CLEAN BIOFUEL PRODUCTION AND PHYTOREMEDIATION SOLUTIONS FROM CONTAMINATED LANDS WORLDWIDE

Ortner, M.[1]; Otto, H.J.[1]; Brunbauer, L.[1]; Kick, C.[2]; Eschen, M.[3]; Sanchis, S.[4]; Audino, F.[4]; Zeremski, T.[5]; Szlek, A.[6]; Petela, K.[6]; Grassi, A.[7]; Capaccioli, S.[7]; Fermeglia, M.[8]; Vanheusden, B.[8]; Perišić, M.[8]; Young, B.[9]; Trickovic, J.[10]; Kidikas, Z.[11]; Gavrilović, O.[12]; Blázquez-Pallí, N.[13]; López Cabornero, D.[14]; Jaggi, C.[15]; Klein, V.[16].

[1]ITS Förderberatung, Vienna, Austria
[2]Fraunhofer UMSICHT, Fraunhofer Institute for Environmental, Safety, and Energy Technology, Sulzbach-Rosenberg, Germany
[3]Aurubis, Hamburg, Germany
[4]Leitat, – Technological Center, Terrassa, Spain
[5]Institute of Field and Vegetable Crops, Novi Sad, Serbia
[6]Silesian University of Technology, Gliwice, Poland
[7]ETA – Florence Renewable Energies, Florence, Italy
[8]Hasselt University, Hasselt, Belgium
[9]Inta, Castelar Centre - Buenos Aires, Argentina
[10]University of Novi Sad Faculty of Sciences, Novi Sad, Serbia
[11]Biovala, Rietavas, Lithuania
[12] Public Water Management Company Vode Vojvodine, Novi Sad, Serbia
[13]Litoclean, Barcelona, Spain
[14]Exolum, Madrid, Spain
[15]Pro Umwelt, Schwerin, Germany
[16]Trägerverein Umwelttechnologie-Cluster Bayern e.V, Augsburg, Germany

ABSTRACT: The overall objective of the H2020 Phy2Climate project is to build the bridge between the phytoremediation of contaminated sites with the production of clean drop-in biofuels. As the project aims for the production of high-quality drop-in biofuels like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590), a biorefinery concept is employed with the thermo-catalytic process (TCR®) at its centre. The produced biofuels will present no Land Use Change risks, thus, the phytoremediation will decontaminate lands from a vast variety of pollutants and make the restored lands available for agriculture, while improving the overall sustainability, legal framework, and economics of the process. In this way, Phy2Climate aims at significantly contributing to the Mission Innovation Challenge for sustainable biofuel production and to almost all UN Sustainable Development Goals, as well as to the EU Biodiversity Strategy for 2030, that is part of the European Green Deal, and to the new EU Soil Strategy for 2030 adopted in 2021. On the one hand, it is unquestionable that there is a growing demand for land, which increases tensions among the different groups of users. Land is a finite resource, and the main competitors are Feed, Food & Fuel. From the available worldwide arable land, about 71% is dedicated to animal feed, about 18% to food and only about 4% to biofuels (another 7% is for material use of crops). The multiple uttered food vs fuel debate is, actually, a food vs feed debate. However, the increasing demand for biofuels and biobased products also contributes to this tension, but in a much smaller dimension. The increasing land demand for energy crops leads to direct and indirect Land Use Change (iLUC), causing deforestation, soil erosion, loss of biodiversity and vital water resources. On the other hand, there is a significant area of land which is contaminated and, therefore, unusable for any purpose. Even worse, the investigation, registration as "contaminated site", as well as the remediation and management of such areas are very cost-intensive, adding even more fuel to the fire.
Keywords: phytoremediation, energy crops, biofuel, biochar, Thermo-Catalytic Reforming (TCR®), sustainability.

1 PHY2CLIMATE PROJECT WITHIN EU CONTEXT

The overall objective of the H2020 Phy2Climate project is to build the bridge between the phytoremediation of contaminated sites with the production of clean drop-in biofuels. These biofuels will present no Land Use Change risks, thus, the phytoremediation will decontaminate lands from a vast variety of pollutants and make the restored lands available for agriculture, while improving the overall sustainability, legal framework, and economics of the process. In this way, Phy2Climate aims at significantly contributing to the Mission Innovation Challenge for sustainable biofuel production and to almost all UN Sustainable Development Goals, as well as to the EU Biodiversity Strategy for 2030, that is part of the European Green Deal, and to the new EU Soil Strategy for 2030 adopted in 2021.

On the one hand, it is unquestionable that there is a growing demand for land, which increases tensions among the different groups of users. Land is a finite resource, and the main competitors are Feed, Food & Fuel. From the available worldwide arable land, about 71% is dedicated to animal feed, about 18% to food and only about 4% to biofuels (another 7% is for material use of crops). The multiple uttered food vs fuel debate is, actually, a food vs feed debate. However, the increasing demand for biofuels and biobased products also contributes to this tension, but in a much smaller dimension. The increasing land demand for energy crops leads to direct and indirect Land Use Change (iLUC), causing deforestation, soil erosion, loss of biodiversity and vital water resources.

On the other hand, there is a significant area of land which is contaminated and, therefore, unusable for any purpose. Even worse, the investigation, registration as "contaminated site", as well as the remediation and management of such areas are very cost-intensive, adding even more fuel to the fire.

Soil pollution degrades major ecosystem services provided by soils, which directly affects human and environmental health, and reduces food and water safety.

Soil pollution is omnipresent and, according to several studies and available official numbers, a large number of contaminated sites are existing. Almost 70% of soil ecosystems in the EU are considered unhealthy and it is estimated that almost 400,000 sites will require remediation to make them safe to use. In the USA, it is estimated that contaminated sites cover about 9 Mio hectare and in China between 13 to 20 Mio.

2 PHY2CLIMATE PROJECT FEATURES

Phy2Climate is a H2020 project with title "A global approach for recovery of arable land through improved phytoremediation coupled with advanced liquid biofuel production and climate friendly copper smelting process". The project consortium has put together 16 partners from 9 countries with long-term expertise in soil remediation, phytoremediation, biofuel technologies and energy processes, environmental and social sustainability, legislative analysis, communication and dissemination, as well as business development for innovative technologies. Phy2Climate project is coordinated by ITS-Förderberatung GmbH (Austria).

Partners include: Fraunhofer UMSICHT, Aurubis AG, Pro Umwelt, Trägerverein Umwelttechnologie-Cluster Bayern e.V. (Germany), Leitat Technological Center, Litoclean, Exolum (Spain), Institute of field and Vegetable Crops - National Institute of the Republic of Serbia, University of Novi Sad Faculty of Sciences, Public Water Management Company Vode Vojvodine (Serbia), Silesian University of Technology (Poland), ETA-Florence Renewable Energies (Italy), Hasselt University - Centre for Government and Law (Belgium), Instituto Nacional de Tecnología Agropecuaria (Argentina), Biovala (Lithuania).

3 PHYTOREMEDIATION METHOD

The method of phytoremediation consists of the use of plants and their associated microbes to stabilize, degrade, volatilize and extract soil pollutants. The long-lasting environmental effect will be verified by means of standardized life cycle assessment (LCA) and by a specially tailored method called thermoecological cost analysis accepting exergy as the only rational measurer of the resource's quality. While phytoremedation is expected to be a cost-effective and environmentally friendly method, there has been still no significant commercial application of phytoremediation and related produced crops.

In this context, the great variety of contamination sources and of phytoremediation strategies all over the world can be a limiting factor, which is being addressed in this project by proposing a global harmonized phytoremediation approach. Furthermore, regulatory roadblocks exist in different countries, both within and outside the EU, which hamper the full viability and uptake of phytoremediation. For example, one of the most important remaining hurdles for the commercial implementation of phytoextraction of heavy metals is the disposal of large amounts of the produced contaminated biomass. Currently, contaminated crops are treated as waste and end up in incineration plants or disposed in landfills. For both options, gate fees incur and valorisation of the contaminated biomass is not given, making these options not economically attractive. The lack of innovation in the contaminated biomass conversion to added value products is evident and needs to be addressed as spurred, among other things, by a more conducive and harmonised legal regime.

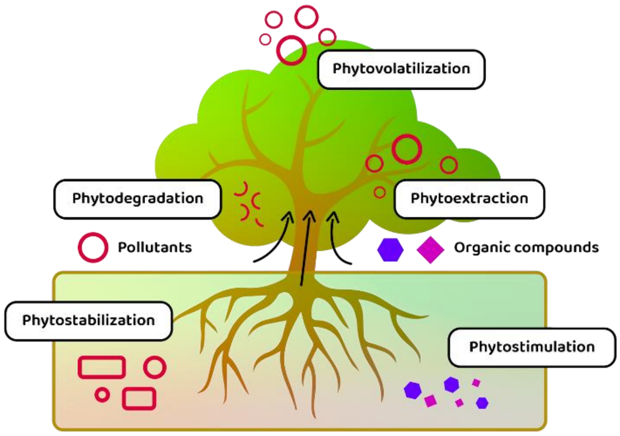

Figure 1: Schematic representation of phytoremediation strategies.
Credit: Phy2Climate project.

4 PROJECT APPROACH

In line with the EU strategy for international cooperation in research and innovation, the Phy2Climate approach synergistically interlinks the remediation of contaminated soil with the production of added value products.

Crops grown on 4 pilot sites in different regions of Europe and South America will be tested as feedstock for biomass thermo-chemical conversion through thermo-catalytic reforming (TCR®). This is an innovative technology that can produce different types of biofuels for road and shipping transport, as well as bio-coke for the metallurgical industry. In case of heavy metal contamination of the soil, the extracted metals and metalloids will be also valorised in the metal smelting process.

The overall regulatory framework for phytoremediation and drop-in biofuels conversion has also been mapped out, unfolding a series of policy and legal areas of intervention that need further scrutiny throughout the above Phy2Climate value chain.

Greenhouse Gas (GHG) reduction will be achieved by substituting fossil fuels and pet-coke, as well as by enhancing the organic carbon content in the soil (Figure 2, Phy2Climate concept). The approach has a significant potential to provide a sustainable and economic solution to lower the pressure in the land-use competition.

Cultivation of energy crops on contaminated land could produce up to 137 million m^3 of drop-in liquid biofuel per year worldwide, while remediating 22 million ha of land. Additionally, such an approach would provide sustainable and economic solutions to lower the pressure in land-use competition, and contribute to GHG reduction through replacing fossil fuels with green energy and storing carbon in soils.

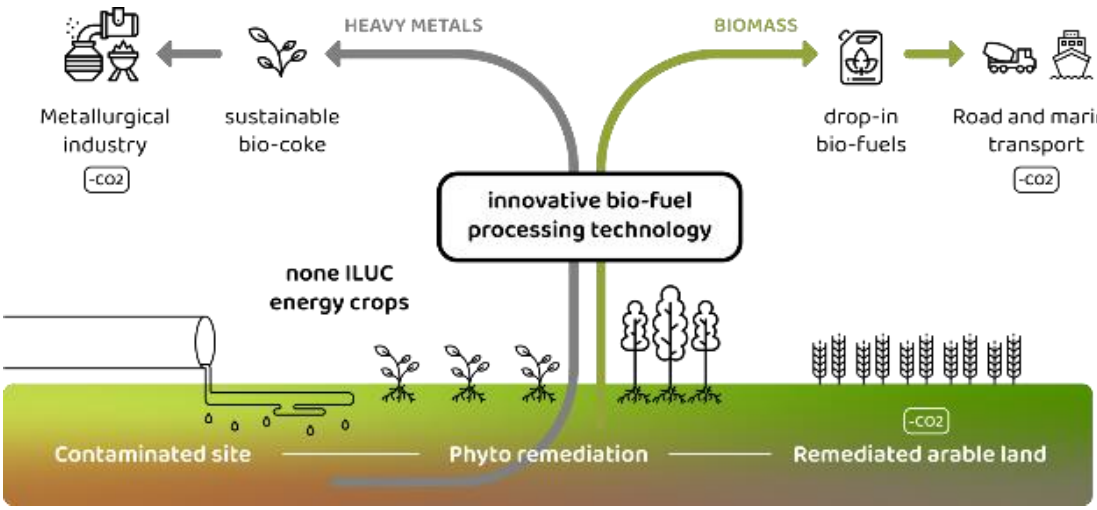

Figure 2: Phy2Climate concept.
Credit: Phy2Climate project.

5 BIOMASS PRODUCTION FROM PILOT SITES

As reported by the EC JRC [1], soil contamination is the occurrence of pollutants in soil above a certain level causing a deterioration or loss of one or more soil functions. Also, soil contamination can be considered as the presence of man-made chemicals or other alteration in the natural soil environment. This type of contamination typically arises from the rupture of underground storage tanks, application of pesticides, percolation of contaminated surface water to subsurface strata, leaching of wastes from landfills or direct discharge of industrial wastes to the soil.

The most common chemicals involved are petroleum hydrocarbons, solvents, pesticides, lead and other heavy metals. The occurrence of this phenomenon is correlated with the degree of industrialization and intensity of chemical usage.

The use of energy crops as phytoremediation species is an incipient approach that is gaining interest in Europe, and worldwide, as an option to valorise the harvest. A high number of energy crop species that show a good phytoremediation capacity have been identified. Most of the investigated energy crops are oleaginous and lignocellulosic species such as *Jatropha curcas*, *Ricinus communis*, *Miscanthus sinensis* or *Populus* varieties. Less common are starch or sugar producing species such as maize.

Phy2Climate will go beyond the State of the Art by building an optimised phytoremediation strategy coupled with biofuel production, which is adapted to different pedoclimatic areas.

Phy2Climate will contribute to expand the knowledge on how to increase the phytoremediation capacity and biomass production by testing a set of energy crops and different soil additives that will provide information on the best combination of those, thus linking phytoremediation, biofuel production and circular economy principles. By using this approach, each Phy2Climate pilot site will define a holistic phytoremediation plan adapted to each site characteristics, with the further objective of remediating the soil to agricultural quality, thus recovering contaminated soil for arable purposes. Furthermore, Phy2Climate will study the relationship between the characteristics of the plant growing conditions (soil properties, contaminant presence, soil additives, etc.) with the quality of the produced biofuel, and link this to the final economic revenue that the phytoremediation strategy brings.

The phytoremediation technology development will be driven by the leaders of each of the five phytoremediation pilot sites in Spain (South Europe), in Serbia (Balkan region), in Lithuania (Baltic region), and in Argentina (South America). In order to guarantee a wholesome approach, the pilot sites will cover different types of contaminants, climate regions in four latitudes, different political contexts, financial and regulation schemes.

One of the biggest hurdles to produce biofuels from phytoremediation energy crops is the handling of the contaminated biomass. Fermentation processes for 1st and 2nd generation bioethanol and biogas production present the problem of contaminant spreading in high volume by-product streams such as fermentation residues or vinasse. Similarly, in state-of-the-art 1G biodiesel, the contaminants can also end up in the products and by-products such as glycerine and press cake. Otherwise, the thermo-chemical processes offer a better alternative to handle the contaminants present in the energy crops. By using technologies such as pyrolysis or gasification, most of the organic contaminants will be cracked and converted into simpler less hazardous or more useful molecules. As the Phy2Climate project aims for the production of high-quality biofuels like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590), a biorefinery concept is employed with the thermo-catalytic process (TCR®) developed at the Fraunhofer Institute UMSICHT in Sulzbach-Rosenberg, Germany at its centre.

6 BIOMASS CONVERSION AND BIOFUEL REFINEMENT

The TCR®-technology comprises out of an enhanced intermediate pyrolysis screw reactor combined with a subsequent reforming process [2] [3]. The principal function of the technology is schematically shown in the figure 3.

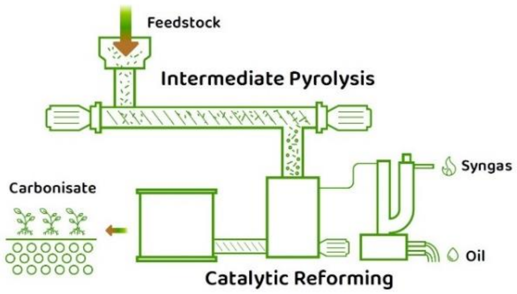

Figure 3: Schematic principle of the Thermo-Catalytic Reforming TCR®: A Platform Technology to use residues and to produce sustainable and storable energy carriers.
Credit: Fraunhofer UMSICHT.

At present, there are several TCR® plants available, ranching from lab-scale with a feed capacity of 2 kg/h until pilot scale with a feed capacity of 500 kg/h [4]. Within the Phy2Climate project, the TCR®2 lab-scale unit shown in figure 4 is used for the conversion of the pelletized and dried biomass collected from the pilot sites.

Figure 4: The lab-scale plant TCR® 2 at the Fraunhofer Institute UMSICHT.
Credit: Fraunhofer UMSICHT.

The pyrolysis step occurs at moderate temperatures between 400−500 °C and a reasonable heating rate of 200−300 °C/min. As products of this pyrolysis step volatile gases and a carbon-rich fraction (further referred as carbonizate and bio-coke) are formed. Successive to the pyrolysis process, the produced volatile gases and the carbonizate are directed into a second unit, called the postreformer. Within this unit, an intensive contact between the pyrolysis gases and the carbonizate is ensured at temperatures of 500−700 °C. In this temperature regime, the carbonizate from the pyrolysis process acts as a catalyst, further refining the pyrolysis gases as well as significantly reducing tars and increasing the hydrogen content within the gas. The products of the TCR® process are therefore bio-coke containing heavy metals originating from the biomass of sites with heavy metal contamination, a condensate consisting of a bio crude oil and an aqueous phase and a hydrogen-rich syngas.

Subsequent to the conversion of the pre-treated biomass to bio-coke, bio crude oil and hydrogen-rich syngas, these intermediate products are further upgraded to high-quality energy carriers like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590). For this, further refinement steps are employed. The bio crude oil is refined by means of a distillation step yielding a light, a medium and a heavy oil fraction, which are thereafter evaluated for direct use as marine fuels according to ISO 8217. The aqueous phase of the TCR® process is purified using an innovative electrooxidation step while at the same time producing hydrogen [5]. The non-condensable gases of the TCR®-process serve together with the produced hydrogen from the electrooxidation of the aqueous phase as feed for a Gas-to-Liquid (GtL) process in order to produce liquid hydrocarbons. In a further step, the produced hydrocarbons from the GtL plant are separated based on their boiling point yielding a gasoline and a diesel fraction. These fractions are eventually analysed with regards to their chemical properties and compared to international diesel and gasoline standards. The produced bio-coke is evaluated for the substitution of petroleum-based coke in the copper smelting industry without further refinement. The whole biorefinery concept as it is employed in the Phy2Climate project is summarized in figure 5.

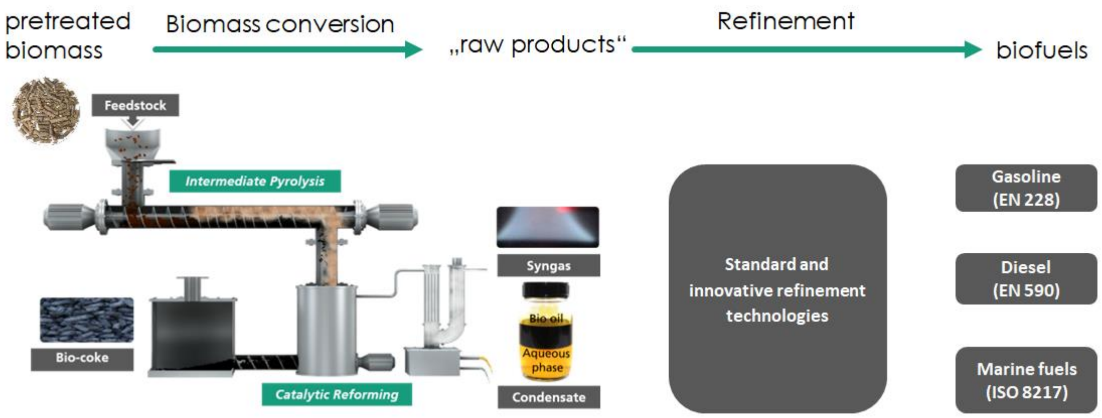

Figure 5: Concept of biorefinery within the Phy2Climate project.
Credit: Fraunhofer UMSICHT.

7 ENVIRONMENTAL IMPACT

The Phy2Climate approach aims at becoming an environmental impact role model by combining different complementing processes with a positive environmental effect. The phytoremediation of contaminated sites in 5 regions all over the world is combined with innovative biomass processing technologies to produce clean drop-in biofuels for the road and shipping transport as well as bio-coke as substitution of petroleum coke (pet-coke) in the metallurgical industry. GHG reduction should be achieved by substituting fossil fuels and pet-coke as well as by enhancing the organic carbon content in the soil. This overall picture of Phy2Climate approach seems very promising, but to be able to fully and independently judge the sustainability of the technology, its environmental impact has to be analysed in terms of the whole life cycle.

The LCA is a standardized tool, however, each technology deserves an individual approach. The analysis of a multi-effect system with variable feedstock scenarios is, indeed, a complex and challenging task. The Silesian University of Technology (SUT) is now preparing the methodology to be able to face that mission. The whole process has to be disassembled into factors and the whole LCA framework for this case has to be built. First steps, now undergoing, are to initially define the goal and scope, system boundaries, functional units, process and reference flows, and data collection rules. LCA is an iterative process and the assumptions can be, luckily, continuously revised the more data appears.

8 SOCIAL SUSTAINABILITY

In order to prove that the technology meets the sustainability principles, it is inevitable to find a balance between environmental, economic and social aspects. It is widely acknowledged that the new energy technology project does not depend on technological advances and favourable economic conditions alone. It is important to recognize the perceptions of social acceptance of new energy technologies in order to better implement and develop such projects.

One of the aims of the Phy2Climate project is to develop a practical toolbox for project managers to deal with societal acceptance issues in the development of a new approach. How does societal acceptance emerge (or does not) in new energy projects and what are the underlying mechanisms? In this project, the social acceptance of the Phy2Climate approach is discussed based on three different dimensions of social acceptance – socio-political, community, and market acceptance. All three are sometimes interdependent categories of social acceptance. SUT-team is now preparing the methodology by defining the target groups and survey thematic fields. In the socio-political dimension, opinion of general public, stakeholder, and policy makers are being considered. The aspects of public acceptance with focus on policy makers will be analysed relying on expertise of the Work Package (WP) 6 leader, Hasselt University, while the stakeholders are recognized by the WP5 leader, ITS. The second dimension of social acceptance – community acceptance will deal with controversies at the local level. Three main factors have revealed for community acceptance, namely, procedural justice, distributional justice and community trust on information. The final aspect of social acceptance is the market acceptance that refers to the adoption of a new technology in a market or the process by which market parties adopt and support the energy innovation. The market acceptance aspects will be revealed with a close cooperation with the WP5 leader, ITS.

9 REGULATORY AND LEGAL ASPECTS

The complex and innovative processes deployed by Phy2Climate brings about several important legal and regulatory issues that arise on every step down the chain. Thus, Phy2Climate will develop legal expertise in order to allow for a smooth realization of the overall project and inform future policy-making in the EU and elsewhere. WP6 appraises all legal bottlenecks arising throughout the implementation of the project by, first, cataloguing potential legal and regulatory issues throughout the entire value-chain in different legal systems (within and outside the EU in a selection of countries), and by mapping potential edges de lege lata and de lege ferenda.

Following this mapping exercise, a legal analysis will be carried out to duly assess the impact that the identified legal hurdles might pose to phytoremediation activities and activities related to recovery of output materials. Lastly, tailored policy recommendations will be devised to advance the development of the current legislative framework governing phytoremediation and related recovery of materials. The research work carried out thus far under WP6 has allowed to achieve the first milestone of the WP as related to the mapping of relevant areas of law to be further investigated in the relevant jurisdictions covered by the project (Argentina, the EU, Lithuania, Serbia, and Spain). This exercise has been supported by all Pilot Site Leaders (Leitat, Bva, Ifvcns and Inta) under WP2 (with regard to phytoremediation techniques and leaded by Leitat) and by Fraunhofer Institute UMSICHT as the WP3 leader (with regard to the deployment and management of the biorefinery). Despite the several differences existing among the legal systems covered by the research, a set of relevant policy and legal areas have been ultimately identified, including the following:

- Health policy on endocrine disrupters and antibiotics
- Invasive alien species
- GMO, fertilisers and pesticides
- Soil quality legislation
- Water quality legislation
- Waste legislation
- Chemicals legislation
- Bioenergy (biofuels and biomass)
- Industrial emissions

The project will, thus, analyse the interplays among the identified relevant fields of law to pinpoint the relevant legal issues arising in connection to every step of the value chain, while enshrining also potential legal and regulatory best practices and solutions as implemented in the domestic legal setups analysed.

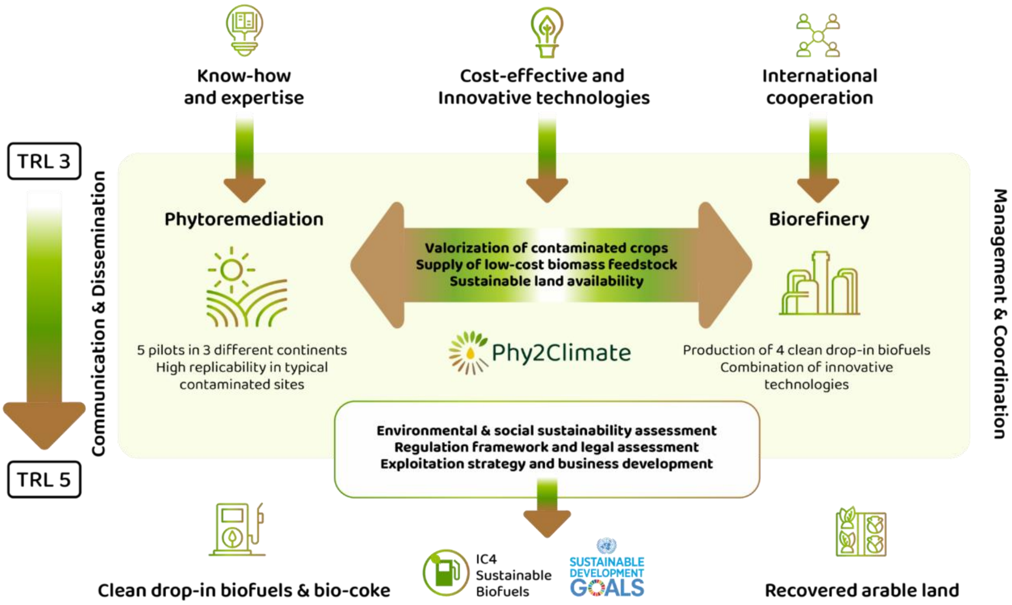

Figure 6: The overall approach of Phy2Climate.
Credit: Phy2Climate project.

10 FIRST RESULTS FROM PILOT SITES

The Pilot Sites have carried out preliminary pot tests with the aim of optimizing the phytoremediation strategy to be applied in situ, according to each specific condition (clime, contamination source/s, and soil).

First, a harmonized pot tests experimental plan, defining a common framework in which pot tests had to be performed, was agreed upon. It provides sampling (including type and frequency of sampling and storing procedure for both soil and energy crops) and monitoring (including soil and energy crop characterisation) procedures and defines the main parameters of the experimental design such as controls, number of replicates and the duration of the experiments.

Visual inspections have also been agreed as important indicators of the plants' response to the hostile conditions. Particularly, the common parameters for soil characterisation included physical parameters (water content, texture), chemical parameters (pH, electrical conductivity, N, C, S, Total C (CT), Total N (NT), organic matter, Mg, Ca, B, Fe, Mn, Na, K, Cd, Cr, Cu, Pb, As, P (available), K (available), P (total), K (total), TPH, PAH), and biological parameters (microbial biomass). For energy crop characterisation, common parameters included yield of production of biomass, which is an important factor to estimate the future available feedstock for biofuel/biodiesel production.

However, each Pilot Site has its own characteristics, where different contamination sources and soil conditions play a major role. Specific targets have been pursued, depending on the site-specific characteristics such as:

- Optimization of the soil – plant species – amendments – fertilizers – biostimulants matrix.
- Biomass production including seeds, for its valorisation as feedstock for biofuels/biodiesel production.
- Seed germination under hostile conditions (contaminated soils) for later transplantation to the pilot parcels.
- Assessment of the phytoremediation mechanism (rhizosphere effect or translocation to roots/stems/leaves/seeds) to, additionally, determine the possible environmental impact of the loss of the contaminated aboveground biomass.

To meet the main and specific objectives, each Pilot Site has defined its own experimental plan to perform pot trials, based on the agreed common framework in which to conduct phytoremediation actions.

Accordingly, after characterising the contaminated site and defining the main contamination sources and contamination level, each Pilot Site Leader has defined the set of vegetative species and amendments / fertilizers / biostimulants to be investigated, as well as the specific experimental conditions (experimental design and experimental set-up).

Specific parameters for soil and energy crop characterisation have been measured together with the common ones, with a minimum frequency of 1 sampling event for season. Translocation and bioaccumulation factors have varied among pilot sites since they are strictly connected to the specific contaminants.

Very interesting and promising results have been obtained by each Pilot Site showing a large potential for a successful clean-up of the contaminated sites in few years.

Figure 7: Pot tests performed at Leitat facilities-Spain Pilot Site; at Bva facilities-Lithuania Pilot Site; at Ifvcns facilities-Serbia Pilot Site; and at Inta facilities-Argentina Pilot Site.
Credit: Leitat; Bva; Ifvcns; Inta.

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13 LOGO SPACE