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# Phytoremediation of Total Petroleum Hydrocarbons-Contaminated Soils: Case Study of Jerusalem Artichokes with Cost Analysis and Biomass Conversion

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**Abstract:** The application of environmentally friendly technologies, such as phytoremediation, for contaminated soil remediation and biofuel generation should be one of the goals of sustainable development. Phytoremediation is based on the use of plants and their associated microorganisms to clean contaminated soils, resulting in a positive impact on the environment and the production of biomass that can be utilized for biofuel production. Combining phytoremediation with advanced thermochemical conversion technologies like thermo-catalytic reforming process (TCR) allows for the production of high-quality biochar, bio-oil comparable to fossil crude oil, and hydrogen-rich syngas. This study presents a full-scale phytoremediation experiment conducted at a former oil storage site using energy crops like Jerusalem artichokes (*Helianthus tuberosus*), where the biomass was later converted into biofuel and other by-products using lab-scale technology. Significant and promising results were obtained: (i) within two years, the initial total petroleum hydrocarbons (TPH) contamination level (698 mg/kg) was reduced to a permissible level (146 mg/kg); (ii) the yield of the harvested Jerusalem artichoke biomass reached 18.3 t/ha dry weight; (iii) the thermochemical conversion produced high-quality products, such as a thermally stable oil a higher heating value (HHV) of 33.85 MJ/kg; (iv) the two-year phytoremediation costs for the rejuvenated soil amounted to3.75 EUR/t.

**Keywords:** thermo-catalytic reforming; Jerusalem artichoke; phytoremediation; field trials; biofuels

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## 1. Introduction

Due to industrial activities such as oil extraction, transportation, refining, and storage, a significant amount of oil has been and continues to be released into the environment. As a result, environmental pollution by total petroleum hydrocarbons (TPH) is one of the most widespread forms of contamination in the world [1–3]. The consequences of soil pollution caused by TPH can be dramatic for the soil's ecological functions. TPH contamination leads to reduced soil hydraulic conductivity, disruption of nutrient balance, impaired soil aeration, and inhibition of plant metabolism and microbial activity [4,5]. Soil contamination by TPH also impacts food security by reducing agricultural production and making crops potentially unsafe for consumption [6]. Therefore, the remediation of contaminated soils is essential to ensure better environmental conditions and public health.

As public concern about the surrounding environment grows and environmental regulations become stricter, there is increasing attention being placed on contaminated

sites and their remediation. Various physical, chemical, and biological methods are used to clean up contaminated areas. Some soil cleaning methods are complex, expensive, and may cause secondary environmental pollution. For example, physical methods such as excavating contaminated soil and treating it at designated facilities require significant logistical and operational costs, while chemical methods such as incineration lead to air pollution when combustion products are released into the atmosphere [7]. Consequently, biological methods like phytoremediation offer a sustainable and cost-effective alternative for managing contaminated sites [5,8,9]. Moreover, the application of phytoremediation contributes to climate change mitigation by sequestering carbon [10].

Despite the comprehensive benefits of phytoremediation in reducing environmental risks, it is essential to carefully consider the management of the harvested biomass in any soil remediation strategy. Consequently, phytoremediation is gaining increased attention as a sustainable method that does not compete with traditional agriculture for biomass production, as it can later be converted into value-added products such as biochar, compost, biomaterials, synthesis gas, and biofuels [11,12]. Additionally, the growing demand for biofuels intensifies the "food versus fuel" competition, and the continuous degradation of fertile soil quality further incentivizes the development and advancement of this concept [13].

The literature most frequently discusses methods for the use of remediated biomass, such as composting, incineration, gasification, and pyrolysis [14,15]. However, each of these methods has its own advantages and disadvantages. For example, composting is a simple and relatively straightforward method for biomass utilization, but there remains a risk that the prepared compost may be contaminated, particularly when dealing with the remediation of heavy metals. Incineration drastically reduces the volume of biomass and generates bioenergy, but the process also produces greenhouse gases (GHGs) and combustion residues that must be properly disposed of in designated landfills [16]. The same is true for gasification processes. Therefore, biomass utilization methods that do not create secondary pollution risks and generate higher value-added products are more advantageous. One such method is thermo-catalytic reforming (TCR®), an intermediate pyrolysis-based process. TCR® is a promising conversion technology for the production of liquid biofuels. The process offers a proven opportunity to convert biological wastes and residues into hydrogen-rich syngas, high-quality oil, and char without volatiles hazardous to health. The bio-oil produced from TCR® has a high carbon content, low water content, low oxygen content, and a high heating value, making it directly applicable as a feedstock in boilers or as a blend in dual-fuel engines. Another benefit of TCR® is the efficient design that can transform most of the introduced energy from the original feedstock [17,18].

A large number of excellent studies on phytoremediation have been published, but most of them are conducted under pot conditions and are focused on the soil cleaning process itself, aiming to improve the efficiency of the remediation process [19–23]. Not many field studies have been conducted, and topics such as the subsequent use of biomass are rarely discussed. Therefore, to enhance our understanding of issues related to the further use of biomass and to bridge the gap between laboratory and real-field conditions, full-scale trials were conducted. This study evaluated the potential of Jerusalem artichokes (*Helianthus tuberosus*) in remediating TPH-contaminated soils and assessed the soil's condition after phytoremediation and included an economic evaluation of the phytoremediation process. Additionally, the conversion of harvested biomass into biofuels and byproducts, such as bio-oil, syngas, and biochar, was validated using TCR® technology. Together, these findings established a foundation for understanding the practical applications of Jerusalem artichokes in both bioremediation and sustainable biomass utilization, offering valuable insights for future research and practical implementation.

## 2. Materials and Methods

### *2.1. Setup of Field Trials*

The contaminated site is in the northern part of Lithuania in the city of Šiauliai (55.903531, 23.259826). The soil on the site is contaminated with petroleum hydrocarbons. The contamination is of historical origin as the site operated as an oil base in the Soviet era. Since 2009, when the last oil tanks were removed, the site has been left unused. Loamy sand dominates the area; however, technosoil with a noticeable share of construction and demolition waste can also be detected. The total field area was 870 $m^2$.

Field tests were carried out in 2022–2023. The site was cleared of bushes and debris, deep tilled, harrowed, and fertilized (Table 1). Jerusalem artichokes were sown in May.

**Table 1.** Information on field preparation, sowing and fertilization.

| | **1st Year** | **2nd Year** |
|---|---|---|
| Soil preparation | Deep tillage<br>Power harrowing | Power harrowing<br>Stones and small debris were collected with a special raking tool.<br>Row formation with agricultural equipment, with a row spacing of 55 cm. |
| Seeding | 1.1 t ww/ha of planting material was used. Tubers were planted using a shovel at the depth of 0.10–0.15 m. The distance between the tubers in a row was ~0.4 m, and the distance between the rows was 0.7 m. | 1.65 t ww/ha of planting material was used. Tubers were planted manually in the preformed rows. The distance between the tubers in a row was ~0.4 m. |
| Fertilizers/soil additives | Vermicompost: 8.9 t ww/ha;<br>NPK(S) 12-11-18-8S (%): 0.60 t/ha;<br>Bacterial additive (a powdered biological material consisting of a blend of *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, *Pseudomonas putida*, and *Rhodococcus rhodochrous*): 500 kg/ha. | NPK(S) 12-11-18-8S (%): 0.60 t/ha;<br>Weed control: herbicide “Barbarian Biograde 360”, 2 L/ha. |

The plants were monitored during the growing season for pests and diseases. Weather monitoring was carried out by the Lithuanian Hydrometeorological Service Station. Both growing seasons passed without prolonged dry periods, but periodic heatwaves were observed. No storms, heavy rainfall, or hailstorms occurred, which could have destroyed the yield.

### *2.2. Soil Characterization*

Initial soil characterization was carried out before the start of field trials and after harvesting. Initial samples were collected in April 2021 before any soil movement with agricultural machinery. A composite soil sample consisting of a minimum of 3 sub-samples was collected for every depth. Composite soil samples were taken at four depths (0–0.2 m, 0.2–0.4 m, 0.4–0.6, and 0.6–1.0 m).

Soil samples were analyzed for pH (CSN ISO 10390); dry matter (CZ_SOP_D06_01_045, CZ_SOP_D06_07_046); organic dry mass (CZ_SOP_D06_07_047.A); P, K, (ISO 11885, samples prepared as per CZ_SOP_D06_07_P02), total N (ISO 11261), total C (ISO 10694), and TPH (TNRCC Method 1005, TNRCC Method 1006). These analyses were performed by ALS Czech Republic, s. r. o. The soil granulometric composition analysis was carried out at the Agrobiology Laboratory of the Institute of Agroecosystems and Soil Sciences within the Faculty of Agronomy at Vytautas Magnus University, Lithuania using the Mastersizer Hydro 2000MU soil testing device (Malvern Instruments Ltd., Malvern, UK).

### 2.3. Evaluation of Phytoremediation Process

Phytoremediation performance was evaluated in two aspects: (i) changes in soil parameters, including general soil properties and contaminants, and (ii) biomass output, which is critically important to make phytoremediation commercially feasible. The phytoremediation potential was evaluated as a ratio between contaminant concentration in the soil before and after the experiment.

### 2.4. Harvesting and Pelletizing

The Jerusalem artichoke's aboveground and belowground parts were harvested in mid-October 2022 and at the end of September 2023. The Jerusalem artichoke and amaranth plants were at the end of the blooming phase, phenological stage BBCH 69, when the stems of the plants were starting to lose their first leaves. Jerusalem artichoke aboveground biomass was harvested using disk trimmers, the biomass was laid into swaths, collected, and transported to the drying facilities after 2 days of field pre-drying. Belowground biomass (tubers) was harvested using manual tools and picked by hand.

The aboveground biomass of Jerusalem artichoke was dried in a hay shed-type facility for one month. After drying the aboveground biomass, it was milled with a regular feed-type grain mill, 6 kW of power through a 6 mm sieve, and with a 50 kg/hour output. The tubers were dried in the drying chamber (up to 50 °C) for 14 days.

To ensure successful biomass conversion, the harvested biomass needed to be pelletized. Milled biomass material was pelletized using a pellet mill CPM-2000 series (California pellet mill Co., Crawfordsville, IN, USA). The pelletizer chamber compression ring die ratio was 1:5, and the holes were 8 mm in diameter. Pellet length was <50 mm.

### 2.5. Thermochemical Conversion Trials

The biomass conversion trials were conducted using a TCR® lab-scale plant with a feed capacity of up to a maximum of 2 kg/h biomass. The plant is based on an advanced two-step intermediate pyrolysis process consisting of an auger reactor and a subsequent post-reforming (PR) unit. After the post-reforming step, the pyrolysis vapors are quenched, yielding a liquid fraction. This liquid is subsequently separated into oil and an aqueous phase for further utilization. The non-condensable gases pass through a primary, coarse gas-cleaning unit consisting of an electrostatic precipitator to eliminate contaminants and harmful particles inside the gas mixture. Biomass conversion tests were carried out with the aboveground biomass from the first year (2022) with different post-reformer temperatures (550 °C, 650 °C, and 750 °C). More details on the methodology can be found in Kick et al. [24].

Analysis of the feedstock and conversion products was performed using standard methods. The bulk density was measured by weighing the sample in a 1 L measuring cylinder. Elemental biomass analysis (C, H, O, N, S), was carried out using an elemental analyzer Vario Macro cube (Elementar Analysensysteme GmbH, Langenselbold, Germany), while the oxygen content was calculated by the difference. The initial moisture content of the feedstock was determined according to the ASTM E1756-08 (2015) standard. The total solids content was calculated as the total mass of the feedstock minus the measured moisture. Ash content was determined using the ASTM E1755-01(2015) standard. The volatile solids content was calculated as the total dry matter of the feedstock minus the measured ash content. The higher heating value was determined with an IKA C5000 bomb calorimeter (IKA-Werke GmbH & Co. KG, Staufen, Germany). The water content of the oil phase was measured according to ISO 760 using a Kompakt-Titrator 915 KF Ti-Touch (Deutsche Metrohm GmbH & Co. KG, Filderstadt, Germany). The kinematic viscosity of the bio-oil was measured according to ISO 3104 at 50 °C.

### *2.6. Cost Assessment of Phytoremediation*

The economic evaluation of the applied phytoremediation technology was carried out by assessing the required agricultural and remediation costs for operating 1 hectare of land. A cost–benefit analysis was conducted to assess agricultural expenses, with cost estimates derived from project-specific economic datasets. The analysis focused on the establishment and operational requirements of an 870 m² field trial involving the Jerusalem artichoke (*Helianthus tuberosus*) for phytoremediation purposes. The agricultural cost analysis was calculated using the agricultural activities database available at https://www.ktbl.de/ (accessed on 27 December 2024) and Microsoft Excel. Due to the highly confidential nature of the business data and the complexity of the information, the evaluation of the TCR technology is not provided.

At the Šiauliai site trial, phytoremediation direct and operational costs were split into agricultural and remediation expenses. In the first year, both pilot site establishment (including debris removal, deep power harrowing, leveling, and bacterial additive application) and agricultural activities (furrowing, seedbed preparation, fertilization, planting, biomass management, and tuber harvest for Jerusalem artichoke) costs were accumulated. In the second year, agricultural and operating costs were incurred. Overall, expenses were categorized into consumables, diesel/energy, labor, and crop monitoring—with certain activities (e.g., debris removal and deep power harrowing) performed only in year one.

## 3. Results and Discussion

### *3.1. Field Trials*

#### 3.1.1. Jerusalem Artichoke Yield

Table 2 presents the biomass output obtained in the Šiauliai site during field trials and a recalculated output for one hectare. Jerusalem artichoke yield in 2023 was almost five times higher than in 2022, increasing from 3.90 to 18.31 t/ha dw of total aboveground biomass and tubers. Aboveground biomass yield in 2023 was 10.17 t/ha dw and 8.14 t/ha tubers dw. This increase in yields was due to better agrotechnical solutions being adopted and row cultivation which was used to help deal with the increase in plant density and weed problems. For comparison with agricultural land in Lithuanian conditions, according to the literature, the Jerusalem artichoke's aboveground biomass yields were approximately 10 t/ha dw. The yield of tuber biomass reached 10.1 t/ha dw [25].

**Table 2.** Jerusalem artichoke yield.

| ***Biomass Origin*** | ***Parcel Area,* ha** | ***Total Biomass Yield,* kg ww** | | ***Total Biomass Yield,* kg dw** | | ***Biomass Yield,* kg/ha dw** | |
|---|---|---|---|---|---|---|---|
| | | 1st year | 2nd year | 1st year | 2nd year | 1st year | 2nd year |
| *Aboveground* | 0.0870 | 300 | 2465 | 110 | 885 | 1264 | 10,167 |
| *Tubers* | | 250 | 3016 | 57 | 709 | 2614 | 8144 |

#### 3.1.2. Soil Characterization

An important component of soil quality assessment is the identification of sensitive soil attributes that reflect the soil's capacity to function. Therefore, Table 3 presents the soil quality assessment results from the field trials over two years, including the initial results. The most commonly proposed indicators for soil quality assessment are organic matter, pH, C, N, P, and K [26,27].

**Table 3.** Soil characterization.

| | Sample Depth, cm | Total Solids, % | Organic Matter, % | pH | Microbial Biomass, CFU/g | Total C, % | Total N, mg/kg | $P_2O_5$, mg/kg | $K_2O$, mg/kg | Mg, mg/kg |
|---|---|---|---|---|---|---|---|---|---|---|
| Before field trial | 0–20 | 99.6 | 4.39 | 8.3 | 1,000,000 | 2.96 | 1.62 | 321 | 1041 | 9580 |
| | 20–40 | 99.4 | 3.16 | 7.7 | 41,000 | 2.25 | 2.72 | 386 | 1415 | 6843 |
| | 40–60 | 99.1 | 3.13 | 7.5 | 44,000 | 1.92 | 3.85 | 553 | 2019 | 4277 |
| | 60–100 | 99.2 | 2.46 | 7.8 | 51,000 | 2.29 | 1.78 | 504 | 3184 | 4820 |
| After 1st year field trial | 0–20 | 93.0 | 3.68 | 8.1 | 30,000,000 | 4.24 | 1390 | 369 | 367 | 432 |
| | 20–40 | 93.2 | 3.88 | 8.6 | 1,100,000 | 3.42 | 1120 | 53.8 | 179 | 204 |
| | 40–60 | 92.8 | 3.73 | 8.7 | 30,000,000 | 3.41 | 430 | 54.9 | 306 | 142 |
| | 60–100 | 88.9 | 4.75 | 8.2 | 12,000,000 | 3.48 | 717 | 58.8 | 358 | 176 |
| After 2nd year field trial | 0–20 | 89.3 | 3.19 | 8.5 | 1,800,000 | 3.65 | 1010 | 38.6 | 285 | 369 |
| | 20–40 | 87.8 | 3.35 | 8.5 | 1,800,000 | 4.03 | 571 | 34.9 | 250 | 309 |
| | 40–60 | 86.6 | 2.85 | 8.5 | 1,600,000 | 2.38 | 502 | 72.9 | 474 | 280 |
| | 60–100 | 88.4 | 1.84 | 8.6 | 1,600,000 | 1.51 | 400 | 101 | 762 | 393 |

A soil parameter like pH is considered a significant soil property as it determines nutrient accessibility and the physical condition of the soil controlling the diversity of microbes in the soil [28]. Comparing the initial soil test results with the results from the first and second years of field trials, it was observed that, except for the surface soil layer (0–20 cm), the soil pH increased; in some cases up to 1 unit. These soil pH results also correlate well with other authors' findings that Jerusalem artichokes tolerate alkaline soil well and can grow in soil with a pH of 8.1 to 8.7 [29].

Such pH changes can be associated with the application of agronomic practices and the incorporation of organic and mineral additives. Since all aboveground biomass was collected and the residues were not incorporated into the soil, along with the evident decrease in basic cations such as $K^+$ and $Mg^{2+}$ (Table 3), it is likely that the changes in soil pH were primarily influenced by plant activity [30]. Plant roots take up water and nutrients, grow, release exudates, and respire. Through some of these biological processes, plant roots can cause pH changes by releasing protons ($H^+$) or hydroxyl ions ($OH^-$) to maintain ion balance, depending on the nutritional status of the plants. Therefore, the pH of the rhizosphere can increase or decrease depending on the prevailing processes and the types of ions released. The dominant mechanism responsible for pH changes in the rhizosphere is the uptake of nutrients by plants in the form of cations and anions, primarily due to the high uptake of inorganic nitrogen by plants. When nitrates dominate within the soil or when their uptake is predominant, plants need to release bicarbonate or hydroxyl ions ($OH^-$) to maintain electrical neutrality at the soil–root interface, resulting in an increase in rhizosphere pH [30,31].

N, P, and K are considered essential soil nutrients that influence various soil properties, plant growth, and microbial activity [28]. It is evident that the application of mineral and organic fertilizers increased N reserves, but nutrients like P and K significantly decreased, especially in the upper soil layers where plant and microbial activity is most intense (Table 3). Numerous studies have been conducted to evaluate various fertilization rates for Jerusalem artichokes, but a universal fertilization solution has not yet been found. Fertilizers should be applied based on soil analysis results [29]. For example, Matías et al. [32] reported that NPK fertilization (9-18-27) at 600 kg/ha is sufficient to produce high aboveground biomass yield (22.7 t/ha); however, the authors did not find significant differences in this parameter at the higher fertilization rate of 1200 kg/ha. Therefore, based on the aboveground yield of the second-year field trials, it can be stated that the plants were adequately supplied with nutrients (Table 3). However, it seems that in the future, it may be necessary to consider increasing the P and K fertilization rates.

To prevent soil degradation, it is desirable for organic carbon in the soil to exceed the critical level of 10–15 g/kg (1.0–1.5%) [33]. In these trials, soil organic carbon was not

specifically measured; however, assuming that organic carbon constitutes a large portion of the total carbon in the soil (50–60%), we can infer that the organic soil carbon content ranged from 0.76% to 2.12%. Of course, such an interpretation of the results is somewhat speculative, and the exact percentage may vary depending on the soil type, condition, climate, and other factors. As seen in Table 3, an increase in the total C in the surface soil layer (0–40 cm) was observed in both the first and second years of the field trials, which suggests that the soil quality improved in this regard. However, this improvement is minimal and hovers around the threshold level.

Quantitative determination of soil bacterial count (in colony forming units (CFU)) is also an important soil health indicator. If CFU/g reaches $10^6$–$10^8$, the soil quality is considered good. Less than $10^6$ CFU/g indicates poor soil conditions, often caused by nutrient deficiency or abiotic stress from extreme pH levels or the toxicity of organic or inorganic pollutants [34]. Based on initial CFU results from Table 3, it is clear that before remediation, the soil condition was very poor, with CFU/g at a depth of 20–100 cm ranging from $4.1 \times 10^4$ to $5.1 \times 10^4$. However, the situation improved significantly after the first field season, with CFU/g reaching $3 \times 10^7$. Unfortunately, after the second season, CFU/g dropped to $1.6 \times 10^6$; however, it was still significantly higher than the initial results and meets the CFU criteria for good soil quality. The CFU increase can be linked to applied remediation strategies, including soil treatment and the use of mineral, organic, and especially biological additives, which led to a sharp rise in microbial numbers. The decline in the second year could be due to the non-use of biological and organic additives and the potential impact of rhizospheric selectivity on the structure and diversity of microbial communities. In contaminated environments, plants selectively recruit microbial communities that break down organic pollutants and promote plant growth, outcompeting less beneficial microbes [1,22,35–37].

#### 3.1.3. Phytoremediation Potential

Figure 1 shows the concentration of heavy (C10–C40) petroleum hydrocarbon fraction in the contaminated soil at the Šiauliai site before and after field trials. Since the site was used as an oil storage facility in the past, diesel and oil fractions prevailed over other contaminants. The light fraction petroleum hydrocarbons (C6–C10) were almost undetectable even during the initial characterization; therefore, it is not included in Figure 1 but the data can be found in Table 4. According to Lithuanian legislation, the maximum permissible concentration (MPC) for petroleum hydrocarbons in the soil in areas with low sensitivity is 200 mg/kg [38]. Therefore, the obtained results are highly promising. It was possible to reduce TPH pollution (from a maximum of 700 mg/kg) in all evaluated depths to the limit value within 2 years following the implementation of soil remediation measures.

The phytoremediation potential was evaluated as the ratio between the contaminants concentration in the soil before and after the experiment, and the results are presented in Table 4. Only values above unity show that the phytoremediation (degradation) process has occurred. The higher the value, the more intensive the process. However, there are values below unity, and in this case, this indicates that the contaminant concentration in the soil after the field trial was higher than before (after the first-year trial at a depth of 20–40 cm). This was due to several reasons: (i) the soil was tilled and thoroughly homogenized. It was likely that more contaminated soil was upturned and brought to the surface; (ii) TPH pollutants migrated vertically due to gravity and capillary forces and horizontally due to convection, dispersion, dissolution, volatilization, adsorption, and desorption. Therefore, the possibility that pollutants migrated from more contaminated layers to less contaminated soil layers cannot be ruled out [39]; (iii) soil contamination at the Šiauliai site was heterogenous. In the second year of the trial, the potential of

phytoremediation was several times higher than in the first year (Figure 1, Table 4). Such positive results in the second season could be due to the improved soil cultivation and preparation methodology.

**Table 4.** Phytoremediation potential at each sampling depth.

| Sampling Depth, cm | 1st Year | 2nd Year | Total |
|---|---|---|---|
| 0–20 | 1.37 | 3.49 | 4.77 |
| 20–40 | 0.66 | 4.75 | 3.15 |
| 40–60 | 1.00 | 1.12 | 1.12 |
| 60–100 | 1.00 | 1.55 | 1.55 |

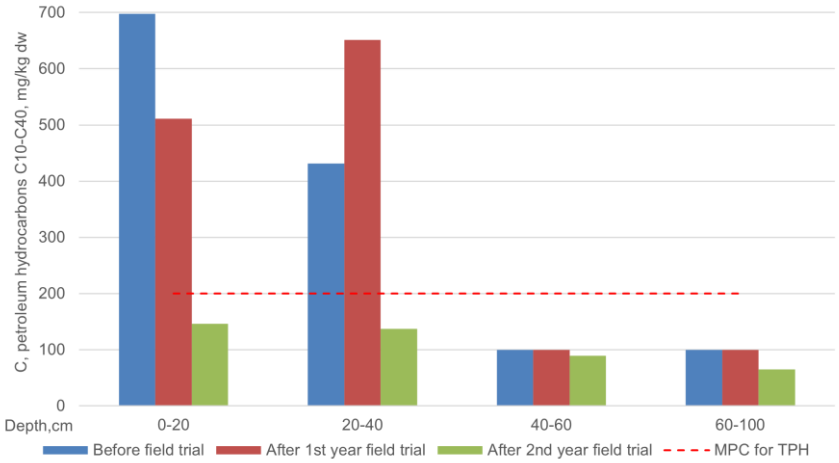



**Figure 1.** The concentration of petroleum hydrocarbons in the contaminated soil before and after the field trial.

According to other researchers, the Jerusalem artichoke is an excellent candidate for the phytoremediation of heavy metals (Cd, Cu, Fe, Mn, Ni, Zn, Pb, and Hg) [40–42]. However, information about TPH remediation is scarce. Only a few sources can be found where studies that examine different types of pollution. One such study was conducted in 2019 in the Ivano-Frankivsk region of Ukraine, at an active oil deposit. Unfortunately, the published information on this study is limited and lacks specificity, limited to conclusions such as "Jerusalem artichoke grows well in highly contaminated soil" [43]. This study is more detailed, revealing that during the field trial the overall two-year phytoremediation potential ranges from 1.12 (at a depth of 40–60 cm depth) to 4.77 (at a depth of 0–20 cm depth) (Table 4).

### *3.2. Thermochemical Conversion*

Thermochemical conversion was not applied to tubers because it was determined that it would not be energetically efficient due to the high energy consumption required for their drying and pelletization. Such feedstock is better utilized for producing various bioproducts (e.g., ethanol, biodiesel, 2,3-butanediol, lactic acid, etc.) and biogas [44–46]. For example, ethanol production from Jerusalem artichokes ranges from a minimum of 1500 L/ha to a maximum of 11,000 L/ha [47]. All the following thermochemical conversion research results were obtained from studies conducted on the aboveground biomass of Jerusalem artichokes from the first year of the study.

Table 5 shows an analysis of the feedstock. After analyzing the feedstock, it was determined that the moisture content slightly exceeded the recommended limit. A moisture content higher than 10% reduces the efficiency of thermal conversion and requires excessive heat during pyrolysis. However, in this case, the observed excess is insignificant and did not affect the subsequent thermo-catalytic conversion process [48]. Feedstock with a high

volatile matter content reacts faster and devolatilizes more efficiently compared to feedstock with a low volatile matter content. In these studies, the volatile solids (VS) were found to be 73.49%, which is similar to feedstocks such as wheat husk and wheat straw pellets [48]. The ash content in Jerusalem artichoke biomass was 26.51%, which may raise some concerns, as a high ash content can lead to contamination, slag formation, and corrosion risks, as well as reduce the devolatilization rate [49]. The high ash content in Jerusalem artichoke biomass is most likely due to inorganic materials present in various aboveground plant parts, such as leaves, leaf bases, stem internodes, and nodes [48].

**Table 5.** Biomass feedstock analysis.

| Total Solids (TS), % | Volatile Solids (VS), % | Bulk Density, kg/m3 | HHV, MJ/kg | N, % | C, % | H, % | S, % | O, % | Ash, % |
|---|---|---|---|---|---|---|---|---|---|
| 89.48 | 73.49 | 609.2 | 17.84 | 1.43 | 44.12 | 6.11 | 0.21 | 21.62 | 26.51 |

The higher heating value of the used feedstock reached 17.84 MJ/kg (Table 5). Following the same research concept, shown in Kick et al. [23], the HHV of Jerusalem artichoke was higher by 0.84 MJ/kg compared to rapeseed and by 4.04 MJ/kg compared to the herbaceous plant mix which was analyzed in previous trials. Furthermore, when comparing these feedstocks, Jerusalem artichokes exhibit lower volatile solids (VS) and oxygen (O) but higher carbon (C) and ash content. Similar trends are also observed when comparing the characteristics of Jerusalem artichoke biomass with traditional feedstocks such as straw [50,51].

The conversion trials indicate that the biomass from Jerusalem artichokes can be effectively transformed into energy-dense intermediates using thermo-catalytic reforming technology (Figure 2). Most of the initial mass is converted to TCR®-gas independent of the applied post-reformer temperature. Biochar is the second largest fraction, followed by the aqueous phase and the bio-oil. Figure 2 also illustrates a clear relationship between product distribution and the post-reformer temperature. The TCR®-gas fraction declines at a lower post-reformer temperature (550 °C), whereas the fractions for bio-oil, aqueous phase, and biochar increase. The losses shown in Figure 2 correspond to product residues within the TCR®-unit during the recovery of the TCR®-products.

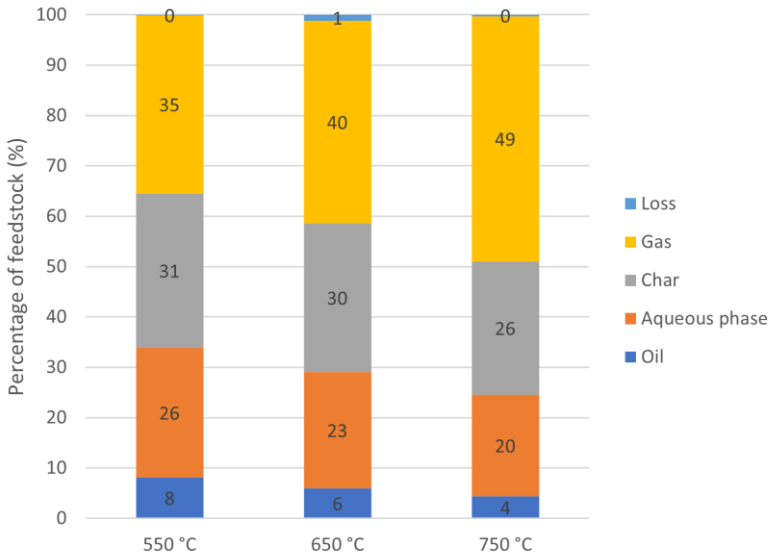



**Figure 2.** Mass balance of the conducted TCR® trials.

After the mass balance, an energy balance was conducted to gain insights of the energy distribution within the TCR®-products. Figure 3 shows the energy distribution within the TCR®-products. According to Figure 3, most of the TCR®-product's energy is present in the TCR®-gas. About 49% of the product's energy can be found in the TCR®-gas for a post-reformer temperature of 750 °C. In analogy to the changing mass distribution at lower PR temperatures, the energy distribution within the TCR®-products also shifts in favor of biochar and bio-oil. The energy content of the aqueous phase is not considered in the energy balance as it normally has a specific energy content of less than 0.2 MJ/kg [52].

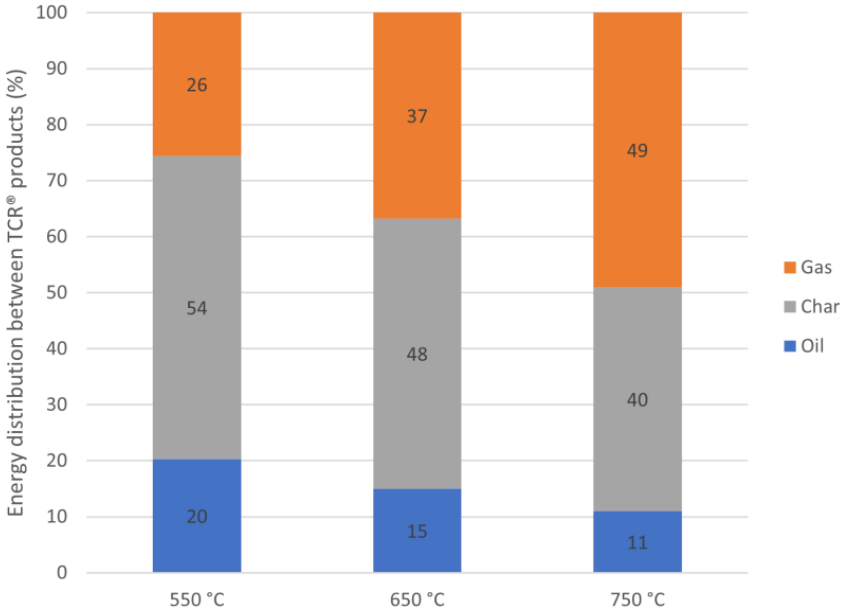



**Figure 3.** Energy balance of conducted TCR® trials.

The conversion trials conducted with Jerusalem artichokes from organically polluted soil indicate that they can be effectively transformed into energy-dense intermediates using thermo-catalytic reforming technology. The most energetically valuable product is the oil, whose HHV at a temperature of 750 °C reaches 33.85 MJ/kg (Table 6). This is slightly lower energy content than that observed in previous studies with a herbaceous plant mix and rapeseed used as feedstock, measured at 34.7 and 34.4 MJ/kg, respectively [39]. In comparison to fast pyrolysis oils, TCR® oil has a low water content. Water in oil not only lowers viscosity and NOx emissions but also boosts the formation of polar-acidic compounds [53]. Due to the low water content, TCR® oil exhibits several interesting and unique properties, such as miscibility with ethanol, biodiesel, vegetable oil, gasoline, diesel, and crude oil [17].

**Table 6.** Analytical results of biorefinery products.

| | Char | | | Oil | | | Aqueous Phase | | |
|---|---|---|---|---|---|---|---|---|---|
| | **550 °C** | **650 °C** | **750 °C** | **550 °C** | **650 °C** | **750 °C** | **550 °C** | **650 °C** | **750 °C** |
| HHV, MJ/kg | 22.42 | 21.58 | 20.23 | 31.91 | 33.38 | 33.85 | | <0.2 | |
| N, % | 1.06 | 1.2 | 1.27 | 3.05 | 4.26 | 4.22 | 1.25 | 2.67 | 3.33 |
| C, % | 62.74 | 63.34 | 60.39 | 64.24 | 70.24 | 75.48 | 3.14 | 3.19 | 3.09 |
| H, % | 1.83 | 1.21 | 0.7 | 9.06 | 8.79 | 7.99 | 11.37 | 11.53 | 11.42 |
| S, % | 0.13 | 0.22 | 0.6 | 0.15 | 0.3 | 0.38 | 0.04 | 0.03 | 0.1 |
| O, % | 2.02 | 1.15 | −0.86 | 23.5 | 16.4 | 11.94 | 84.2 | 82.58 | 82.06 |
| Ash, % | 32.22 | 32.88 | 37.9 | | - | | | - | |
| Water content, % | | - | | 8.09 | 5.69 | 1.75 | | - | |

When evaluating the HHV of biochar, this study obtained a significantly higher energy content of 22.42 MJ/kg, whereas in previous studies it was about 14 MJ/kg [24]. Although many properties of the feedstock are similar to wood chips, the properties of biochar differ significantly. For example, after the catalytic reforming step at 700 °C, the HHV and carbon content of biochar from wood chips are 30.6 MJ/kg and 84.9%, respectively [54]. The oxygen content gradually decreases with higher reforming temperatures which indicates a higher stability of the char at higher temperatures. The negative value of −0.86% at a reforming temperature of 750 °C is a purely theoretical result of the individual measuring inaccuracies of the applied analytical methods. It is most likely that it is lower than for the other reforming temperatures but still positive, as it cannot be negative.

Depending on the properties of the feedstock and the process parameters used for biochar production, biochar can have a wide range of applications. Biochar can be used as a biosorbent, a soil amendment, or as a fuel for combustion and gasification processes [17]. From the biochar results presented in Table 6, it can be observed that the biochar obtained from Jerusalem artichoke feedstock has a high ash content (32.22–37.9%), which arises due to the transformation of inorganic materials into alkali and alkaline metal oxides during reforming. This high ash content indicates the biochar's alkaline nature, which is desirable for soil amendment properties [48].

Biochar is also a promising alternative to conventional traditional carbon-based catalysts, which are environmentally unfriendly and expensive [18]. Biochar acts as a reducing medium converting metal oxides into the metallic state, thus enhancing catalytic performance [55]. Specifically, previous research planned to use the produced biochar as a reducing agent in the metallurgical industry. Experiments related to the reactivity of biochar derived from herbaceous plant mix and rapeseed revealed promising properties (biochar from Jerusalem artichoke has not been tested yet), suggesting that industrial use of biochar in metallurgical processes should be feasible [24]. Therefore, similar results are expected to be achieved with Jerusalem artichoke feedstock.

The gas yields and the gas composition depend on the post-reforming temperature (Table 7). At higher reforming temperatures the gas yield increases. The largest differences can be found in the decrease in $CO_2$ and the strong increase in $H_2$. In terms of hydrogen production, high post-reforming temperatures offer the best performance (at 750 °C, yielding 39.63 vol. % $H_2$) (Table 7). A similar concept in the H2020 EU project "CERESiS" which gasified contaminated biomass under supercritical water conditions at 650 °C resulted in approximately 30 vol. % $H_2$ and about 50 vol. % $CO_2$ in the produced gas [56]. Thus, in terms of energy value and sustainability, TCR technology is superior to technologies such as conventional pyrolysis or gasification [52].

**Table 7.** Composition of gas products.

| | Gas | | |
|---|---|---|---|
| | **550 °C** | **650 °C** | **750 °C** |
| HHV, MJ/kg | 9.2 | 12.06 | 13.49 |
| $N_2$, vol. % | 2.45 | 2.35 | 2.23 |
| $H_2$, vol. % | 24.88 | 35.78 | 39.63 |
| CO, vol. % | 8.87 | 12.94 | 20.09 |
| $CO_2$, vol. % | 33.37 | 27.79 | 23.27 |
| $C_xH_y$, vol. % | 32.88 | 23.5 | 17.00 |
| Density, kg/m³ | 1.22 | 1.06 | 0.97 |

### *3.3. Cost Assessment of Phytoremediation*

The cost analysis of agricultural and remediation-related activities indicated that approximately 20,780.67 EUR was required to remediate 1 hectare of contaminated soil using Jerusalem artichoke, during the first year of establishment (Table 8). Despite this, it was ob-

served that during the second year of phytoremediation, the expenses dropped significantly to 3958.49 EUR (Table 8). In conclusion, based on the remediation of a 40 cm soil layer over a two-year period, the average cost of phytoremediation per ton of soil was calculated to be 3.75 EUR. This is a competitive and attractive soil remediation cost compared to other methods such as thermal treatment (48–141 EUR/t), soil washing (49.29–256.08 EUR/t), bioventing (6.51–37.20 EUR/t), and landfarming and biopiling (19.53–110.11 EUR/t) [57].

**Table 8.** Estimated costs for the remediation of 1 hectare of contaminated soil using Jerusalem artichoke.

| Type of Cost, EUR/ha | 1st Year | 2nd Year |
|---|---|---|
| Consumables | 15,444.00 | 1502.20 |
| Diesel | 3553.23 | 672.86 |
| Labor | 325.44 | 325.44 |
| Monitoring | 1458.00 | 1458.00 |
| TOTAL | 20,780.67 | 3958.49 |

Mostly due to the first year costs, which consisted of site preparation and remediation establishment activities (74%): debris removal, deep power harrowing, and leveling for pilot site homogenization, and application of a biological additive (Figure 4). In the second year, with a significant reduction in consumable expenses, the costs were distributed as follows: 38% for monitoring, 37% for consumables, 17% for fuel, and 8% for labor (Figure 4).

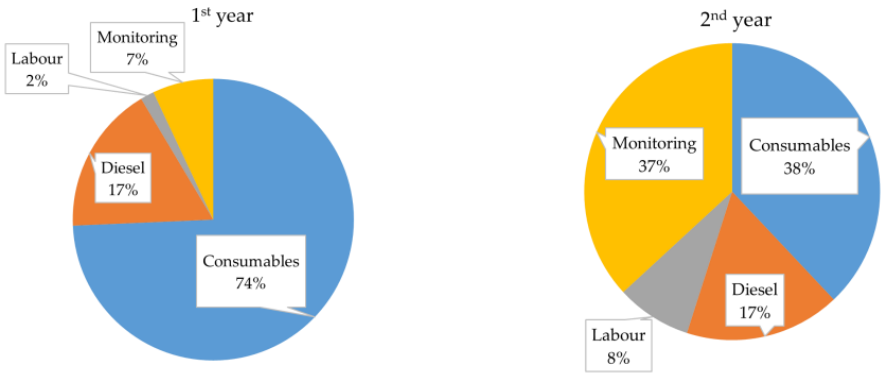



**Figure 4.** Cost analysis for the remediation of 1 hectare of contaminated soil.

It was estimated that up to 87% of the consumable expenses incurred in the first year were attributed to the use of the biological additive. To enhance TPH degradation, approximately 400 kg of bacterial additive would need to be used per hectare, with a market price of 28 EUR/kg. The use of bacterial additives, which stems from remediation activities, would account for about 50% of the estimated budget. Therefore, the use of any additive should be carefully evaluated.

## 4. Conclusions

The results of the conducted study confirm the idea that combining phytoremediation with biofuel production is a sustainable and technologically promising method for biofuel production and contaminated soil remediation. By using plants such as the Jerusalem artichoke and applying appropriate biotechnological and agronomic solutions, it is possible to reduce low concentrations of TPH contamination in soil to permissible levels within two years. Our study shows that the yield of aboveground biomass from contaminated soil can match or exceed that from clean arable land, reaching over 10 tons per hectare.

Thermo-catalytic reforming is a suitable method for producing high-quality products from the aboveground biomass of Jerusalem artichokes. This process produces hydrogen-rich gas, oil with low oxygen and water content, and biochar. The quantity and quality of

these products depend on the post-reforming temperature. The hydrogen-rich gas can be used in dual-fuel engines, as syngas, or for hydrotreating TCR® oil. TCR® biochar can be an excellent fuel source in the metallurgical sector, or act as a carbon sink, and, due to its large surface area, can be converted into activated carbon. The bio-oil has promising properties such as low water content, combustibility, low oxygen content, and high carbon content.

The initial soil composition and physical condition of the site are crucial factors that influence the cost. The cost analysis showed that the first year of phytoremediation using the Jerusalem artichoke required significant expenses, mainly for site preparation and biological additive application, with the additive accounting for 87% of consumable costs. In the second year, costs dropped significantly, with the majority allocated to monitoring and consumables. Overall, the average cost per ton of soil treated over two years was 3.75 EUR.

In conclusion, the conducted research significantly contributes to a better understanding of the issues related to biomass obtained after phytoremediation and potential solutions, as well as helps reduce the gap between laboratory and real-field studies. It is expected that these results will provide both practitioners and researchers with a clearer and more accurate view of the methodological and technological aspects, as well as cost analysis. Furthermore, this study is expected to inspire new large-scale phytoremediation studies with Jerusalem artichokes, addressing the processing of tubers and the effectiveness of soil remediation at higher pollution levels.

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