



Dariusz WŁÓKA¹, Marzena SMOL², Małgorzata KACPRZAK³

Energy efficiency of the phytoremediation process supported with the use of energy crops – *P. arundinacea* L. and *Brassica napus* L.

ABSTRACT: The objective of the experiment was to evaluate the energy efficiency of the phytoremediation process, supported using energy crops. The scope of conducted work includes the preparation of a field experiment. During the evaluation, 2 factors were into consideration – total energy demand and total energy benefit. The case study, used as an origin of data, consists a 3-years field study, conducted with the use of 2 energy crops – *Phalaris arundinacea* L. and *Brassica napus* L. The area subjected to the experiment was polluted with polycyclic aromatic hydrocarbons (PAHs) and herbicides, classified as phenoxy acids (2, 4 D). The experimental design consisted of 4 groups of fields, divided according to the used plant species and type of treatment. For each energy crop, 2 types of fertilization strategies were used. Therefore the 1st and 3rd sets of fields were not treated with any soil amendment while the 2nd and 4th sets were fertilized with compost.

✉ Corresponding Author: Dariusz Włóka; e-mail: dwloka@min-pan.krakow.pl

¹ Division of Biogenic Raw Materials, Mineral and Energy Economy Research Institute, Kraków, Poland; ORCID iD: 0000-0001-9087-3304; e-mail: dwloka@min-pan.krakow.pl

² Division of Biogenic Raw Materials, Mineral and Energy Economy Research Institute, Kraków, Poland; ORCID iD: 0000-0001-5833-2954; e-mail: smol@min-pan.krakow.pl

³ Institute of Environmental Engineering, Faculty of Infrastructure and Environment, Częstochowa University of Technology, Częstochowa, Poland; e-mail: mkacprzak@is.pcz.czest.pl



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The obtained data allowed to observe that the cultivation of *P. arundinacea* L. and *B. napus* L. allowed a positive energy balance of the process to be achieved. However, it should be noted, that the *B. napus* L. growth in the first vegetation season was not sufficient to fully compensate a total energy demand. Such a goal, in the mentioned case, was possible after the 2nd vegetation season. The collected results show also that the best energetic potential combined with the most effective soil remediation were obtained on the fields with the cultivation of *P. arundinacea* L. fertilized with compost. The number of biofuels, collected from the 1 ha of such fields, can reach a value equal even to 12.76 Mg of coal equivalent.

KEYWORDS: energy crops, phytoremediation, energy efficiency, organic pollutants, polycyclic aromatic hydrocarbons (PAHs)

Introduction

The European Union (EU) energetic policy, consisting in the “Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy” (COM/2015/080 final), puts an emphasis on the 3 key objectives, that can be described as actions aimed at energy efficiency, leadership within the field of renewable energies and the distribution of a fair deal for all consumers. The mentioned goals, in general, should provide both the sustainability in the energy sector and the prevention of the negative effects, that may inflict climate changes. Actions that are consisted in the estimated framework include: the decarbonization of energy production, an increase of green-job share within the energy sector, the decrease of the CO₂ emission and the increase of the overall share of removable energy production (Scarlat et al. 2015; Szulecki et al. 2016).

To reach the listed above objectives, dedicated changes both on the legislation and technological level should be undertaken. According to the statistics (EuroStat 2019), some European countries, including: the Netherlands (6.4% in 2017), Belgium (9.0% in 2017) or Poland (10.9% in 2017), still have a relatively small share of energy, that is produced from renewable sources. These values, due to the European Union recommendations, need to be increased to at least 15% in 2020. Therefore, it is important to evaluate new opportunities, conduct studies and commercialized new technologies that can contribute to the increase of the renewable energy resources production (GUS 2018; Chen 2017).

A potential generation of bio-based alternative fuels, such as biomass, can be given to the actions that can be classified as relevant for the noted aspect. According to the definition, included in the Polish Act on Renewable Energy Sources (Journal of laws 2015, item 478), biomass is a material, product, waste fraction or agriculture origin biological residues, that is biodegradable. Materials with such characteristics, due to the energy stored within the chemical bonds of organic matter, have a large utilitarian potential (Kozłowski 2018). Depending on the specific physical and chemical properties, biomass can be subjected to direct thermal conversion or in-

direct fermentation or gasification processes. The parameter that is critical for the biomass fate classification is its humidity. Dry materials can be burned easily, which makes them potentially useful for heat and electric power generation. Humid materials are, however, more unstable. Therefore biological processes are more relevant for the treatment of such materials. More complex descriptions of the individual conversion methods can be found in works published by Chen (2017).

One of the most efficient ways to produce a large amount of biomass is the cultivation of energy crops. Species, that make up this group of plants are characterized as fast-growing, and highly efficient in terms of cost and maintenance. Many organisms that have such properties are present in the region of Central Europe. The following species can be listed as an example: *Phalaris arundinacea* L., *Brassica napus* L., *Salix* L. or *Populus* L. (Lewandowski and Ryms 2013; Anawar and Strezov 2018).

One of the most interesting aspects, associated with the growth of the energy crops is the fact that according to legislation, this type of procedure has lower environmental and methodological restrictions than the cultivation of plants for food or animal feeding purposes. In practice, this feature can inflict the possible increase of the applicability range of this type of technology. For example, the energy crops can be used as tools, during soil phytoremediation. Such an approach was well described by scientists such as Pandey et al. (2016) and Trinh et al. (2019).

In general, the implementation of energy crops in soil remediation technology may be considered as a way to increase a share of biobased fuels production. This type of method, at the same time, can contribute to the improvement of environmental remediation efficiency and provide an additional stream of renewable energy resource in form of biomass, seeds, wood or even fruits and vegetables (resources for fermentation and bioethanol production) (Lewandowski and Ryms 2013). However, it should be also noted, that despite the listed benefits, the proposed procedure can be associated with the negative postprocedural effects. Increased soil carbon mineralization, point exhaustion of internal nutrients content or even increased CO₂ emission from soil can be given as the most important issues of such a case. Those problems are mainly applicable for the cases when the overall phytoremediation procedure is designed in an unsustainable way. To compensate those issues, a dedicated fertilization procedure, followed by the agrotechnical works, should be implemented. The proper development of this type of actions requires specific data, that can support the potential environmental risk assessment (Rosikon et al. 2015; Włóka et al. 2019).

The objective of the current study was to evaluate the energy efficiency of the phytoremediation method, supported using energy crops. The general approach during the implementation of a research task will be focused on the identification of trends within process energy input and output pathways. Such a procedure will allow a set of potentially useful information, that can, in the future, be used within legislation or technological sectors, to be collected.

1. Materials and methods

The scope of the work conducted under the experiment includes a preparation of 3-years case study and the calculation of the energy efficiency coefficients, on different stages of the phyto-remediation process. This method allows a possible change of the energy balance of studied soil remediation technology, supported with the use of 2 selected energy crops to be illustrated. Main parameters used for the energy efficiency evaluation were total energy input (work, material energy use – energy stored in seeds and fertilizers) and total energy output (the energy, that can be generated during the direct conversion of collected biomass and seeds). Based on the obtained data, a future prediction of possible changes in the energy balance was assessed within the studied systems.

1.1. Description of case study

The case study was conducted in *in situ* conditions. The area selected for the experiment was located in Silesia region of Poland, on the post agriculture terrain. This area was heavily polluted during the road renovation works. Some of residuals, that were generated during construction works, were stored on the near fields, which affects the soil condition. After the preliminary studies, this soil was classified as heavily polluted with polycyclic aromatic hydrocarbons (PAHs). The additional analysis also indicates that soil material from the selected area contains a load of herbicides from the phenoxyacids group – 2.4 D. This solution was used during the weed-control on fields subjected for study. The specific physical and chemical properties of soils that were collected from the area of the case study are presented in Table 1.

The designed experiment consists of 12 experimental fields, 9 m² each (3 × 3 m), divided into 4 groups according to the used energy crop and type of treatment. The *Phalaris arundinacea* L. was planted on first 2 sets of plots. *Brassica napus* L. was grown on 3rd and 4th sets of fields. The 1st and 3rd fields were not treated with any soil additive while the 2nd and 4th fields were fertilized with use of compost. The used compost was produced in the experimental composting site, located on the area of the Czestochowa University of Technology. Substrates used for composting procedure includes: sewage sludge collected from the food industry (65%), green wastes (30%) and households organic wastes (5%). Composting was carried out on out-door prisms. The physical and chemical parameters of this material are presented in Table 1. The doses of compost for the m² was equal to 0.45 kg of dry matter. The scheme of the experiment with additional indications of agrotechnical works and energy in-put/out-put routs are presented on Figure 1.

TABLE 1. The physical and chemical parameters of soil samples and compost samples

TABELA 1. Fizyczne i chemiczne właściwości gleby i kompostu

Parameter	P CS	P F	Compost for P	B CS	B F	Compost for B
Dry matter [%]	91.24 ± 1.12	90.28 ± 0.50	45.22 ± 1.05	92.14 ± 1.20	91.89 ± 0.10	48.10 ± 1.10
LOI [%]	5.14 ± 0.52	3.98 ± 0.20	84.22 ± 0.82	5.20 ± 0.46	4.46 ± 0.22	82.43 ± 0.42
pH (H ₂ O)	6.89 ± 0.10	6.88 ± 0.05	6.92 ± 0.05	6.79 ± 0.15	6.82 ± 0.02	6.92 ± 0.10
pH (KCl)	6.34 ± 0.05	6.30 ± 0.05	6.58 ± 0.10	6.40 ± 0.10	6.42 ± 0.08	6.48 ± 0.10
CEC [cmol(+) kg ⁻¹]	45.22 ± 1.10	39.54 ± 1.10	–	46.10 ± 1.12	42.09 ± 0.92	–
C [g kg ⁻¹ d.m.]	115.28 ± 5.37	99.51 ± 2.65	276.20 ± 8.21	120.08 ± 4.22	100.22 ± 1.10	240.10 ± 7.10
N [g kg ⁻¹ d.m.]	4.18 ± 0.22	3.82 ± 0.12	39.11 ± 2.82	3.98 ± 0.12	4.24 ± 0.14	42.81 ± 3.20
P [g kg ⁻¹ d.m.]	0.62 ± 0.18	0.70 ± 0.10	3.28 ± 0.10	0.78 ± 0.20	0.64 ± 0.02	4.86 ± 0.10
Cd [mg kg ⁻¹ d.m.]	1.04 ± 0.12	0.98 ± 0.12	0.24 ± 0.10	1.10 ± 0.02	0.92 ± 0.31	0.64 ± 0.18
Cr [mg kg ⁻¹ d.m.]	12.57 ± 0.08	9.59 ± 0.14	11.24 ± 0.41	12.05 ± 0.18	9.24 ± 0.08	12.14 ± 0.21
Ni [mg kg ⁻¹ d.m.]	0.82 ± 0.06	0.48 ± 0.15	0.08 ± 0.05	0.28 ± 0.16	0.08 ± 0.05	0.28 ± 0.07
Pb [mg kg ⁻¹ d.m.]	12.14 ± 0.20	9.20 ± 0.08	4.05 ± 0.18	10.42 ± 0.22	10.72 ± 0.05	2.27 ± 0.28

P – *P. arundinacea* L.; B – *B. napus* L.; CS – control samples (area not treated with fertilizers; F – area fertilized with compost, LOI – lost on ignition, CEC – cation exchange capacity. Results presented as means with standard deviations, n = 3.

1.2. Soil and compost sampling procedure

All the sampling procedures conducted during the study were conducted according to PN-I-SO 10381-1 standard and with regard to the statistical data standardization. In the case of soil and compost, the collection was conducted from 10 randomly chosen points located on the surface of each experimental fields (soil) and prism (compost). Next, the acquired materials were mixed and subjected to the drying in room conditions. The air dry material was additionally homogenized with use of ceramic mortar. Samples after the described above pre-treatments were subjected to individual analytical procedures.

1.3. Physical and chemical analyses

All the physical and chemical analyses were conducted according to the International Standardization System recommendations (ISO) and based on methodologies published in indexed scientific articles. The list of used analytical techniques includes: soil and compost pH analysis; soil, compost and biomass dry matter analysis; soil and compost lost on ignition (LOI); soil

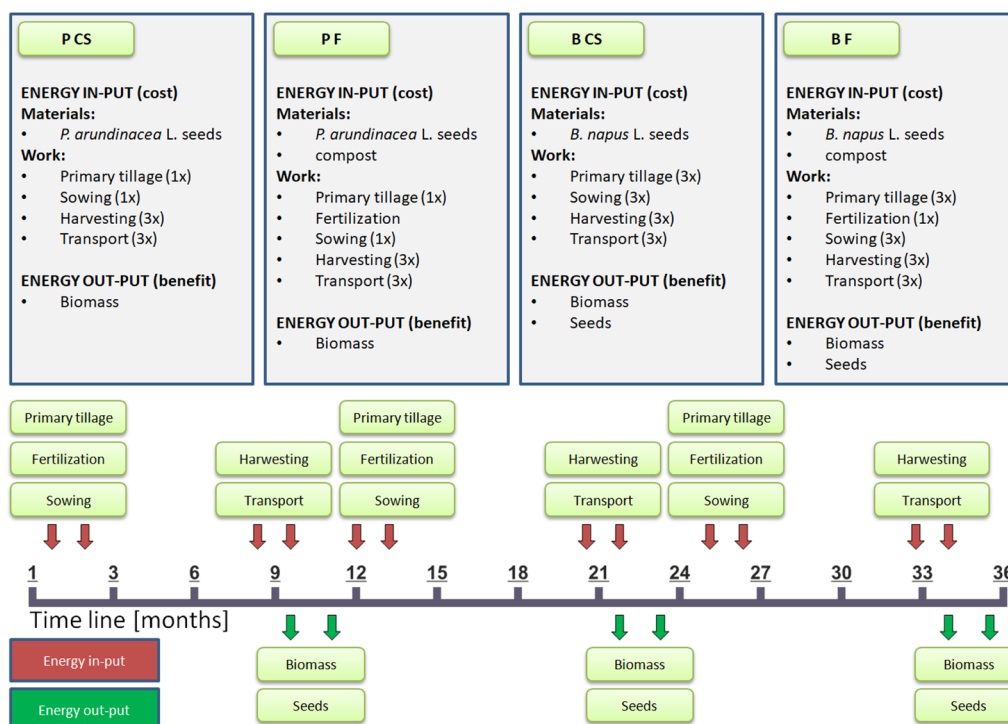


Fig. 1. The scheme of the experiment with additional indications of agrotechnical works scheduled across the studied period of time and energy in-put/out-put pathways.

P – *P. arundinacea* L.; B – *B. napus* L.; CS – control samples (area not treated with fertilizers);
 F – area fertilized with compost

Rys. 1. Schemat eksperymentu wraz z wykazem prac agrotechnicznych, zaplanowanych do przeprowadzenia w badanym okresie czasu oraz zaznaczeniem dróg kosztu i zysku energii

cation exchange capacity (CEC); soil, compost and biomass total carbon (C), nitrogen (N) and phosphorous (P) contents analysis (Karczewska and Kabała 2008; Tyszkiewicz et al. 2019); soil, compost and biomass heavy metals content (Cr, Cd, Ni and Pb) determination (Karczewska and Kabała 2008; Placek et al. 2018); biomass energy value – calorimetric analysis on LECO-system; PAHs and 2, 4 D analysis in soil, compost and biomass – HPLC technique according to Włóka et al (2015) and Smol et al. (2014). Each analysis was conducted in 3 replicants.

The evaluations of pollutants content in the soil and compost samples were conducted using Thermo Scientific SpectraSystem on columns: Restek Pinnacle II PAH (analysis of PAHs), Restek Ultra Aqueous C18 (analysis of phenoxyacids herbicides). External standards used during the analyses were: Restek 16 PAHs MIX A (16 PAHs according to US EPA: naphthalene (nap); 3-ring PAHs – acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene; 4-ring PAHs – fluoranthene, pyrene, benzo(a)anthracene, chrysene; 5-ring PAHs – benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene; 6-ring PAHs – indeno(1.2.3-c.d)pyrene, benzo(g,h,i)perylene) and Restek 2,4-D (2,4-Dichlorophenoxyacetic acid) solution.

1.4. Description of factors used for the estimation of process energy efficiency

The evaluation of the energy efficiency of the phytoremediation method was based on two main factors – total energy input and total energy output. The total energy input consists of 2 general types of energy demands: energy value associated with the conducted work (fuel consumption during agrotechnical works and transport) and energy stored within used materials (seeds, compost). In order to ensure a universal nature of the performed calculations, the parameters utilized within energy input, associated with work were based on the literature data (Grisso et al. 2004; Omid-Arjenaki et al. 2016). Those parameters include a total energy consumption in MJ (values calculated on the base of total diesel fuel consumption), needed to conduct the following tasks: primary tillage (agrotechnical works), seeds sowing, fertilization, harvesting of yield and the transportation of crops from remediated area to the unit responsible for the conversion of fuel into energy. The general units used during the evaluation, with the estimated energy demand values, for each mentioned task are presented in Table 2. It should be additionally indicated, that

TABLE 2. The list of all parameters used for the evaluation of the energy efficiency of the phytoremediation method

TABELA 2. Lista parametrów wykorzystanych podczas oceny efektywności energetycznej procesu fitoremediacji

Energy input – energy costs associated with work		
Parameter	Diesel fuel consumption [l ha ⁻¹]	Energy value [MJ ha ⁻¹]
Primary tillage	20.30	783.58
Fertilization	3.40	131.24
Sowing	3.10	119.66
Harvesting	13.80	532.68
Transport (10 km)	0.31	119.66
Energy input – materials energetic values		
Parameter	Main unit [kg ha ⁻¹]	Energy value [MJ ha ⁻¹]
<i>P. arundinacea</i> L. seeds	0.75	9.07
<i>B. napus</i> L. seeds	3.75	144.86
Compost	5700	15619.25
Energy output (predicted benefit)		
	Main unit [kg]	Energy value [MJ kg]
<i>P. arundinacea</i> L. biomass	1	14.68 ± 0.22
<i>B. napus</i> L. biomass	1	18.69 ± 0.05
<i>B. napus</i> L. seeds	1	38.63 ± 0.96

due to the different types of treatments and different growth characteristic of the selected crops species, the quantity of the implemented tasks, were different for each tested samples group. The detailed information about each samples group, with regard to the quantity and utilization of tasks is presented in Figure 1.

The total energy output was estimated on the base of the data collected during the realization of case study. Main parameters used for this purpose were the quantity of annual yield and the energy values of collected materials. For *P. arundinacea* L. only the generation of biomass has been taken into consideration, however the growth of *B. napus* L. allowed biomass and seeds to be obtained. Therefore, in case of *B. napus* L. cultivation the 2 types of potential energy resources were taken into consideration.

1.5. Post experimental data treatment

Data collected during the case study was subjected to the further evaluation with use of StratSoft Statistica and Microsoft Excel software. This procedure includes a calculation of the one-way ANOVA test and post-hoc Tukey test. Those analyses were aimed to evaluate the statistically valid differences and similarities within tested groups of samples. Additionally, in order to present a energy input changes across the tested period of time, the logarithmic trend lines for this parameter were plotted. The estimation of the final energy efficiency of studied method was presented as a energetic balance coefficient, which was calculated according to the following equation: $E_{\text{process}} = (\sum E_{\text{output}}) - (\sum E_{\text{input}})$, where the “E” is the energy value in J.

2. Results and discussion

2.1. Pollutants removal efficiency

The first set of data – figure 2, illustrates the pollution level on the studied area – parameter analyzed before the implementation of the phytoremediation technology. The second graph – Figure 3, presents the final effect of the tested process. This data contains a percentage of pollutants removal efficiency, noted after 3 vegetation seasons.

Based on the data consisted in Table 1, it can be noted, that the levels of pollutants in soils collected from the studied area are very high. According to other authors, the average 16 PAHs content, in European agricultural soils, stays in range from $63 \mu\text{g kg}^{-1}$ (Norway) to $700 \mu\text{g kg}^{-1}$ (United Kingdom) (Nam et al. 2008). In current study, the lowest observed

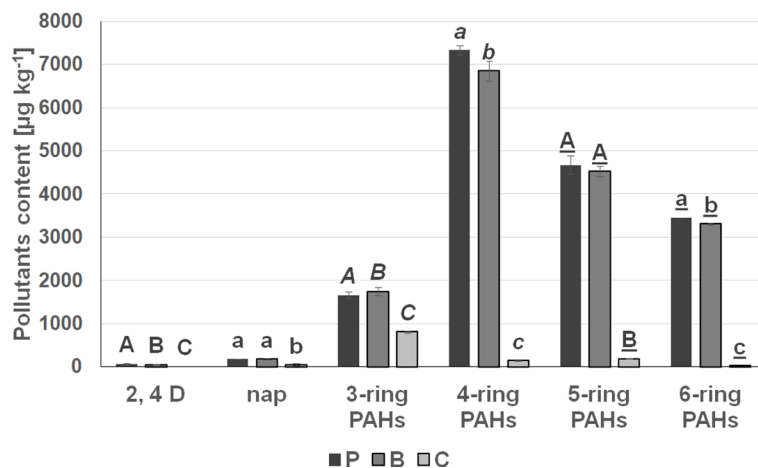


Fig. 2. The initial concentration of selected pollutants in soil and compost. Parameter analyzed before the implementation of phytoremediation method
P – *P. arundinacea* L.; B – *B. napus* L.; C – compost; nap – naphthalene. Results presented as means with standard deviations, n = 3

Rys. 2. Stężenie wybranych zanieczyszczeń w glebie i kompoście. Parametr analizowany przed wdrożeniem metody fitoremediacji

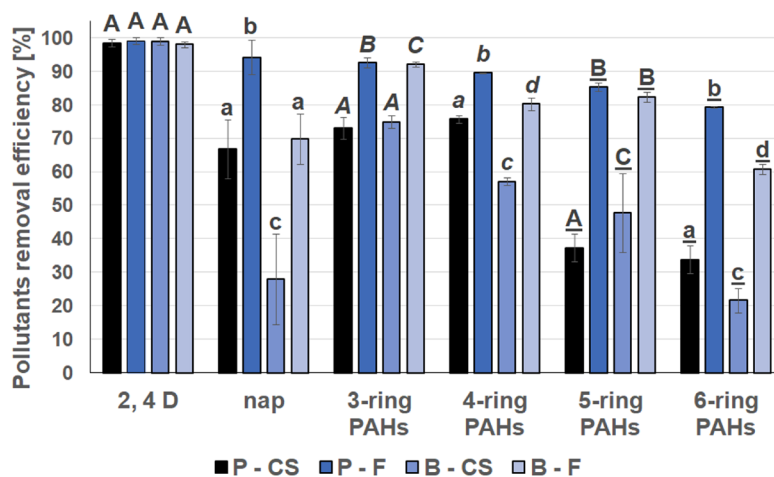


Fig. 3. The percentage pollutants removal efficiency, analyzed after 3 vegetation seasons
P – *P. arundinacea* L.; B – *B. napus* L.; CS – control samples (area not treated with fertilizers; F – area fertilized with compost; nap - naphthalene. Results presented as means with standard deviations, n = 3

Rys. 3. Procentowa skuteczność usuwania zanieczyszczeń, analizowana po 3 sezonach wegetacyjnych

values for this parameter were around 2.5 higher than those presented in mentioned work. The similar pollution level can be found in the industrial soils. Materials collected from the areas that are associated with the energy, transport or heavy industry sectors may contain a increased pollutants load, including PAHs (Bispo et al. 1999; Wang et al. 2017). The observed situation allows to confirm that the implementation of the soil remediation procedure on selected area was environmentally justified.

The evaluation of the second part of the data is presented in Figure 3. It shows that samples collected from fields treated with compost have a higher pollutants removal efficiency than control samples (fields not treated with any soil additive). The additional comparison of the studied parameter, regarding the used plant species indicates that cultivation of *P. arundinacea* L. has higher impact on the process efficiency than *B. napus* L. Similar trends were observed during earlier studies (Włóka et al. 2018, 2019), which may inform, that grass type of plants, such as *P. arundinacea* L. could have a higher tolerance to the negative influence of pollutants such as PAHs or herbicides from the phenoxyacids group. In the case of phenoxyacid herbicides, the mentioned effect is natural due to the action of 2, 4 D compound which is aimed at the inhibition of dicotyledonous plant growth (Robertson and Kirkwood 1970). The increased process efficiency, induced by the use of organic soil amendment, can be associated with the direct delivery of nutrients and various group of microorganisms into soil. Waste origin materials, such as compost, may contain a number of bacterial or fungi strains that are adapted to the raw conditions of the contaminated environment. Such a property may promote a positive interaction between pollutants and microflora, which in effect can lead to the better biodegradation efficiency (Kuppusamy et al. 2017; Sigmund et al. 2018).

The additional statistical data treatment showed that most of analyzed group of samples within the tested sets of data are statistically different to each other. Only the 2, 4 D removal efficiency for all types of treatments was statistically similar. This effect was associated with the fact that analyzed herbicides have a relatively short live time period in environmental conditions. Therefore the 3-years period combined with no additional weed-control, resulted in the high percentage removal in all tested cases. The statistically valid similarity between the samples treated with compost for both plant species was also noted in the set of samples associated to the percentage removal of 5-ringed PAHs. Such an effect may inform that the composting procedure independently of the used plant species, can increase the process efficiency.

In conclusion, it can be noted, that the proper selection of the plant species, combined with the dedicated soil fertilization, can lead to the highly effective pollutants removal from soil. During 3-years case study, the average decrease of pollutants level, in samples treated with compost, on fields where *P. arundinacea* L. was cultivated, reach a level higher than 89%. Such efficiency can be considered as a complete implementation of the general aim of polluted soil remediation procedure. A similar effect can be also found in results published by other authors, such as Huang et al. (2004) or Oleszczuk (2006).

2.2. The efficiency of biofuels (biomass, seeds) production

Biofuels production efficiency was assessed on the basis of the quantitative analysis of the annual yield generation, obtained from each group of samples during the completion of the case study. All the data collected for this purpose was converted into the equivalents for 1 ha. The demonstration of this set of results is presented in Table 3.

TABLE 3. The quantitative data of the yield collected during the implementation of phytoremediation

TABELA 3. Wielkość plonów uzyskiwanych podczas fitoremediacji

Parameter	Biomass [Mg ha ⁻¹]				Seeds [Mg ha ⁻¹]	
	P – CS	P – F	B – CS	B – F	B – CS	B – F
1 st vegetation season	0.995 _{±0.005}	2.626 _{±0.012}	0.012 _{±0.001}	0.625 _{±0.001}	0.001 _{±0.001}	0.010 _{±0.002}
2 nd vegetation season	2.188 _{±0.011}	6.173 _{±0.008}	0.174 _{±0.001}	0.866 _{±0.005}	0.015 _{±0.001}	0.064 _{±0.001}
3 rd vegetation season	4.512 _{±0.005}	7.922 _{±0.011}	0.500 _{±0.002}	1.123 _{±0.004}	0.054 _{±0.002}	0.205 _{±0.003}

P – *P. arundinacea* L.; B – *B. napus* L.; CS – control samples (area not treated with fertilizers; F – area fertilized with compost. Results presented as means with standard deviations, n = 3.

The data contained in Table 3 informs, that similarly as in case of pollutants removal efficiency, the highest amounts of yield were produced on fields treated with compost. *P. arundinacea* L. biomass generation. In this case it also was more efficient than the growth of *B. napus* L. This effect can be directly related to the pollutants removal trends described above. Both aspects of possible tolerance to the negative conditions and the delivery of nutrients may be considered as positive from the plant's growth and development perspective (Vendrame et al. 2005; Hussein et al. 2006). The comparison of the individual values, observed during the different vegetation seasons also indicates that both plants increased the yield production across the studied period of time. Thus, this can be associated with the decreasing content of pollutants. It is widely confirmed that compounds such as PAHs can have a toxic effect on the plants. Such an effect is highly correlated with the pollutant's concentration, which may be considered as an explanation of the observed phenomenon. The increased growth efficiency, during the further (2nd, 3rd) vegetation seasons can also be associated with the induced tolerance level of crops to the local environmental conditions (including the level of pollutants). Such an effect can especially be applied to the *P. arundinacea* L. specie. In contrast to *B. napus* L., the grass type of plants were sown once during the experiment. Therefore, growth in the 2nd and 3rd vegetation seasons has a secondary-characteristic, which may impact the increased adaptation mechanisms (Antosiewicz 1992; Calfapietra et al. 2015).

2.3. The energy efficiency of the phytoremediation process

The final assessment of the energy efficiency of the process conducted under the current study was based on data presented in graphs 4 (energy input), 5 (energy output) and Table 4 (the energy balance of the studied phytoremediation process).

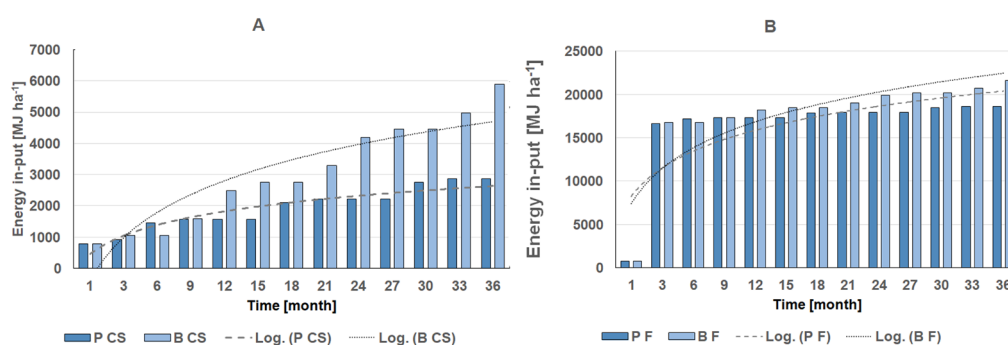


Fig. 4. The changes of the total energy input, during the implementation of the phytoremediation method. Graph (A) shows the data for plots not treated with any soil additives (control samples). Graph (B) consists of data for samples fertilized with compost. P – *P. arundinacea* L.; B – *B. napus* L.; CS – control samples (area not treated with fertilizers); F – area fertilized with compost.

Rys. 4. Zmiany zapotrzebowania energetycznego, zachodzące podczas realizacji fitoremediacji. Wykres (A) pokazuje dane dla prób nietraktowanych kompostem (próby kontrolne). Wykres (B) – dane dla prób nawożonych kompostem.

Values illustrated on Figure 4 showed that the samples treated with compost have the highest energy demand. This fact can be directly associated with the amount of material that should be introduced to soil in order to acquire an environmentally valid effect. It should be noted however that the proposed phytoremediation method includes only one fertilization procedure (in the beginning of the process). Such an approach originates from the fact that the general aim of the soil remediation is the removal of pollutants. Therefore, based on the results described in the previous sections, such an objective was achieved after the 3rd vegetation season. Due to this fact, further soil treatment should be considered as not technologically justified. The additional analysis of the logarithmic trend lines, plotted on the graphs associated with the energy input, allow to demonstrate that most of the energy consumption is associated with the initial preparation of the phytoremediation process. After agrotechnical works, the sowing of crops and soil fertilization, the curve stabilizes and rises only during yield harvesting and the transportation of obtained biofuels to the terminal unit. This means that the eventual prolongation of the proposed method should not significantly affect its energy requirements.

Another set of data presents the total energy output which can be achieved during the implementation of the phytoremediation technology, supported with the use of energy crops. Data demonstrated on graphs 4(A) and 4(B) are a direct conversion of the values included in Table 3. Therefore, it consists of a similar set of information. Based on this information it can be conc-

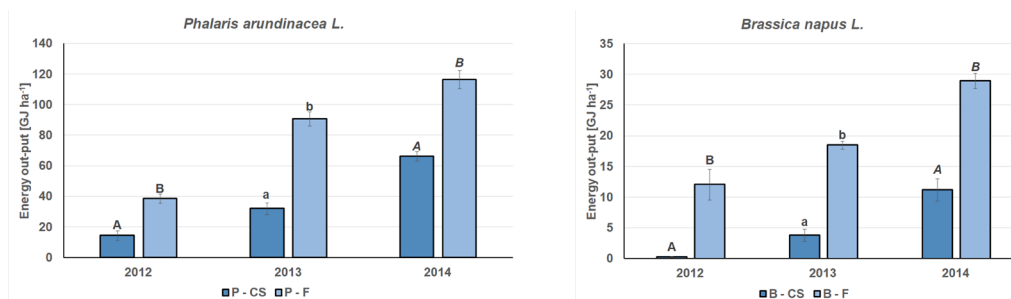


Fig. 5. The changes of the total energy output, during the implementation of the phytoremediation method

Rys. 5. Zmiany w korzyści energetycznej, zachodzące podczas realizacji procesu fitoremediacji

luded that from the energy generation perspective, the highest possible output can be generated through the cultivation of *P. arundinacea*, fertilized with compost. *B. napus L.* despite a possibility to collect 2 types of yield (biomass and seeds), in the evaluated case, showed lower values of the total energy output. Such a phenomenon may result from the fact, that some plant species that are cultivated in stress conditions may react in specific way. Based on the work published by Alkio et al. (2005), it can be noted that plants stress reaction induced by the exposure to PAHs, is mainly focused on the generative parts of the organisms. In such places the increased cell division reactions can be observed, which makes them vulnerable to toxic interaction between compounds from the PAHs group and the DNA molecules. Those interactions may lead to the appearances of errors within genes and further cell damage. From the macroscopic perspective, the mentioned reaction can be considered as an origin of the inhibition of the growth development of newly formed plant tissues, such as blooms and seeds (Maliszewska-Kordybach and Smreczak 2000).

After compressional analysis of the both sets of data, included in Figures 4 and 5, the estimation of the final phytoremediation process energy efficiency can be possible. The effects of such procedure are presented in Table 4. This set of data illustrates an energy balance between total energy consumption (energy input), on different stages of the performed phytoremediation technique and the total energy benefit (energy output) assumed on the base of the quantitative analysis of the obtained crops yield.

Values included in Table 4 informs, that almost all analyzed groups of samples, showed a positive energy balance. Only 2 groups of samples (B CS and B F) in 1st vegetation season showed a negative result. In the first case, (1st vegetation season of *B. napus L.* growth without fertilization), the quantity of both obtained biofuels types (biomass and seed) were at a very low level. Therefore, they cannot fully compensate the total work and material energy costs, associated with the initiation of phytoremediation method. The second negative result was directly associated with the high energy value, stored within the compost material. In this case both the seeds and biomass production were higher than in the case of the control sample. However, the obtained benefit still was not sufficient for the full coverage of the total energy demand. The rest of the analyzed samples groups were on levels which from the 1st vegetation season can provide

TABLE 4. The energy efficiency of the phytoremediation technology supported with the use of energy crops.

TABELA 4. Efektywność energetyczna procesu fitoremediacji, wspomaganego użyciem roślin energetycznych

Sample	Total energy in-put [GJ ha ⁻¹]	Total energy out-put [GJ ha ⁻¹]	Energy balance [GJ ha ⁻¹]	Black coal equivalent [Mg]
P CS – 1 st vegetation season	1.68	14.61	12.92	0.73
P CS – 2 nd vegetation season	2.34	46.74	44.40	2.50
P CS – 3 rd vegetation season	2.99	112.98	109.99	6.19
P F – 1 st vegetation season	17.32	38.55	21.23	1.19
P F – 2 nd vegetation season	17.97	129.18	111.21	6.25
P F – 3 rd vegetation season	18.62	245.48	226.86	12.76
B CS – 1 st vegetation season	1.58	0.26	-1.33	0
B CS – 2 nd vegetation season	3.28	4.08	0.80	0.04
B CS – 3 rd vegetation season	5.88	15.29	9.41	0.53
B F – 1 st vegetation season	17.33	12.06	-5.27	0
B F – 2 nd vegetation season	19.03	30.57	11.53	0.65
B F – 3 rd vegetation season	21.64	59.51	37.87	2.13

energy values higher than the total process energy demand. The best obtained energy efficiency was noted for fields where *P. arundinacea* L., fertilized with compost was cultivated.

Based on all data collected during the study, it can be indicated that the usage of energy crops as a remediation agent can provide a high environmental benefit and is justified from the energy usage perspective. Such an approach, despite direct soil remediation activity, allow for the additional generation of a new stream of removable energy resources in the form of biomass or other yield. In the current study, energy that can be generated from the collected materials can reach values that can be considered as an equivalent of even 12.76 Mg of black coal (*P. arundinacea* L. in the 3rd vegetation season with additional composting) or 2.13 Mg of black coal (*B. napus* L. the in 3rd vegetation season with additional composting) (Fisher 2003).

From the European Union's energy policy perspective, the results obtained during the study can be considered as a pilot case which through the presented data can attract increased attention to the described aspect of environmental management. The data collected under the execution of the proposed phytoremediation method informs that a possible increase of the commercialization of similar techniques can contribute to the increase of energy produced from renewable sources. These types of activities are very relevant, especially from the necessity to implement European Union strategy goals (Vassilev et al. 2015; Kulczycka et al. 2016).

The use of energy crops as remediation agents also has an additional important feature. The overall implementations of bio-based remediation technologies are associated with the induction

of biodegradation and organic matter mineralization. One of the products of such processes is the CO₂ – gas responsible for the generation of the greenhouse effect and future climate change. The implementation of plants into the system provides a possibility to preserve some amount of the emitted carbon within the growing biomass. Such an action is generally called carbon phytosequestration and should be more evaluated in more detail during the completion of future studies (Placek et al. 2017).

Conclusion

The wide implementation of the phytoremediation techniques which are supported with the use of energy crops can lead to an increase in the production of removable energy resources such as biomass or oil seeds. The highest energetic and environmental benefit were achieved using the *P. arundinacea* L. plant on fields additionally treated with compost.

This type of approach due to the joint effects of soil remediation and the introduction of green-fuels to the energy sector, can be considered as sustainable. This statement originates from the fact that the increased share of removable resources usage may affect the decreased secondary pollutants stream emission. Such an activity is very positive both from the environmental and social perspective, therefore it should be taken into consideration during future legislation and technology design.

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Dariusz WŁÓKA, Marzena SMOL, Małgorzata KACPRZAK

Efektywność energetyczna procesu fitoremediacji wspomaganego użyciem roślin energetycznych – *P. arundinacea* L. i *Brassica napus* L.

Streszczenie

Celem eksperymentu było dokonanie oceny efektywności energetycznej procesu fitoremediacji, wspieranego przez uprawy roślin energetycznych. Zakres prowadzonych prac obejmował przygotowanie badań polowych. Podczas oceny wzięto pod uwagę całkowite zużycie energii i całkowitą korzyść energetyczną uzyskaną z termicznej konwersji zebranych biopaliw. Badane studium przypadku składało się z trzyletniego doświadczenia, prowadzonego z użyciem 2 roślin energetycznych – *P. arundinacea* L. i *B. napus* L. Obszar objęty pracami zanieczyszczony był wielopierścieniowymi węglowodorami aromatycznymi (WWA) oraz herbicydami (2,4 D). Eksperyment składał się z 4 grup poletek, podzielonych według stosowanego gatunku roślin i rodzaju wykonanego zabiegu pomocniczego. Dla każdej z wybranych roślin zastosowano dwa rodzaje strategii nawożenia: poletka 1 i 3 nie były nawożone, poletka 2 i 4 natomiast nawożono kompostem.

Uzyskane dane pozwoliły zaobserwować, że uprawa *P. arundinacea* L. i *B. napus* L. pozwala osiągnąć dodatni bilans energetyczny procesu. Należy jednak zauważyć, że wzrost *B. napus* L. w pierwszym sezonie wegetacyjnym nie był wystarczający, aby w pełni zrekompensować całkowite zapotrzebowanie energetyczne. Osiągnięcie celu energetycznego we wspomnianym przypadku było możliwe po drugim sezonie wegetacyjnym. W doświadczeniu zaobserwowano również, że najlepszy potencjał energetyczny w połączeniu z najskuteczniejszą rekultywacją gleby uzyskano na polach z uprawą *P. arundinacea* nawożonego kompostem. Ilość biopaliwa zebranego z 1 ha pozwoliło osiągnąć wartość równą nawet 12,76 Mg ekwiwalentu węgla.

SŁOWA KLUCZOWE: rośliny energetyczne, fitoremediacja, efektywność energetyczna, zanieczyszczenia organiczne, wielopierścieniowe węglowodory aromatyczne (WWA)