
	Ponds	72326	4125	2092	4957	3873	7384	4081	6131
	Ditches	135365	8799	8128	17340	3588	3166	4360	16527

Source: based on *Statistical Yearbook of Agriculture*, Halina Dmochowska (Editor), Central Statistical Office, Department of Statistical Publications, Warsaw, 2011.

Grade I and II soils make up approximately 1% of the surface area of the voivodeship. Grade III soils account for 5%. They are primarily found in the *powiat*s (county level) of Kutno, Łowicz, and Łęczyca (9% of the surface area of the Voivodeship). Soil of the lowest quality, Grades V and VI, are dominant, especially in the southern and southeastern parts of the region (46% of the Voivodeship area). Table No. 3 presents agricultural land use in the Voivodeship of Łódź by soil quality. Soil that has been degraded and devastated by industry, including mainly power engineering, mining, and building construction, occupies approximately 4,000 ha in the Voivodeship of Łódź, but its surface area is continuously growing (Ochal 2009). Bearing in mind the specified data, it is possible to identify areas of the Voivodeship that could specialize in the production of energy crops with their simultaneous potential for cleaning pollution using the phytoremediation method.

Table 3. Agricultural land by soil quality and voivodeship

		Poland	Voivodships						
			Łódzkie	Kujawsko–pomorskie	Mazowieckie	Świętokrzyskie	Śląskie	Opolskie	Wielkopolskie
Total		18536936	1271856	1157838	2405579	742732	639364	585621	1899188
Soil Quality Grades	I	67782	97	2104	1715	18906	1189	2988	54
	II	536413	11556	29230	16360	60108	8715	43599	14440
	III	4201920	228307	367805	409860	155262	119071	199035	407835
	IV	7402942	444843	469734	892418	241474	279393	212430	682062
	V	4197220	382484	182133	683322	163488	165691	91540	485334
	VI	2114888	204569	103054	399847	100921	64105	35965	309211
	VIz	154335	15727	12021	31391	10235	7209	251	18255
Other[1]		15771	—	3778	2057	2573	1200	64	252

Source: based on Statistical Yearbook of Agriculture, Halina Dmochowska (Editor), Central Statistical Office, Department of Statistical Publications, Warsaw, 2011.

Pursuant to Central Statistical Office (GUS) data from the year 2010, soil in the Voivodeship of Łódź requiring recultivation amounted to 4,497 ha (54 ha more than in the previous year), of which 4,312 ha consisted of devastated soil while 184 was classified as degraded. The sustainable growing of selected varieties of energy plants with the highest tolerance to unfavorable environmental conditions, including the presence of heavy metals, and with phytoremediation properties, could become a widely applied method for recultivating the areas.

In addition to industrial, municipal, and motorization pollution, agriculture can also play a role in contaminating soil with heavy metals through the universal use of fertilizers. Approximately 40% of the soil of the Voivodeship of Łódź is marked by very low phosphorus content (Ochal 2009). The phosphorus fertilizers used can be a significant source of heavy metal soil pollution, especially cadmium. The average trace element content in phosphorus

[1] Land not covered by the soil classification system.

fertilizers forms the series as follows: Cd < Cu < Pb < Ni < Zn. The form of fertilizer has a significant impact on variations in content (Sady and Smoleń, 2004). This is linked with the quality of raw materials—phosphorites and apatites—used in production. Percentage growth in nutrient content—phosphorus—is accompanied by a fall in quantity of heavy metals introduced into the soil. Thus, phosphate meal and monocalcium phosphate introduce more of them than tricalcium phosphate. Systematic use of phosphate fertilizers may result in an increase in the content of cadmium in the soil that is easily accessible to plants (Gorlach and Gambuś 1997; Kabata–Pendias and Pendias 1999).

The share of potassium in the soil of the Voivodeship of Łódź is even lower than in the case of phosphorus, reaching 62% of the arable land (Ochal 2009). Depending on the form in which it is applied, potassium fertilizer may increase or decrease the quantity of heavy metals accessible to plants. The direction of this process is dependent on the type of metal and the physical–chemical properties of the soil being fertilized. The application of potassium chloride (KCl) results in a greater leaching away of cadmium, copper, lead, and aluminum (Al) as compared with the used of potassium sulfate (K_2SO_4) (Sady and Smoleń 2004).

Calcium needs of the soils of the Voivodeship of Łódź are significantly greater than the national average and it is vital for over 50% of the agricultural land area (Ochal 2009). Calcium fertilizer may contain many trace elements, including arsenic (0.2–24 ppm d.m.), lead (20–1250 ppm d.m.), and manganese (40–1200 ppm d.m.) (Kabata–Pendias and Pendias 1999).

The impact of fertilization using nitrogen on the quantity of heavy metals accessible to plants depends on the dosage and dates of application of the fertilizer (Sady and Smoleń, 2004). Soil pH is lowered and the content of available forms of heavy metals increase in the case use of fertilizers containing reduced forms of nitrogen such as ammonium sulfate and urea on plants. This results in an increase in the accumulation of these elements in plants (Gębski and Mercik 1997; Gębski 1998). Growth in the dosage of nitrogen in the soil causes an increase the accumulation of cadmium. However, no impact on the uptake of copper and lead has been demonstrated (Sady and Smoleń 2004).

From among applied fertilizers, the smallest amounts of trace elements are found in manure, while the greatest variations in their content are seen in municipal sewage. Depending on their place of origin, zinc content in municipal sewage may range from 700 to 49,000 ppm d.m., chromium from 20 to 40,6000 ppm d.m., nickel from 16 to 5,300 ppm d.m., and cadmium from 2 to 1,500 ppm d.m. Because of these differences, it is vital to test trace element content prior to using municipal sewage as fertilizer. Allowable heavy metal content in agricultural soil is presented in Table No. 4.

Table 4. Allowable heavy metal content in soils for agricultural use of sewage sludge

Chemical element	Content in soil (mg kg^{-1} d.m.)		
	Light soils	Medium soils	Heavy soils
Lead (Pb)	40	60	80
Cadmium (Cd)	1	2	3
Mercury (Hg)	0.8	1.2	1.5
Nickel (Ni)	20	35	50
Zink (Zn)	80	120	180
Copper (Cu)	25	50	75
Chromium (Cr)	50	75	100

Source: based on the Directive of the Minister of Environment of July 8, 2004 on conditions to be met in introducing sewage into waters or the earth as well as on substances that are particularly hazardous to the water environment (Journal of Laws of 2004, No. 168, item 1763).

One of the main factors influencing the form of heavy metals and their accessibility by plants is the acidity of the soil (Chłopecka 1994; Gębski 1998; Kabata–Pendias and Pendias 1999). Acidic soil most frequently causes the release of heavy metals. Very acidic and acidic soils account for over 50% of the area of Poland. To a great extent, this covers the share of very light and light soils. Very acidic and acidic soils account for 60%–80% of the area of the Voivodeships of Łódź, Mazowieckie, Podlaskie, and Podkarpackie. A special hazard is created by soils that are very acidic—a pH value below 4.5. They occupy over 40% of the agricultural use area of the voivodeships of Łódź, Mazowieckie, and Podlaskie, and over 35% of the Podkarpackie. Studies conducted over the years 2004–2007 indicate a maintaining of unfavorable tendencies in the matter of acidity of the soil in the Voivodeship of Łódź. Out of the 86,380 samples collected throughout the Voivodeship, 70% were very acidic or acidic, approximately 20% slightly acidic, and a mere 10% alkaline. The *powiat*s of Kutno and Łęczyca came out the as being the most favorable with acidic soils occupying only 37% and 45% of their area, respectively. A fall in soil pH to slightly acidic and acidic results in an increase in the concentration of mobile forms of heavy metals in a soil solution. They are available to plant and thus increase the indicator for their accumulation in tissues (Chłopecka 1994; Gębski 1998). This is caused by an increase in solubility of the chemical bonds of these elements as well as a decrease in absorption by soil colloids (Sady and Smoleń 2004). Cadmium and zinc are most susceptible to changes in the pH level. Their mobility starts to grow with a fall in pH below 6.0–6.5. Copper and lead do not demonstrate this property until pH < 5.0 (Gębski 1998).

Allowable content of heavy metals has been defined (as presented in Table No. 6) in order to protect the food chain against the harmful impact of these elements and in order to maintain balance in specific ecosystems. The basis for an environmental assessment of soil chemical properties is the reaction of individual elements of the ecosystem to various levels of pollution. It is for this purpose that three levels of soil pollution have been identified:

1) Natural chemical balance,
2) Upset chemical balance, and
3) Complete chemical degradation and significant threat to the ecological function of the soil.

Depending on the environmental factors taken into account, the values between levels 1 and 2 may vary. However, level 3 may be clearly defined for specific types of soil. Levels of selected heavy metals that cause complete chemical degradation of the soil are Cd – 5–20 mg kg^{-1}, Cu – 200–500 mg kg^{-1}, Ni – 150–600 mg kg^{-1}, Cr – 300–600 mg kg^{-1}, Pb – 1000–6000 mg kg^{-1}, and Zn – 1500–7000 mg kg^{-1} (Kabata–Pendias et al. 1995). These are critical values that rule out the proper functioning of the ecosystem, albeit significantly lower concentrations demonstrate the toxic impact of heavy metals on organisms. In the case of soil used for crop growing, especially plants designated for consumption by people and animals, the allowable levels of heavy metal pollution are significantly lower (Table No. 5).

Table 5. Boundary values for heavy metals in soils as specified in the annex to the directive of the ministry of environment on standards for soil quality

Contamination	**Group A**[2]	**Group B**[3]						**Group C**[4]	
		Depth (m ppt)							
		0–0.3	0.3–15.0		>15		0–2	2–15	
			Soil permeability (m s^{-1})						
			Above	Below	Above	Below		Above	Below
			1 10^{-7}		1 10^{-7}			1 10^{-7}	
Arsenic	20	20	20	25	25	55	60	25	100
Boron	200	200	250	320	300	650	1000	300	3000
Chromium	50	150	150	190	150	380	500	150	800
Tin	20	20	30	50	40	300	350	40	300
Zinc	100	300	350	300	300	720	1000	300	3000
Cadmium	1	4	5	6	4	10	15	6	20
Cobalt	20	20	30	60	50	120	200	50	300
Copper	30	150	100	100	100	200	600	200	1000
Molybdenum	10	10	10	40	30	210	250	30	200
Nickel (Ni)	35	100	50	100	30	210	300	70	500
Lead (Pb)	50	100	100	200	100	200	600	200	1000
Mercury (Hg)	0.5	2	3	5	4	10	30	4	50

Source: based on The Directive of the Minister of Environment of September 9, 2002 on Soil Quality Standards and Land Quality Standards (Journal of Laws of 2002, No. 165, item 1359).

Soils have been subdivided into six purity grades, where boundary values for heavy metal contents have been defined for each grade. Land throughout Poland has been described by voivodeship applying this classification system. Table No. 6 presents the percentage of individual grades of soil in the

[2] Land that is a part of the area subject to protection pursuant to the Water Code as well as areas protected pursuant to legislation covering environmental protection if the maintaining of the current state of soil pollution does not create a threat to human health or the environment.

[3] Land classed as agricultural land, excluding land designated for ponds and ditches, forest and wooded land as well as land with shrubbery, and built–up and urbanized land, excluding industrial land, mining land, and land for traffic circulation.

[4] Industrial land, mining land, and land designated for traffic circulation.

Voivodeship of Łódź and adjacent voivodeships, taking into account the most and least polluted voivodeships in Poland. Data from the year 1999 show that soil polluted by heavy metals accounts for less than 1% of the area of the Voivodeship of Łódź, where this pollution is highest in the *powiat*s of Łódź, Grodzisk, Opoczno, Pabianice, Pajęczno, and Zgierz (Ochal 2009).

Table 6. Agricultural land surface soil layer contamination by heavy metals (%)

Voivodeship	Number of samples	Degree of soil contamination[5]							
		0	I	II	III	IV	V	0+I	II–V
Łódzkie	3426	86.2	12.1	0.9	0.3	0.3	0.0	98.4	1.6
Kujawsko–pomorskie	3042	94.7	4.8	0.5	0.0	0.0	0.0	99.4	0.6
Mazowieckie	5971	91.7	7.4	0.7	0.1	0.0	0.0	99.2	0.8
Świętokrzyskie	2133	68.5	29.2	2.2	0.0	0.0	0.1	97.7	2.3
Śląskie	2187	20.3	52.8	17.0	5.6	3.0	1.3	73.1	26.9
Opolskie	1746	73.7	23.1	2.1	0.5	0.4	0.2	96.3	3.1
Wielkopolskie	4463	89.9	9.1	0.8	0.1	0.1	0.0	99.0	1.0

Source: based on Kabata–Pendias A. and Pendias H. (1999), *Biogeochemia pierwiastków śladowych (Bio–geo–chemical trace elements)*, 2nd Edition, Revised, PWN Scientific Publishers, Warsaw.

Recommended ways of use for specific soil purity grades:

0° – Uncontaminated soil – May be used for the growing of garden plants as well as agricultural ones, especially those designated for consumption by babies and children. Such areas should be encompassed by special protection against the introduction of anthropogenic heavy metals.

I° – Soil with an increased amount of metals – May be used for the growing of all field crops, with restrictions on vegetables designated for processing and direct consumption by children.

II° – Slightly contaminated soil – Plants grown on such soils may be chemically contaminated. For this reason it is necessary to exclude certain vegetables—e.g. cauliflower, spinach, lettuce, etc.—from being grown on them. However, cereals, root vegetables, and forage may be grown, and use for mowing and meadowlands is permitted. An alternative is the use of such land for the growing of energy crops.

[5] Degrees of soil contamination are described in the text.

III° – Moderately contaminated soil – Plants grown on such soils are exposed to contamination by heavy metals. The growing of cereals, root vegetables, and forage is recommended, where they should be periodically monitored for metal content in the consumable and fodder parts of the plant. Also allowed is the growing of industrial and energy plants and for the production of seed material. Groundwater may be at risk of pollution by heavy metals, especially cadmium, zinc, and nickel. In the case of meadowlands, they should be monitored for the intake of heavy metals by animals.

IV° – Strongly contaminated soil – It is especially light soils that should be excluded from agricultural production. It is recommended that better types of soils (heavier) should be used for the growing of industrial crops (hemp and linen), wicker, cereals and grasses (sowing material), potatoes, and cereals earmarked for the production of alcohol, rapeseed for technical oils, tree and shrub seedlings, etc. Green use should be restricted. Recultivation efforts are recommended, particularly liming and the introduction of organic substances. Such soils may be used for growing bio–energy crops.

V° – Highly contaminated soil – Such soils should be completely excluded from agricultural production and forested due to the travel of pollutants with soil particulate matter. The growing of selected varieties of energy plants with the most effective phytoremediation properties may significantly limit the transfer of heavy metals to successive food levels and be an alternative to forestation.

Rural areas are characterized by significant variety in terms of level of economic development, investment level, technical and social infrastructure development, as well as the affluence of the local government and the living conditions of the inhabitants. Changes taking place in the function of rural areas are a challenge for the nation’s agricultural and regional policy. Plant production for consumption should be located on the best soils, free of contaminants, while arable land with limited agricultural usefulness should be designated for the growing of optimally selected energy plants. To a great extent this requires a change in the manner of thinking of farmers and the participation of the local authorities in raising the awareness of inhabitants and conducting a campaign promoting the development of alternate energy sources. The relevant field units of the Voivodeship of Łódź that are responsible for oversight and the sanitary state of the soil should develop a constructive strategy that will work against anthropogenic pollution. These services should especially pay attention to the application of safe and modern technologies that have a favorable impact on protection of the natural environment.

4. Conclusion

Phytoremediation using energy plants is a cost effective, promising, and dynamically developing technology for cleaning the environment, especially large areas for which currently known mechanical methods for removing heavy metals is loss–generating and unjustified. The phytoremediation properties of energy plants make possible the use of poor and degraded soils for agricultural development to return a part of such soil to the sustainable agricultural environment. Phytoextraction is the only economically viable method for removing valuable trace elements from the soil, including gold, cobalt, and platinum. A major share of poor and polluted soils in the country require the immediate development of a constructive strategy for application of phytoremediation and its economic analysis in reinstating a sustainable environment.

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Streszczenie

EKONOMICZNE I GLEBOWE UWARUNKOWANIA ZASTOSOWANIA FITOREMEDIACJI W PRZYWRACANIU ZRÓWNOWAŻONEGO ROZWOJU ŚRODOWISKA

Celem niniejszego artykułu jest przedstawienie priorytetowych zagadnień i powiązań, dotyczących ekonomicznych i glebowych uwarunkowań zastosowania technologii fitoremediacji w przywracaniu zrównoważonego rozwoju środowiska. Analizie poddano zasadność stosowania fitoremediacji w przywracaniu zrównoważonego środowiska jako metody alternatywnej do kosztownej rekultywacji terenów w celu usuwania zanieczyszczeń, które jest niewykonalne do przeprowadzenia na dużych areałach. Wykazano opłacalność stosowania fitoremediacji w odzyskiwaniu pierwiastków śladowych z gleby w procesie phytominingu.

Przeanalizowano jakość gleb występujących w województwie łódzkim w aspekcie potencjalnego zastosowania metody fitoremediacji z uwzględnieniem podziału metali ciężkich zawartych w glebach uwzględniający ich pochodzenie oraz właściwości. Przedstawiono klasy czystości gleb i wyznaczone w nich graniczne zawartości metali ciężkich.