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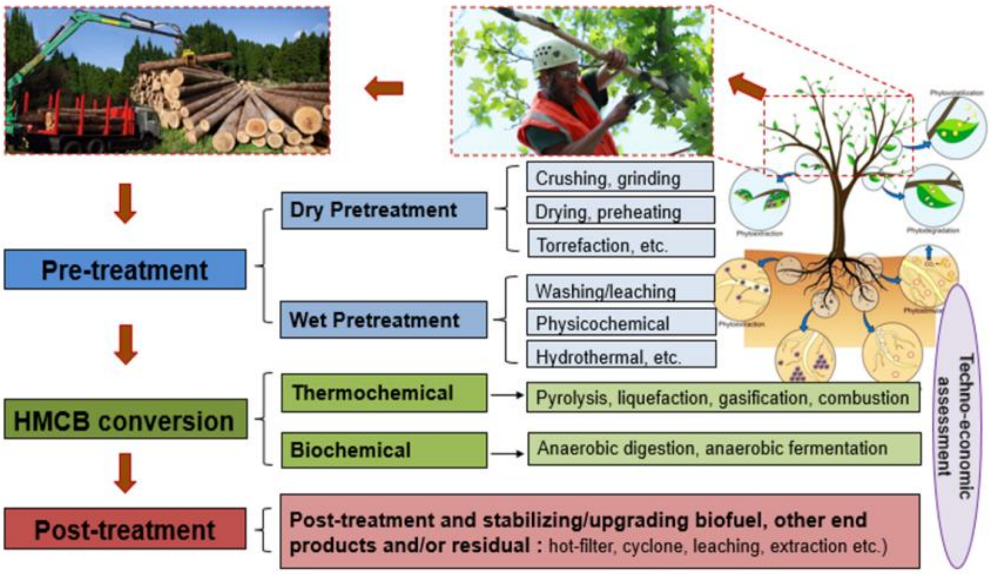

Phytomanagement of Contaminated Land to Produce Biofuels for the Maritime Sector

A feasibility study

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Preface

This report has been prepared on behalf of Soyagroup AB. We would like to extend a big thank you to the following people who contributed valuable information and knowledge during the work:

- Per Tunell at Soyagroup who provided constructive and valuable feedback during the work.
- Michel Mench (INRAE, FR) and Yvonne Andersson-Sköld (VTI) who contributed their knowledge and shared it in interviews.

Gothenburg, April 2025
Paul Drenning, Jenny Norrman, Martin Weih, Dan Berggren Kleja

Abstract

This study investigates the feasibility of phytomanagement— the long-term combination of profitable crop production with gentle remediation options (GRO) for risk management and providing environmental co-benefits like ecosystem services—for producing valuable biomass that can be used to produce biofuels suitable for the maritime sector. A focus of this study has been to identify and assess the potential of different bioenergy crops for phytoremediation and the technological maturity for producing different types of biofuels, including key challenges or barriers and associated environmental co-benefits. Several bioenergy crops were selected upon review of the scientific literature, which were separated broadly into oil crops (e.g., rapeseed, sunflower, mustard, etc.) and lignocellulosic crops (e.g., willow, poplar, sorghum, other grasses). The selected bioenergy crops were evaluated according to both their phytoremediation capability and technological feasibility (i.e., technology readiness level, TRL) for use as feedstock to produce various biofuels.

In general, biofuel production involves a series of processes including pre-treatment, conversion (thermochemical, biochemical, and chemical), and refining. These processes yield various types of biofuels such as biodiesel, ethanol, and biomethane, but differ depending on the type of biomass. An important challenge is that the presence of contaminants in the biomass produced during phytomanagement, particularly metal(loid)s, can negatively impact the resulting biofuel quality, especially from thermal conversion. Specific pre- or post-treatment methods may be necessary as well as managing by-products and waste since contaminants may accumulate in ashes, biochar, digestate, etc. that necessitate waste management and emission control systems that may pose complications to their usage.

The most feasible pathways forward for phytomanagement and biofuel production are likely a combination of a short-term and a long-term strategy. A short-term strategy utilises primarily first-generation energy oilseed crops like rapeseed, sunflower and mustard (biodiesel/HVO) and sugar-rich crops like sorghum (bioethanol) for phytomanagement and biofuel production due to the well-established markets and high TRL >7. A long-term strategy employs second-generation biofuels produced from lignocellulosic biomass (grasses and trees), which has a greater net benefit but is not yet a mature technology (TRL 3-5), but can be more advantageous when the technology has sufficiently developed. Marginal and contaminated lands across Europe—particularly in regions like central and eastern Europe, northern Italy, eastern Germany, and northern France—present a significant opportunity for bioenergy crop cultivation. These areas often comprise abandoned agricultural land of good quality with proximity to existing or potential biorefineries, enhancing logistical and financial feasibility. However, while technically feasible, ensuring the financial viability of phytomanagement projects remains a significant challenge and there are important issues to address in developing the business model for different stakeholders.

Svensk sammanfattning

Chalmers tekniska högskola har fått i uppdrag av Soya Group AB att genomföra en förstudie om möjligheten att kombinera fytosanering av förorenad mark med biomassaproduktion och omvandling till biobränslen för sjöfartssektorn. Arbetet har gjorts i samverkan med forskare från Sveriges lantbruksuniversitet. Rapporten sammanfattar och sammanför befintlig kunskap samt ger goda exempel och insikter från intervjuade experter. Begreppet ”phytomanagement” används vilket är ett begrepp för att beskriva en typ av markförvaltning där man med hjälp av växter minskar föroreningar eller på annat sätt förbättrar mark och samtidigt får nyttor av den produktion som sker på platsen, dels direkt via värdefull biomassa, men också indirekt genom en ökad tillgång på ekosystemtjänster. Nedan följer en kort sammanfattning av rapporten.

Kapitel 2 beskriver fytosanering som är en teknik för att efterbehandla förorenad mark och vatten genom att använda växter och associerade mikroorganismer, jordförbättringsmedel och agronomiska tekniker. Den här typen av metoder kan ta bort, stabilisera eller minska giftigheten hos miljöföroreningar. Tekniken inkluderar olika processer som fytoextraktion, fytodegradering, rhizodegradering, fytostabilisering och fytovolatilisering. Växter som används för fytosanering kan absorbera och lagra föroreningar, bryta ner organiska föroreningar, filtrera föroreningar från vatten och stabilisera föroreningar i marken. Effektiviteten kan förbättras genom att använda jordförbättringsmedel och mikroorganismer. Fytosanering är särskilt användbar för att hantera måttliga eller låga koncentrationer av föroreningar och kan ge ekonomiska, sociala och miljömässiga fördelar. Tidsåtgången för att helt ta bort föroreningar kan dock vara mycket omfattande beroende på den specifika situationen.

Kapitel 3 beskriver olika typer av biobränslen som används inom den maritima sektorn samt olika produktionsprocesser. Det finns olika typer av biobränslen relevanta för sjöfartssektorn, inklusive konventionella ”drop-in” bränslen (kan användas direkt utan att modifiera fartygsmotorer), avancerade bränslen (kan behöva modifiera fartygsmotorer eller har komplicerade produktionsprocesser) och biogas (kräver viss typ av fartygsmotorer). Bioenergi kan produceras från olika typer av biomassa och produktionen av biobränslen involverar tre huvudsakliga steg: 1) förbehandling av biomassa, 2) konvertering (via termokemiska, kemiska, biokemiska, biologiska processer eller kombinationer av dessa) och 3) raffinering och uppgradering till biobränsle. Termokemiska processer som pyrolys och förgasning är väl lämpade för vedartad biomassa. Biokemiska processer som fermentering och anaerob nedbrytning använder mikroorganismer för att producera etanol och biogas. Kemiska processer omvandlar t.ex. vegetabiliska oljor till biodiesel. Flera europeiska projekt undersöker möjligheterna att kombinera fytosanering med biobränsleproduktion, t.ex. GOLD, Phy2Climate och CERESIS. Ett antal kommersiella produktionsanläggningar för biobränsle finns i Europa och det finns flera företag som arbetar inom området.

Kapitel 4 handlar om olika växters potential för fytosanering och som biomassa för biobränsle. Inom transportsektorn används främst ett-åriga olje- och stärkelsegrödor, medan inom produktion av elektricitet och för uppvärmning används fleråriga vedartade växter. Första generationens bioenergigrödor (oljeväxter och stärkelse/spannmålsgrödor) omgärdas av många kontroverser gällande att odla dessa för att producera bränsle på bördig jordbruksmark istället för matgrödor. Andra och efterföljande generationens bioenergigrödor (vedartade grödor eller rester från jordbruks- och trävarusektorn), är inte livsmedelsgrödor och bidrar därför inte indirekt till konkurrens om matproduktion men kräver mer komplicerad teknik för att producera biobränslen av. Andra generationens bioenergigrödor är generellt bättre lämpade för förorenad och/eller lågproduktiv mark. Ett urval av oljeväxter och vedartade växter beskrivs utifrån odlingsförhållande, fytosaneringspotential, produktionskapacitet och hur färdig tekniken är både avseende jordbrukstekniker samt biobränsleproduktionsteknik. Oljeväxter som beskrivs är solros, raps, senap, oljedådra (camelina), senap, oljekål (crambe) och tistel. Vedartade träd och gräsarter som beskrivs är sälg/vide/pil, poppel, elefantgräs, rödhirs, durra, pålrör, rörflen och hampa.

Kapitel 5 handlar om produktion av biobränslen med förorenad biomassa. Föroreningarnas öde under omvandlingsprocesserna till biobränsle är komplext och varierar beroende på typ av förorening och temperatur. Det finns ännu inte tydliga regler och standarder för etablerade föroreningsgränser i biomassan. Metaller i biomassan kan orsaka problem som slaggformation, skador på katalysatorer eller korrosion i anläggningen. Föroreningar kan även påverka kvaliteten på biomassa och slutprodukten. För stärkelse- och oljebaserade energigrödor behöver den förorenade biomassan som blir över efter att stärkelse eller olja har extraherats hanteras på ett korrekt sätt, eventuellt för bioenergiproduktion genom förbränning, då med krav på rökgasfilter och ansvarsfull hantering av aska. Askan kan ha förhöjda halter av metaller och i dessa fall bör den ej spridas i naturen. Ett annat sätt att hantera problemen med förorenad biomassa är att odla grödor som specifikt inte tar upp föroreningar.

Kapitel 6 handlar om markens förbättring över tid och andra typer av nyttor med fytosanering. Odling av bioenergigrödor kan ge flera fördelar, inklusive ökad kolinlagring, förbättrad markhälsa, ökad biologisk mångfald och andra ekosystemtjänster. Vid fytostabilisering kan spridning av föroreningar begränsas. Markens biologiska mångfald kan förbättras genom odling av bioenergigrödor, särskilt om grödorna odlas i så kallad polykultur. Vedartade växter ger habitat för fåglar och insekter, vilket främjar ekosystemtjänster som pollinering. Agroekologiska metoder, som växtföljd och samodling (intercropping), kan öka avkastningen och förbättra markens kvalitet. Agroforestry-system, där träd integreras med andra grödor, kan maximera ekosystemtjänster som kolinlagring och minskning av erosion. Markförbättring genom tillsats av organiskt material som kompost och biokol kan vara nödvändiga för att stödja växtlighet och öka avkastningen, speciellt om marken inte är av god kvalitet.

Kapitel 7 ger en översikt över tillgången på mark som kan vara lämplig. Inom EU är mer än 1/3 av den förorenade marken påverkad av metaller, ca 1/3 med oljeföroreningar och ca. 13% med PAHer. Globalt uppskattas 380 – 470 miljoner hektar mark vara olämplig för livsmedelsproduktion på grund av föroreningar men kan vara lämplig för bioenergigrödor. I Europa finns det miljontals hektar förorenad mark som kan användas för att producera bioenergigrödor, vilket kan motsvara ca. 10 – 50 % av den nuvarande globala konsumtionen av flytande bränsle. En undersökning inom GOLD-projektet uppskattade att cirka 2 miljoner hektar av den förorenade marken i EU är lämpliga för fytosanering. Frankrike, Tyskland, Spanien och Storbritannien har de största områdena av potentiellt förorenade platser. Det finns också landspecifika uppskattningar, inklusive cirka 900 tusen ha i Rumänien och 750 tusen ha i Sverige. Europa, främst centrala och östra Europa, norra Italien, östra Tyskland och norra Frankrike, har goda möjligheter för odling av bioenergigrödor på övergiven jordbruksmark som kan också eventuellt ligga nära befintliga eller potentiella biobränsleproduktionsanläggningar.

Sammanfattningsvis så är idén om phytomanagement av förorenad mark för att förbättra jordar och producera användbar biomassa för biobränsleproduktion till konkurrenskraftiga priser genomförbar. Det finns dock en del frågeställningar som kvarstår för att säkerställa ekonomisk genomförbarhet. Höga kostnader för biomassa och produktion gör biobränslen mindre konkurrenskraftiga jämfört med fossila bränslen, varför en effektiv bioenergiproduktion och hantering av förorenad restbiomassa är avgörande. Transportavstånd från biomassaproduktion till biobränsleproduktion och sedan för färdig produkt får inte vara för långt. En affärsmodell krävs även för de lantbrukare som äger mark och/eller brukar mark så att investeringar i bioenergigrödor kan löna sig. På kort sikt är första generationens grödor med oljeväxter på övergiven jordbruksmark mest genomförbart, men på längre sikt, när tekniken för att producera biobränslen från vedartade växter har mognat blir även andra möjligheter större.

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1 Introduction

Chalmers University has received the commission from Soya Group AB to conduct a feasibility study (*förstudie*) into the possibility of combining phytomanagement of contaminated land with biomass production and conversion into biofuels for the maritime sector. This report is the synthesis of the knowledge gained from the collection and investigation phase, including good examples and best practices, as well as insights from experts received during individual interviews. The report culminates in some practical recommendations that include suggestions for bioenergy crops that are likely to be most suitable, relevant biomass conversion processes, considerations regarding land availability and suitability, and discussion about factors that may impact the overall project proposal as well as things to consider for future pilot projects.

While this study focuses primarily on contaminated land, the term *marginal land* (or *marginal soil*) is also used frequently in this report. The terms can be fuzzy but a working definition is as follows: "*lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors*" (Elbersen et al., 2019).

1.1 Aim and objectives

The overall aim of this feasibility study is to address the following question:

Can biofuels for the maritime sector be sustainably produced from plants used for phytoremediation of contaminated lands at equal/lower cost than expected market prices?

In consideration of the overall aim, the combined phytoremediation and bioenergy production project would achieve three main goals:

1. Remediate contaminated lands
2. Produce biofuels for the maritime (shipping) industry
3. Increase biodiversity and provide other ecosystem services

This report provides support for evaluating the overall feasibility of the project proposal and suggest ways forward to achieve the stated goals.

Although not fully answered, the following questions are investigated:

- What is the potential for this type of project to achieve the goals stated above?
- Which are the most suitable plants and conversion pathways to produce biofuels?
- Does contamination hinder the use of phytoremediation biomass to produce biofuels?
- Which are the important barriers?
- If there is potential for some approaches, what should the next steps be?
- What are the necessary pre-conditions for greatest likelihood of success?

- Which areas of Europe are most suitable?
- How mature is the current market and does it seem likely to change in the future?
- Would the project likely be financially viable from a company perspective?
- Which are the most important stakeholders?

1.2 Limitations

The important boundary conditions and limitations of this study include the following:

- Limited to a set of crops that can be suitable for producing desired biofuels and capability for phytoremediation.
- Focus on biomass conversion processes amenable for biofuel production.
- Geographic limitation – focused primarily on northern/eastern Europe, temperate climate.
- Uncertainties requiring land availability, prices, legislation, biomass conversion processes, and presence of local value chains.
- Difficulties obtaining information about e.g., existing biorefineries.

2 What is phytoremediation?

Phytoremediation[1] is an *in-situ* remediation technology that uses vegetation and its associated microbiota, soil amendments, and agronomic techniques to remove, contain, or reduce the toxicity of environmental contaminants (US EPA FRTR, n.d.). The term 'phytotechnologies' has also been used to emphasise that it includes plant-based technologies that stabilise contaminants because phyto-'remediation' is often interpreted to indicate the sole aim of 'removing' the contaminants (i.e., the source) (ITRC, 2009), which may or may not be the risk management objective.

Phytoremediation is considered a 'gentle remediation option' (GRO), which are nature-based solutions that can be applied to manage risks at brownfields and provide or maintain vital ecosystem services through revegetation (Cundy et al., 2016). GRO is an umbrella term covering a set of remediation technologies based upon the use of plant (phyto-), fungi (myco-), and/or bacteria-based (bio-) methods with or without the use of chemical additives or soil amendments. Phytoremediation is used to manage the risks posed by contaminated soils by gradually removing the bioavailable pool of inorganic contaminants (*phytoextraction*), degrading organic contaminants in the plant or root zone (*phyto- and rhizodegradation*), filtering contaminants from surface water and waste water (*rhizofiltration*) or groundwater (*phytohydraulics*), and stabilising contaminants in the soil matrix (*phytostabilisation, in-situ immobilisation*) often in combination with vegetation cover using excluder plants (*phytoexclusion*) (Table 1).

Table 1. List of definitions for GRO, adapted from (Bardos et al., 2020; Cundy et al., 2016; GREENLAND, 2014; OVAM, 2019).

GRO	Definition
Phytoextraction	Process in which plants and their associated microorganisms absorb contaminants and fix them in above-ground plant tissue that can then be removed from the site during harvesting.
Phytodegradation/ phytotransformation	The use of plants (and associated microorganisms like endophytic bacteria) to uptake, store and degrade contaminants.
Rhizodegradation	The use of plant enzymes and rhizospheric (in root zone) microorganisms to degrade organic contaminants.
Phytostabilisation	Reduction in the bioavailability and mobility of contaminants by immobilisation in root systems and/or living dead biomass in the rhizosphere soil.
Phytovolatilisation	The use of plants to remove contaminants from the growth matrix, transform them to less toxic forms and disperse them (or their degradation products) into the atmosphere.
In-situ immobilisation	Reduction in the bioavailability of contaminants by immobilisation or binding them to the soil matrix through the incorporation into the soil of organic or inorganic compounds to prevent excessive uptake and transfer into the food chain.
Phytoexclusion	The implementation of a stable vegetation cover using excluder plants which do not accumulate contaminants in the harvestable biomass, often combined with in-situ immobilisation.
Rhizofiltration	The removal of contaminants from aqueous sources by plant roots and associated microorganisms.
Phytohydraulics	Process in which plants and their microorganisms take up and evaporate water and thereby influence the groundwater level, the direction and velocity of the groundwater flow.
Bioremediation	Generic term applied to a range of remediation and risk management technologies which utilise soil microorganisms to degrade, stabilise or reduce the bioavailability of contaminants.
Mycoremediation	A form of bioremediation in which fungi-based methods are used to degrade, extract, stabilise or reduce the bioavailability or contaminants.
Vermiremediation	A remediation technique which utilises earthworms to remove or stabilise soil contaminants.

[1] Se *Åtgärdsportalen* för information på svenska: https://atgardsportalen.se/fytosanering-oversikt/

If well-designed, phytoremediation can be customised to provide risk management along Source-Pathway-Receptor contaminant linkages via i) gradual removal or immobilisation (i.e., reducing bioavailability/solubility) of the contaminant source, ii) managing the flux of contaminants along exposure pathways and breaking connections to receptors through containment and stabilisation, and iii) managing the receptor's access to the contaminated medium thus preventing exposure (Bardos et al., 2020; Cundy et al., 2016; GREENLAND, 2014), Figure 1.

Phytoremediation has been proven successful to manage both organic and inorganic contaminants.

Phytoremediation of organics by degradation aims for complete mineralisation of organic contaminants into carbon dioxide, nitrate, chlorine, ammonia and other non-toxic breakdown products (Mench et al., 2010; OVAM, 2019). This remediation strategy has been proven viable for a wide variety of organic compounds in some situations, including 1) petroleum products – polycyclic aromatic hydrocarbons (PAHs), aliphatic hydrocarbons, fuels and BTEX compounds; 2) persistent organic pollutants – polychlorinated biphenyls (PCBs), DDT and other pesticides; 3) explosives – nitro-aromatics such as trinitrotoluene (TNT); and 4) chlorinated solvents – linear halogenated hydrocarbons such as trichlorethylene (TCE) (Gerhardt et al., 2017; Kennen and Kirkwood, 2015; Mench et al., 2010; OVAM, 2019).

Phytoremediation of inorganics can mitigate risks by either 1) gradually removing the source of the contamination by harvesting plants that have accumulated the contaminants (extraction), or 2) managing the exposure pathways by reducing contaminant bioavailability and the spreading of contaminants in porewater, groundwater or the atmosphere (stabilization) (Mench et al., 2010; OVAM, 2019; Robinson et al., 2006; Vangronsveld et al., 2009). These two strategies are predominantly applied to manage metal(loid)s, including As, Cd, Cu, Cr, Hg, Ni, Pb, Zn, etc., as well as salts, excess nutrients, radionuclides and even certain organic contaminants like DDT and PCBs (Gerhardt et al., 2017; Kennen and Kirkwood, 2015; Mench et al., 2010; OVAM, 2019; Vangronsveld et al., 2009). Phytoextraction is best applied for soil polishing (reducing marginally elevated concentrations to threshold levels) and bioavailable contaminant stripping (reducing the soluble, plant-available fraction of metals thereby reducing environmental risk). Bioavailable contaminant stripping targets the labile (i.e., soluble and exchangeable) contaminant pool instead of the total content for removal, which can shorten remediation times from decades to just a few years.

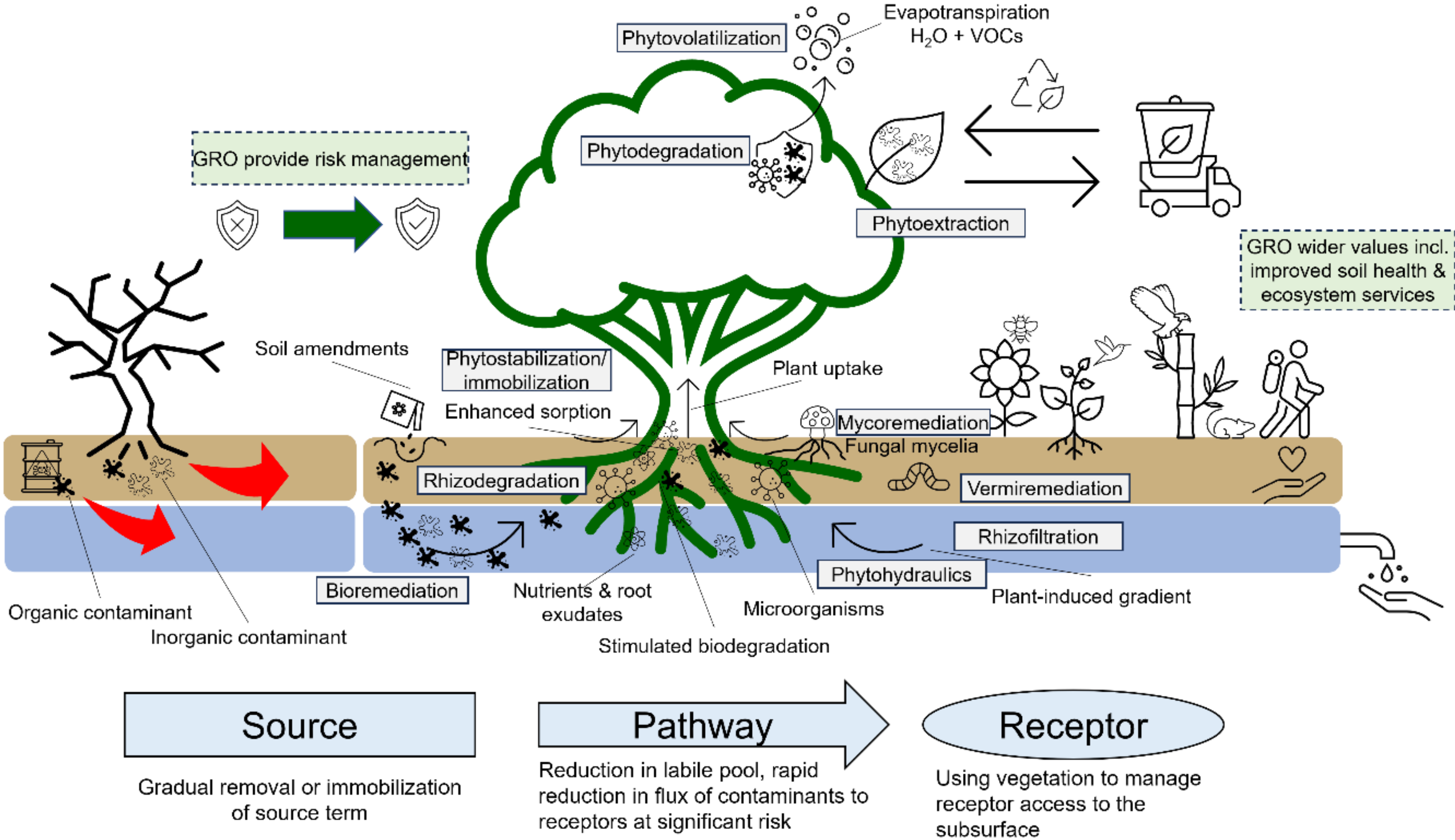

Figure 1. GRO applications for sustainable and risk-based land management and providing wider values, from (Drenning, 2024).

2.1 Which plants are suitable for phytoremediation?

Methodologies for selecting plants can be checklist-based procedures as in the ITRC (ITRC, 2009) plant species screen process or the Rejuvenate decision-support tool (Andersson-Sköld et al., 2013b; Y. Andersson-Sköld et al., 2014). Upon selecting potentially viable plant species, they should be tested in small-scale pilot tests before implementing at full field scale. An important note is that the capacity for accumulation of metals can vary significantly between clones of the same plant species (e.g., willow species), which can impact the selection of specific cultivars for use in extraction or stabilisation (Enell et al., 2016; Greger and Landberg, 1999; Keller, 2005; Meers et al., 2007; van Slycken et al., 2013).

Fast-growing plants that produce large amounts of biomass in a single growing season can be suitable for both phytoremediation (e.g., phytoextraction) and bioenergy production. Some examples of high biomass, metal accumulating plant species that are commonly applied include:

- **Tree species** like *Salix* spp. (willow) and *Populus* spp. (poplar) for Cd, Zn, Cu and other metals (Chalot et al., 2020; Greger and Landberg, 1999; Kacálková et al., 2015; Meers et al., 2005; Mench et al., 2010; Quintela-Sabarís et al., 2017; Ruttens et al., 2011; Touceda-González et al., 2017b; van Slycken et al., 2013; Witters et al., 2009);
- **Annual crops** that are grown sequentially in combination (crop rotations), *Helianthus annus* (sunflower) and *Nicotiana tabacum* (tobacco) in particular, for Cd, Zn, Pb, Cu and other metals (Burges et al., 2020; Fässler et al., 2010; Herzig et al., 2014; Kidd et al., 2015; Mench et al., 2010, 2018; Quintela-Sabarís et al., 2017; Thijs et al., 2018; Touceda-González et al., 2017b; Vangronsveld et al., 2009). Other annual crops can also accumulate significant amounts of metals, e.g., *Brassica juncea* (Indian mustard), *B. napus* (rapeseed) and other *Brassica* spp., *Zea mays* (maize), and *Triticum aestivum* (wheat) (Fässler et al., 2010; Gomes, 2012; Meers et al., 2010; Mench et al., 2010; Van Ginneken et al., 2007);
- **Fast-growing perennial, herbaceous legumes** (e.g., *Medicago sativa* (alfalfa/lucerne), *Trifolium repens* and *T. pratense* (clover), *Glycine max* (soybean), *Lupinus albus, L.* spp. (lupin)) can be grown in combination with other crops (intercropping/row cropping) have also been shown to accumulate metals and are especially valued due to their high tolerance to contaminants (Edrisi and Abhilash, 2016; Gawronski et al., 2011; Gomes, 2012; GREENLAND, 2014; Kidd et al., 2015; Mench et al., 2010; Tang et al., 2012; Tripathi et al., 2016). These and other so-called 'green manure' plants like borage (*Borago officinalis*) and white mustard (*Sinapsis alba*) can be highly useful for both restoring soil quality as well as reducing bioavailability and ecotoxicity of metal(loid)s (Foucault et al., 2013);
- Large biomass producing, perennial **bioenergy grasses** like *Miscanthus x giganteus* (giant perennial silvergrass, elephant grass, or miscanthus), *Phalaris arundinacea* (reed canarygrass) and others have also been shown to accumulate various metals and produce useful biomass on contaminated sites (Kidd et al., 2015; Lord, 2015; Mehmood et al., 2017; Moreira et al., 2021; Nsanganwimana et

al., 2014; Pandey et al., 2016; Tripathi et al., 2016). This can also include **grasses** that are not usually grown for bioenergy purposes but are commonly used for phytostabilization (e.g., *Lolium perenne* (English ryegrass), *Lolium multiflorum* (Italian ryegrass), *Festuca rubra* (red fescue), *F. arundinacea* (tall fescue) and *F. ovina* (sheep's fescue)) (Edrisi and Abhilash, 2016; Gawronski et al., 2011; Gomes, 2012; GREENLAND, 2014; Kidd et al., 2015; Mench et al., 2010; Tang et al., 2012; Tripathi et al., 2016).

2.2 How can effectiveness be improved?

To improve the effectiveness of phytoremediation, the treatment can be enhanced (or 'aided' or 'microorganism-assisted') by enriching the microbes in the rhizosphere or within the plant itself by bioaugmentation (i.e., introducing external species to the site that may be better suited for degrading specific contaminants) and biostimulation (i.e., enhancing the already existing microbes by the use of soil amendments) that can promote plant growth and tolerance and increase degradation and extraction rates (Mench et al., 2010; OVAM, 2019; Thijs et al., 2017, 2016; Vangronsveld et al., 2009). Soil amendments are frequently used to enhance the effectiveness of phytoremediation by reducing (or increasing) the bioavailability of metals in soil and uptake in plants as well improve soil quality. Organic amendments in particular (e.g., compost, biochar, domestic wastes, sewage sludge or biosolids, animal manures and slurries) are especially useful for improving soil quality to enable the establishment of vegetation in poor soils by e.g., improving soil physical properties like bulk density and pore structure, improving water infiltration and holding capacity, improving soil fertility by adding essential micro- and macronutrients, balancing soil pH, re-establishing microbial communities and increasing soil organic matter (Burges et al., 2018; Epelde et al., 2009; GREENLAND, 2014; Kidd et al., 2015; Vangronsveld et al., 2009). Figure 2 presents an overview of the different dimensions of assisted phytoremediation. Note that agronomic techniques (not shown in Figure 2) like intercropping, co-cropping, crop rotations, agroforestry, etc. (see Section 6.3) can also be used to improve plant productivity and yield, treatment effectiveness as well as improve overall soil functionality (Kidd et al., 2015; Mench et al., 2010), though the effectiveness of all of the above techniques is context-dependent.

An important caveat with using additives to improve effectiveness, in particular with chemical additives such as chelates that can greatly increase the bioavailability and solubility of contaminants like metals, is that they can increase the risk of leaching and spreading contaminants deeper into the soil profile and the groundwater. Such chemical additives should be used with caution and after careful consideration of the site-specific conditions. Also, inoculation of additional microorganisms, as with bioaugmentation, may be shown to be effective in a laboratory setting, but there is a lack of studies showing similarly significant improvement in field conditions, which may be due to, e.g., competition with existing microorganisms or not being adapted to the local environment. Many commercial microorganism inoculant products are on the market that can potentially be beneficial, but they vary widely in quality and can potentially introduce foreign species.

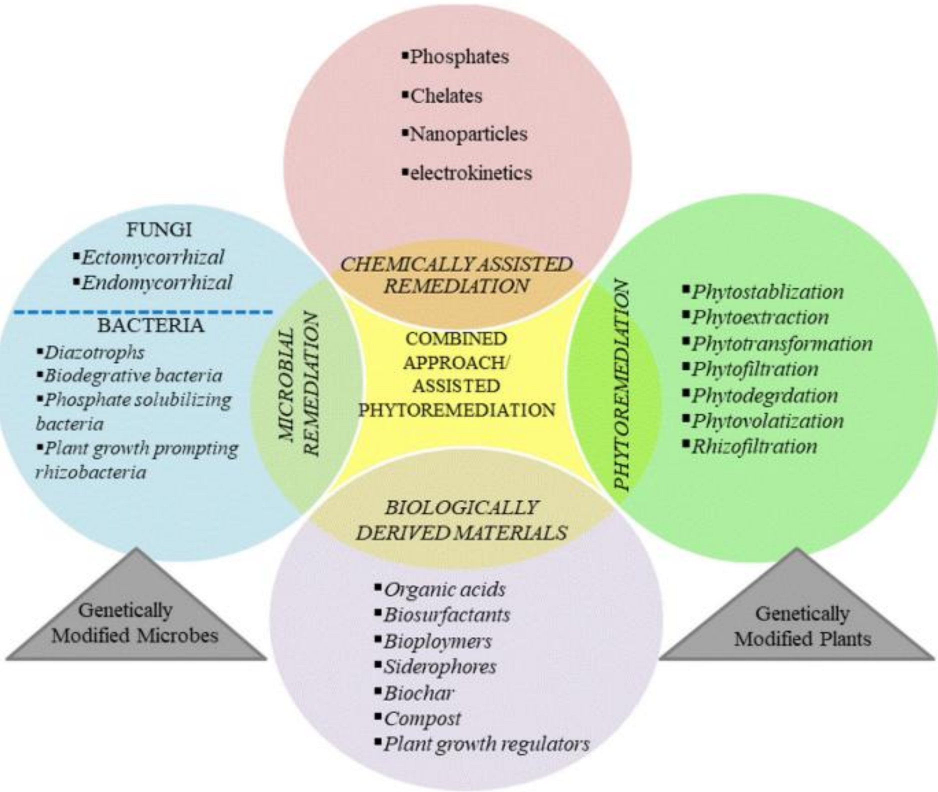

Figure 2. Schematic representation of different dimensions of assisted phytoremediation, from (Pandey et al., 2024)

2.3 Where can phytoremediation be used most effectively?

In general, phytoremediation can be used for i) remediation of moderate or low concentrations of inorganic and organic contaminants, even if they are spread over large areas; ii) remediation of residual contamination after removal of source zones with traditional remediation (e.g., excavation, multi-phase extraction); iii) to prevent the infiltration of contaminants into groundwater or to reduce the leaching of fertilizers and pesticides into rivers; iv) to control the spreading of diffuse contaminants (e.g., air deposition); and v) to provide an active form of controlled natural attenuation (OVAM, 2019).

While GRO may not be well-suited to highly contaminated sites, hotspots or point source terms such as buried tanks or oil spills, they are particularly suitable for large areas and contaminated sites that pose low to medium risks to human health and the environment (Y. Andersson-Sköld et al., 2014; Cundy et al., 2016; Enell et al., 2016; GREENLAND, 2014). GRO are useful as 'primary prevention strategies' in various applications to reduce or eliminate human (and non-human) exposure to contaminants (Henry et al., 2013). GRO can also be used for source removal of inorganic and organic contaminants though the timeframe for remediation can differ significantly between the contaminants and the mechanisms involved (Drenning et al., 2022; Kennen and Kirkwood, 2015; OVAM, 2019).

As a general starting point, the operating windows identified in the Greenland project could be used to preliminarily screen brownfields to identify where GRO may be feasible for a particular site (GREENLAND, 2014, 2014), which include where i) there are budgetary and deployment constraints (e.g., large areas with diffuse contamination not causing immediate concern such as abandoned rail tracks); ii) biological functioning is desired post remediation for soft reuse (e.g., greenspaces); iii) ecosystem services are highly valued (e.g., riverbank greens, urban wilderness); iv) there is a need to restore land and a potential to produce non-food crops (e.g., marginal land for biofuel production).

Conversely, it is just as important to identify where GRO has limited potential such as where there is time pressure for short-term redevelopment of a site (i.e., within 1-2 years), the majority of the site is or will be under hard cover or has buildings under active use, and other site-specific factors constraining deployment due to e.g., poor soil quality, water availability, depth of contamination, climate, site topography and other local factors (GREENLAND, 2014, 2014).

2.4 What other benefits can be expected from phytoremediation?

Phytomanagement refers to the long-term combination of profitable crop production with GRO leading gradually to the reduction of contaminant linkages and restoration of ecosystem services such as nutrient cycling, carbon storage, water regulation and purification, erosion control, fertility maintenance, etc. (Cundy et al., 2016; GREENLAND, 2014; Robinson et al., 2009), see Figure 3. Many economic (e.g., biomass production), social (e.g., leisure and recreation), and environmental (e.g., ecosystem services and restoration of plant and microbial and animal communities) co-benefits can be generated during phytomanagement (Cundy et al., 2016, 2013; GREENLAND, 2014).

For commercial application, to create a ‘self-funding land management regime’, careful selection of plant species to produce valuable biomass and generate wider environmental and economic benefits is crucial (Andersson-Sköld et al., 2013b; Bardos et al., 2011; Conesa et al., 2012; Cundy et al., 2016; Enell et al., 2016; Evangelou et al., 2012; Gomes, 2012). The presence of local conversion chains for the produced biomass is instrumental to success (Cundy et al., 2016). In long-term operations at metal contaminated sites, source removal via phytoextraction may be secondary to the overall goal of producing valuable biomass while mitigating health and environmental risks through other mechanisms. A 'reasonable timeframe' of <25 years can be useful to distinguish between practical phytoextraction and long-term phytomanagement (GREENLAND, 2014; Robinson et al., 2009). For biomass production, a long time frame may not necessarily be a significant disadvantage.

Stabilisation, rather than uptake of contaminants, may be preferable since the future usage and economic return of the produced biomass can be dependent upon contaminant concentrations in the various plant tissue (Andersson-Sköld et al., 2013b; Y. Andersson-Sköld et al., 2014; Enell et al., 2016; Evangelou et al., 2012). Also, large land areas, preferably even >5 ha, are more advantageous than small, fragmented or high-value urban sites for economically feasible bioenergy crop production (Y. Andersson-Sköld et al., 2014; Evangelou et al., 2012). Many studies have evaluated the significant possibilities of producing biomass on contaminated or marginal land to provide additional economic and environmental benefits while producing crops for bioenergy during phytoremediation (Evangelou et al., 2012; Gomes, 2012; Lacalle et al., 2020; Licht and Isebrands, 2005; Schröder et al., 2018). It may also be possible to safely grow food crops in contaminated agricultural soils in some cases (e.g., (GREENLAND, 2014; Haller and Jonsson, 2020; Kidd et al., 2015; Tang et al., 2012)).

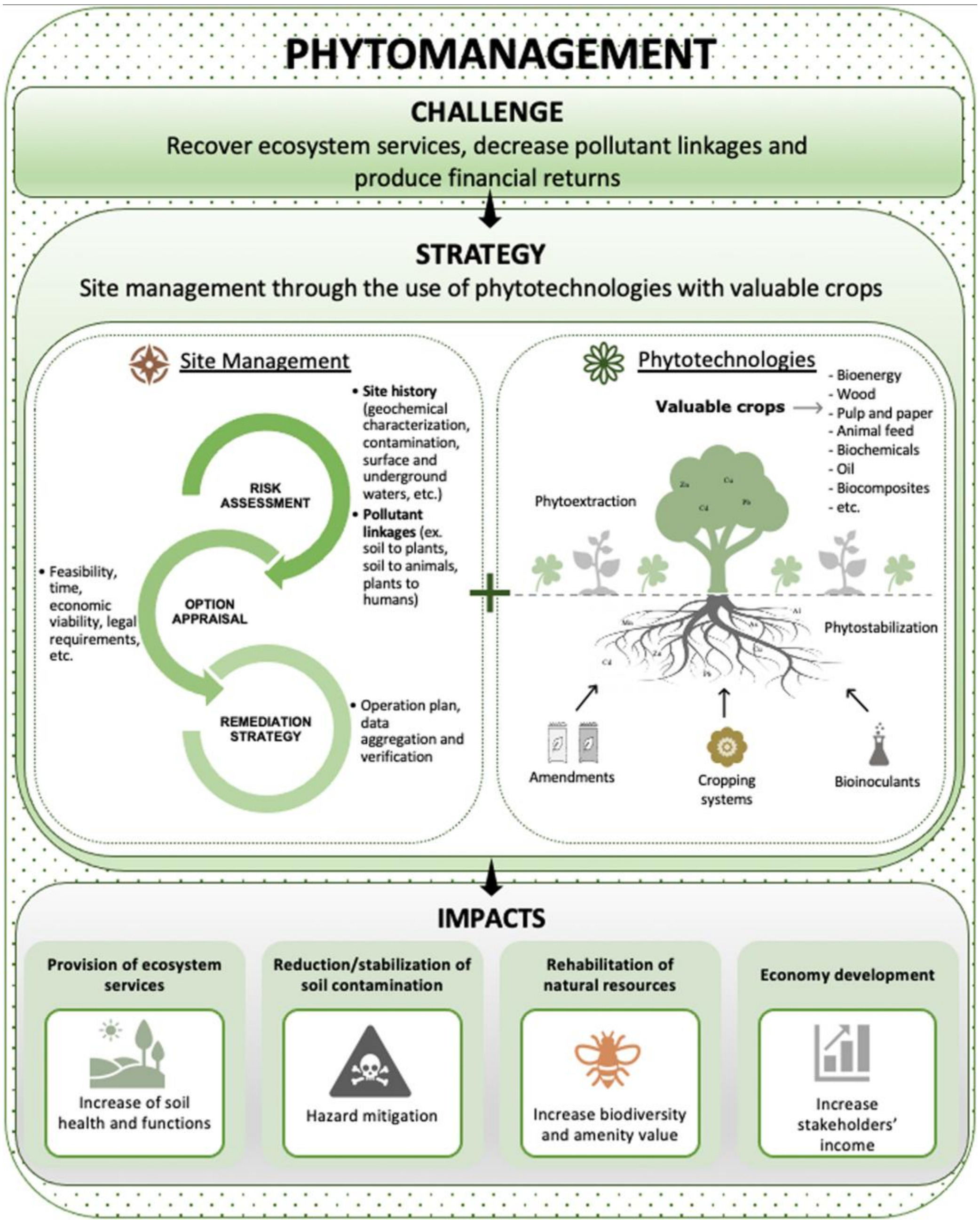

Figure 3. Phytomanagement of metal-contaminated soils: challenge, strategy and impacts, from (Moreira et al., 2021).

2.5 What are the challenges and limitations of GRO?

Despite the great potential of GRO to manage risks and improve soil functionality on contaminated land, they are still seldom used in practice. The availability (or lack thereof) of demonstration projects does not provide a convincing body-of-evidence. In general, the main challenges and limitations to the application of GRO include the following[2]:

- Uncertainties relating to the required timeframes for GRO and their effectiveness (both short- and long-term) as risk management methods
- Lack of awareness about GRO as viable remediation alternatives and perceived lack of applicability for some types of sites and contaminants
- Insufficient knowledge and experience in applying GRO
- Need for long-term monitoring
- Lack of convincing pilot projects and field studies, particularly long-term studies
- Limited availability of consultants and contractors offering GRO commercially
- Type and concentration of contaminants – more effective for specific groups of contaminants and at low-medium levels of contamination to prevent phytotoxicity
- Depth to contamination – works best at a depth of <1m
- Time requirements – difficult to predict but typically requires 5-15 years
- Future land use – how sensitive is the land use?
- Soil quality – poor quality soils will require more inputs to restore functionality and ensure good plant growth
- Ecological risks – including risks of 'secondary poisoning' or transfer of metals into the food chain due to contaminant accumulation in plants
- Biomass management – depending on the regulatory environment and concentrations it could be classified as a waste or resource

2.6 How long does phytoremediation take?

GRO are well-suited to mitigate the risks posed by low to medium concentrations of both inorganic and organic contaminants though the timeframe for remediation can differ significantly between the contaminants and the mechanisms involved (Figure 4). An important note is that the estimated time for full source removal (e.g., via extraction or degradation) can vary significantly depending on if total or bioavailable concentrations are used to measure success.

In general, due to the excessive time requirements to achieve reduction targets, many studies consider phytoextraction to be infeasible in most cases, especially if national regulation is based on total soil contaminant concentrations instead of bioavailable concentrations (Dickinson et al., 2009; Mertens et al., 2005; Neaman et al., 2020; Robinson et al., 2015; Santa-Cruz et al., 2022; Van Nevel et al., 2007). The opportunity windows for phytoextraction are greatest for low contaminant concentrations (only slightly exceeding soil guideline values) that are readily bioavailable for effective extraction and bioaccumulation by plants. There are, however, still obstacles and uncertainties regarding replenishment of bioavailable pools and acceptance by regulatory agencies (Neaman et al., 2020; Santa-Cruz et al., 2022; Thijs et al., 2018). Estimating the time required for phytoextraction, which can potentially take up to a few

[2] See also https://atgardsportalen.se/viktiga-fragor-fytosanering/

decades, is thus a critical aspect of determining the feasibility of phytoextraction (Drenning et al., 2024a).

Long-term monitoring and maintenance to evaluate the effectiveness of GRO will entail non-negligible costs and effort that must be considered early in collaboration with stakeholders and regulators when planning a GRO project (Cundy et al., 2020). Adaptive management (i.e., maintenance and monitoring programs that evolve iteratively to reduce uncertainty as management proceeds) can be advantageous for phytomanagement projects.

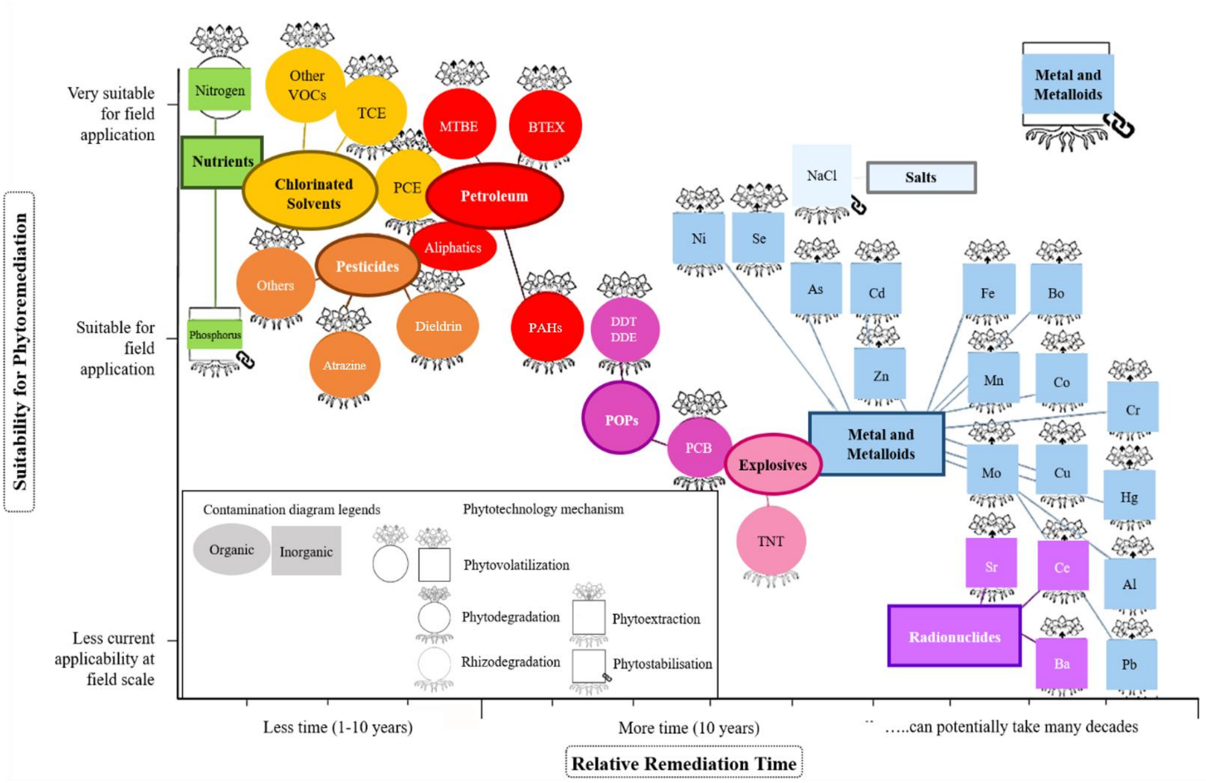

Figure 4. Relative remediation time for source removal and applicability of GRO (phytoremediation) mechanisms for groupings of contaminants. From (Chowdhury et al., 2020), after (OVAM, 2019) and (Kennen and Kirkwood, 2015).

3 Types of biofuel and production processes

There are many different avenues of bioenergy production from different types of biomass. This study will focus on the processes to produce biofuels – biodiesel, ethanol, biomethane – that can be used in large ship engines. Recent analyses suggests that blending biofuels will be the main short-term solution that entails the lowest costs for shipowners and that more advanced fuels (e.g., e-fuels) may only be cost-competitive by 2050 (Trosvik and Brynolf, 2024). In general, biofuels offer a net reduction of carbon emissions, especially those produced from second generation feedstocks, and thus lower the carbon emissions produced by the marine shipping sector. An overall reduction of GHG emissions in the shipping sector would most likely be achieved through a combination of improvements in ship design, port infrastructure, and fuel technology (Hsieh and Felby, 2017). The use of biofuels in the maritime shipping industry is promising and has received growing interest in recent years. Strength, weakness, opportunity and threat (SWOT) analysis of biofuels for the marine shipping sector indicates their current possibilities and challenges (Figure 5).

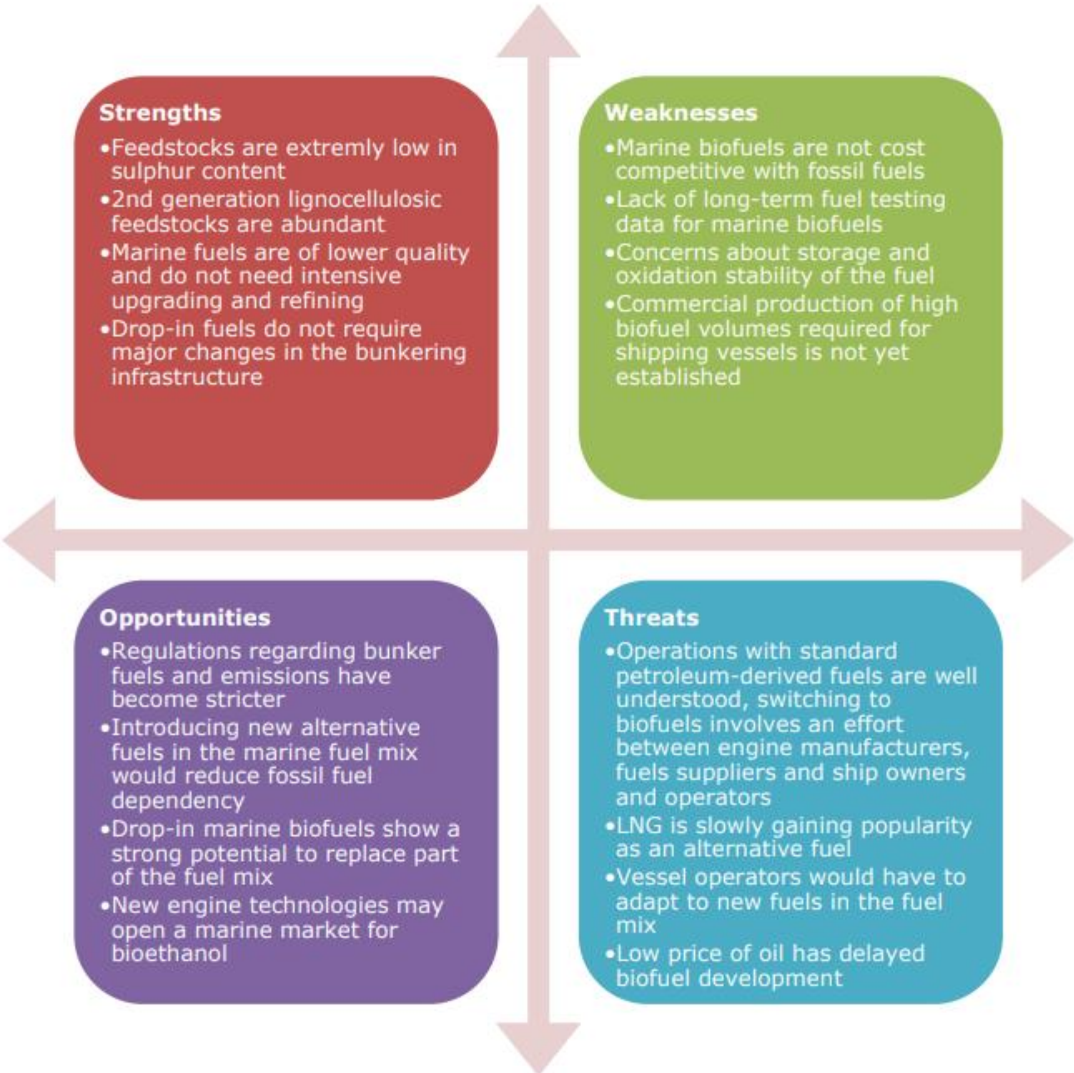

Figure 5. SWOT analysis of marine fuels from biomass, from (Hsieh and Felby, 2017).

3.1 Types of biofuel for maritime shipping

Broadly speaking, there are a few main types of biofuels relevant for the maritime shipping sector, including conventional, drop-in fuels, advanced fuels, and biogas power (Hsieh and Felby, 2017), see Figure 6.

Drop-in fuels are liquid bio-hydrocarbons that are functionally equivalent to petroleum-derived fuels and fully compatible with existing engines without modification and in combination with fossil fuels (Hsieh and Felby, 2017; Karatzos et al., 2014). These include, for example, bioethanol and methanol, biodiesel, and vegetable oils like straight vegetable oil (SVO) or its refined form hydrotreated vegetable oil (HVO), which is also referred to as renewable diesel. The production processes and use of these types of fuels is well-established. Biodiesel is produced through transesterification, which converts feedstocks into fatty acid methyl esters (FAME). Biodiesel meets the ASTM D6751 specification to be used in existing diesel engines and would function as a drop-in fuel in a marine diesel engine. Renewable diesel is a drop-in diesel replacement similar to biodiesel that meets ASTM D975 which is the same standard for petroleum diesel.

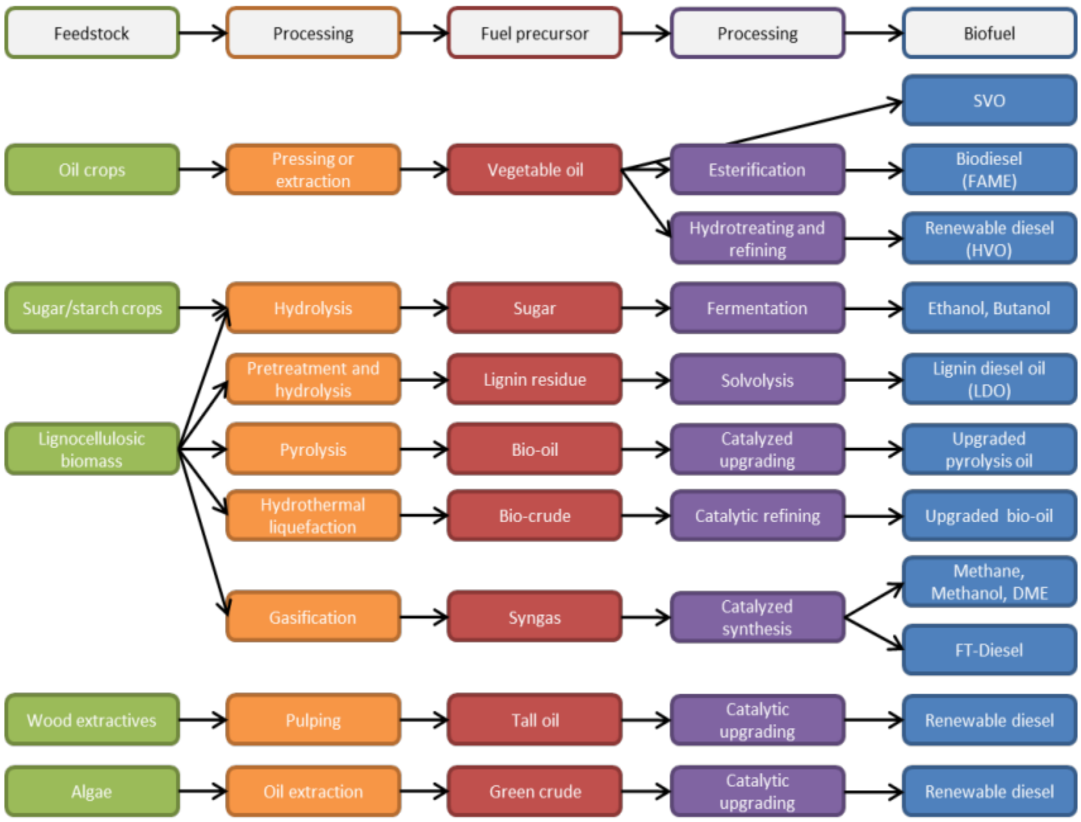

Figure 6. Overview of different feedstock conversion routes to marine biofuels including both conventional and advanced biofuels, from (Hsieh and Felby, 2017).

Advanced biofuels are those that may require modification of engines or simply more advanced production processes. Many of these technologies based on lignocellulosic biomass are not yet fully commercialized or widely available and include, for example, lignin diesel oil (LDO), pyrolysis or bio-oil that may or may not be upgraded, and other forms of upgraded fuels.

Some ships have been modified to burn biogas or synthetic gas (syngas) produced from fermentation or anaerobic digestion of biomass, which makes these valuable bio-products for maritime shipping if produced in sufficient quantities.

3.2 Biofuel production processes

The types and quality of the end bioproduct from the biomass conversion process depends on the type of biomass and feedstock being used in a particular biorefinery. In general, however, there are a few main steps in the conversion process from raw feedstock to produce biofuels: 1) Pre-treatment of biomass feedstock, 2) Conversion, and 3) Refining and upgrading (or post-treatment), shown in Figure 7, Figure 8, and described in more detail below.

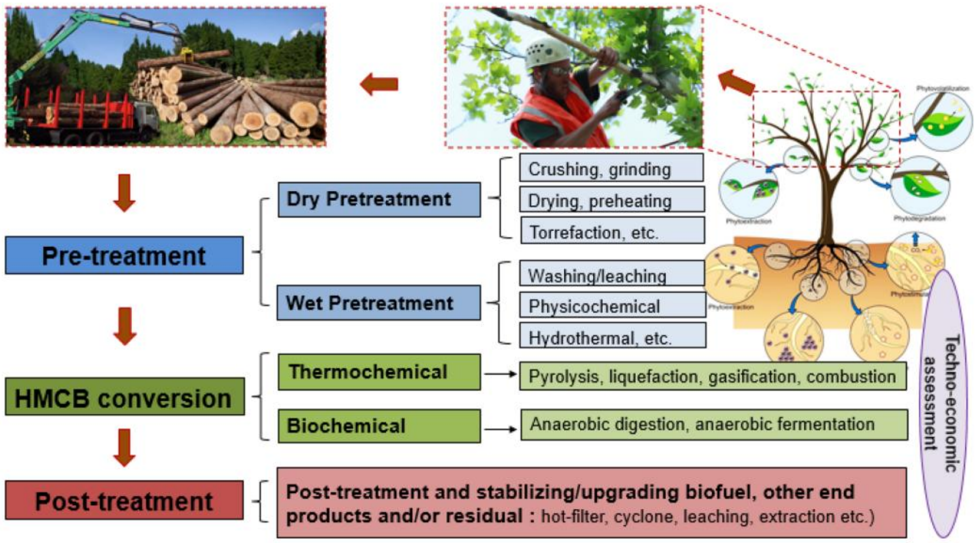

Figure 7. The valorisation pathways of heavy metal contaminated biomass (HMCB) into various biofuels and chemical, from (Dastyar et al., 2019).

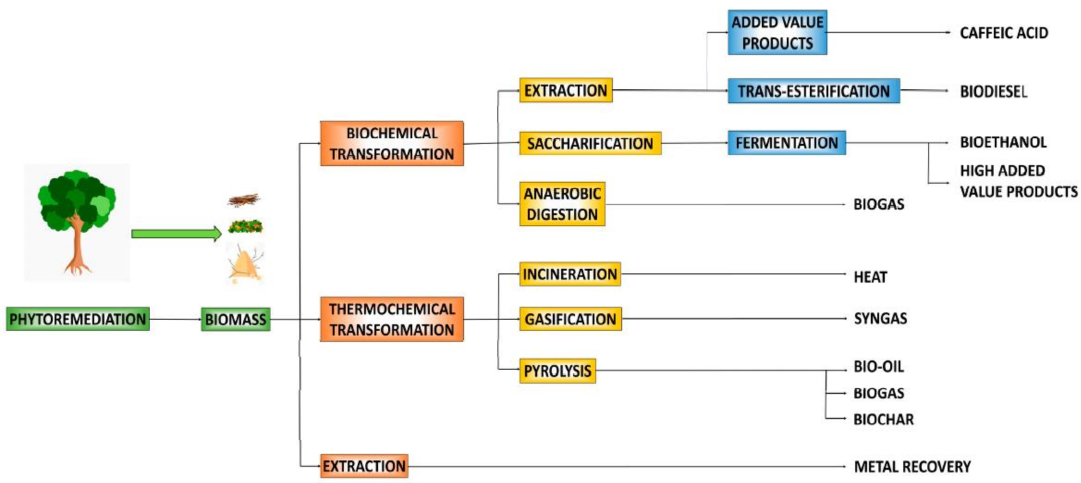

Figure 8. Schematic illustration of different routes for post-phytoremediation biomass reutilization towards biofuels (bioethanol, biogas biodiesel), added value products (biochar, bio-oil, caffeic acid) and metal recovery, from (Ionata et al., 2024).

1. Pre-treatment of biomass feedstock – usually requires some form of drying/liquification of the biomass soon after harvest for transport and to prevent rotting in route, particle size reduction to a more convenient and uniform size (e.g., chips or pellets), and then potentially a chemical or physical process to extract the constituent compounds needed for the next steps (e.g., vegetable oil, sugars) or delignification to break down lignin and hemicellulose in lignocellulosic biomass into a slurry. Drying, for example, can be a highly energy intensive process, so biomass with a high water content is best prepared as a slurry or for fermentation in subsequent processing steps. For contaminated biomass, a variety of pretreatment methods are available to mitigate the effects of contaminants on processes and products and/or prepare the biomass for the next conversion process.

2. Conversion – can occur via thermal, thermochemical, chemical, biochemical, biological, or a combination processes to produce bioproducts or residues that can be used directly in some applications (e.g., biochar as a residual product from pyrolysis thermal treatment), heat and intermediate products (e.g., syngas, bio-oils) that are then upgraded in further steps to produce refined biofuels.

Thermochemical – usually a combination of processes that involved high temperatures to break down biomass into energy-dense products and are well-suited for lignocellulosic biomass, including:

- **Pyrolysis –** is the thermal decomposition of biomass in the absence of oxygen at temperatures ranging from 300-900°C. Pyrolysis produces biochar (as a residue product), bio-oil (liquid fuel that is usable as a marine fuel after refining), and syngas (a mixture of hydrogen, methane and carbon monoxide that is used to produce synthetic diesel or methanol, or combusted directly). Generally, for the conversion of lignocellulose feedstock, fast pyrolysis with high heating rates (20–300 °C s^{-1}) and short GRTs of few second (5–10 s) contributes to high bio-oil yields (40–50 wt%) (Dastyar et al., 2019).
- **Gasification –** is the partial oxidation of biomass at 700-1200°C. The procedure is primarily used to produce syngas that can then be converted into liquid fuels via Fischer-Tropsch synthesis. Biochar is also produced as a byproduct.
- **Hydrothermal liquefaction** – converts wet biomass into biocrude under high pressure (200-350 bar) and moderate temperatures (250-350°C). The output is biocrude, which is then upgraded into renewable diesel or heavy fuel oil.

Biochemical – uses a combination of biological and chemical processes that utilise microorganisms like yeast or bacteria and enzymes to convert the sugars extracted from biomass into (bio)ethanol, which are well-established, high efficiency processes for sugar- and starch-rich crops, though less suited for lignocellulosic biomass.

- **Fermentation** – sugars or starches from crops are fermented by microbes to produce ethanol (cellulose and hemicellulose from lignocellulosic crops must be separated into fermentable sugars via enzymatic hydrolysis before fermentation), see Figure 9. The resulting bioethanol can be blended with conventional marine fuels or converted into higher grade fuels.
- **Anaerobic digestion –** the decomposition of organic matter by microorganisms in the absence of oxygen, which produces biogas (a methane-rich gas that can be

upgraded to biomethane for use in maritime engines) and a digestate residual product that can be used as a fertiliser.

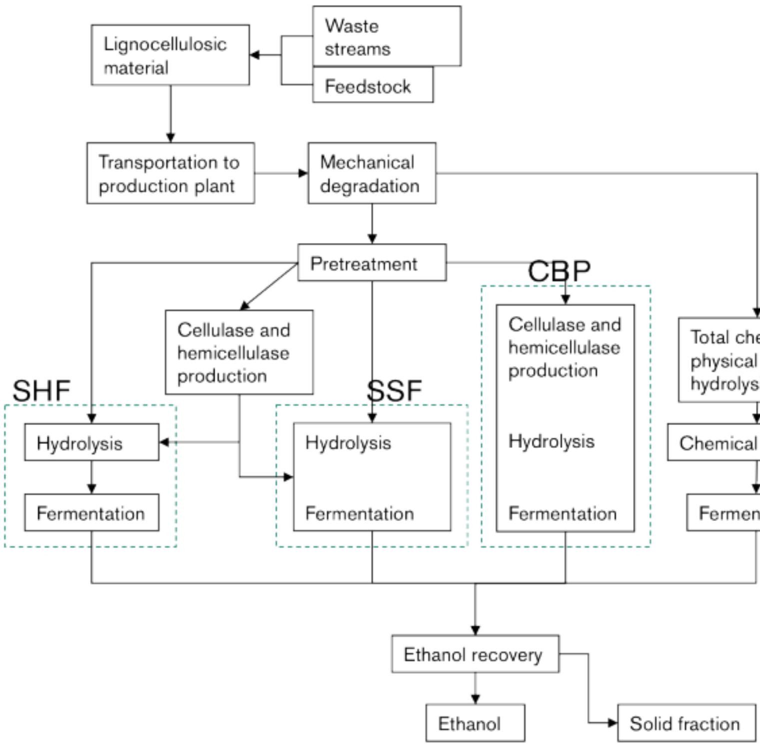

Figure 9. Examples of fermentation routes for producing bioethanol from lignocellulosic materials. SHF = Separate hydrolysis and fermentation, SSF = Simultaneous saccharification and fermentation, CPB = Consolidated bioprocessing. From (Janssen, 2012).

Chemical – following extraction of vegetable oils and fats from oil crops, chemical processes can be used to convert the intermediate products into biofuels.

- **Transesterification** – the crude vegetable oil is reacted with alcohol (methanol or ethanol) in the presence of a catalyst (e.g., sodium hydroxide) to produce biodiesel, which is compatible with marine diesel engines.

3. Refining and upgrading – intermediate products can be further refined in subsequent chemical processes to create bioproducts for final use such as drop-in biofuels and biodiesel. Depending on the quality of the intermediate products, refining and upgrading processes can be energy intensive. With contaminated biomass, an additional treatment step to remove contaminants such as metals that transferred into the intermediate product may be necessary.

- **Hydrotreating** (HVO/Renewable diesel production) – hydrogen is used to remove oxygen from bio-oil or biocrude to produce high-quality renewable diesel that is chemically similar to traditional diesel.
- **Fischer-Tropsch synthesis** – syngas is converted into liquid hydrocarbons (diesel, kerosene) via a catalytic reaction to produce synthetic diesel or marine fuel oil.

- **Blending** – biofuels can be mixed with conventional marine fuels (such as with ethanol in automobile engines) to achieve compatibility and reduce the fossil fuel required.

All the aforementioned valorisation routes shown in Figure 7 and Figure 8 not only could convert contaminated biomass into metal-free biofuels but also reduce the waste biomass volume considerably; and the final residue(s) could undergo further treatments or metal extraction processes prior to the eventual safe disposal or use (Dastyar et al., 2019). However, while there are a variety of biomass conversion theoretically available, not all of them are equally viable or efficient for all types of biomass feedstocks to produce biofuels for the maritime sector. For example, production of biogas/biomethane is a relatively high efficiency process (50-85%), while producing first generation biofuels (25-70%) and second generation biofuels (50-60%) are less efficient (EEA, 2024).

3.3 Phytoremediation and biorefinery

The same, or modified, conversion processes may be possible to develop a **biorefinery** for converting biomass generated during phytoremediation to different types of biofuels and other bioproducts (Figure 10). Biorefinery, is an increasingly studied concept that refers to a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass (Berntsson et al., 2012).

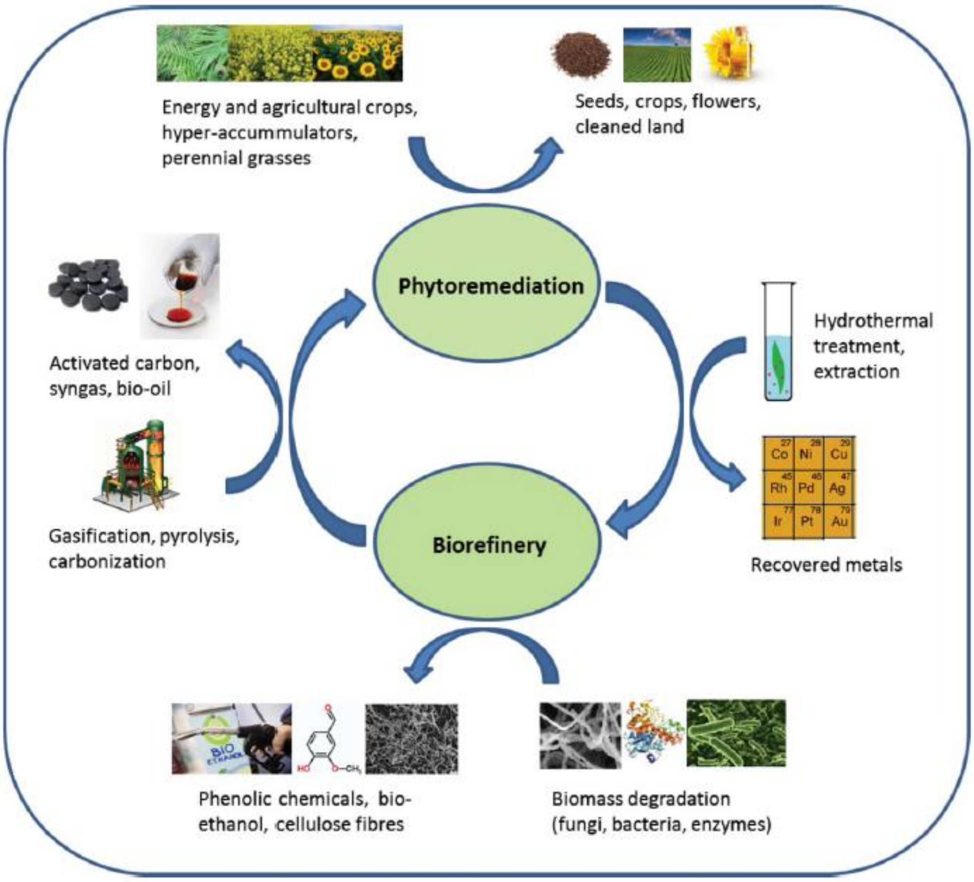

Figure 10. Example scheme of a tandem phytoremediation-biorefinery process, from (Sotenko et al., 2017).

There are several ongoing European projects, with experimental sies in different climate zones, exploring the potential of phytoremediation with energy crops for biofuel production, some of which are described below. Fundamental tasks of these recent and sizably funded projects are those that pursue the development of suitable technological solutions by which to optimize the exploitation of post-phytoremediation biomass to produce biofuels that are clean from contaminants, with the aim of eliminating the risks of secondary pollution. In this regard, of particular importance will be the implementation of novel and more effective methodologies aimed at the recovery of metal from plant biomass. This will also ensure high profitability margins, especially in the case of rare and/or precious ores with high added value for high tech industrial applications (Ionata et al., 2024).

- **GOLD** – explores two conversion routes for lignocellulosic biomass (miscanthus, switchgrass, sorghum and industrial hemp): i) high temperature entrained flow gasification, and ii) autothermal biomass pyrolysis. High temperature entrained flow gasification will produce a clean syngas which is further fermented into liquid biofuels. Autothermal biomass pyrolysis will produce bioproducts that are refinery-compatible intermediates and Fischer-Tropsch fuels.
- **Phy2Climate** – applies a biorefinery process for oil and lignocellulosic biomass based on thermocatalytic reactions consisting of a synergistic combination of many of the abovementioned conversion pathways (Figure 11). All generated intermediates will be further converted in a second step to clean drop-in biofuels for the road and shipping transport sectors applying different technologies such as distillation, electrooxidation and Gas to Liquid processes (GtL).
- **CERESIS** – explores two thermochemical conversion processes for lignocellulosic biomass: i) supercritical water gasification with Fischer-Tropsch upgrading, and ii) fast pyrolysis. The two processes are combined with novel separation technologies for the conversion of harvested energy crops into biofuels or biofuel precursors.

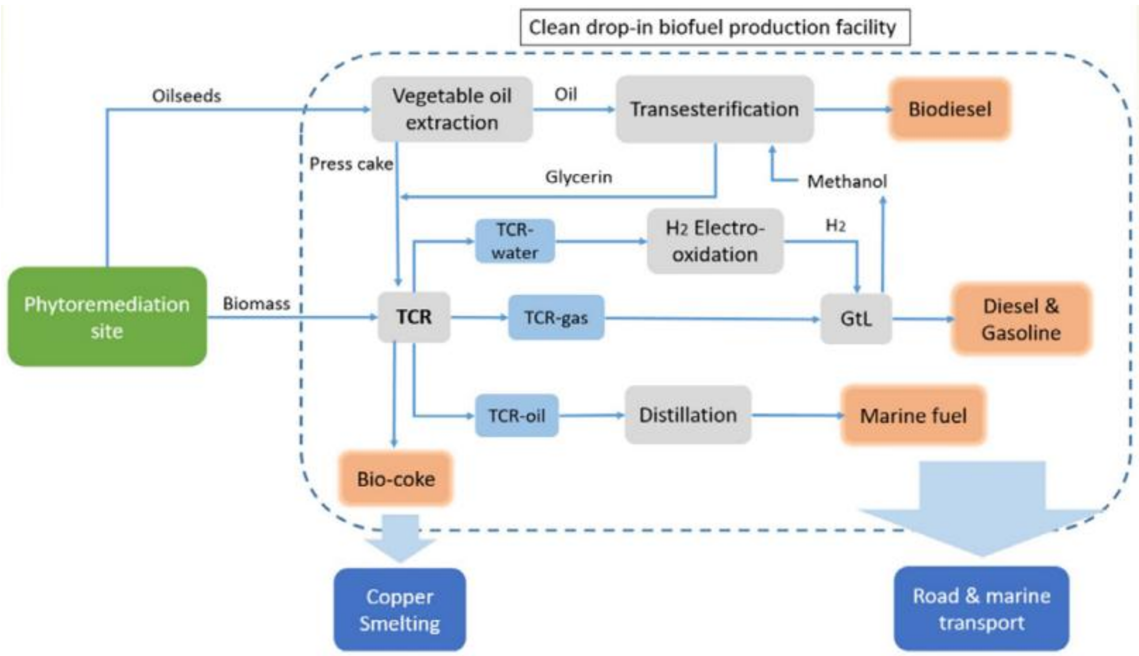

Figure 11. Developed biorefinery concept within the EU project 'Phy2Climate', Credit: Biofpr.

3.4 Commercial biofuel production plants in Europe

Several reports from the International Energy Agency (Hsieh and Felby, 2017; Karatzos et al., 2014) provide multiple examples, or ‘success stories’[3], of bioenergy facilities producing various types of biofuels in different parts of Europe that could be important future partners. Also, the database of bio-based industry in Europe[4] shows 2,362 total facilities of which 339 produce ‘liquid biofuels’. A selection of these located in Europe is provided below (see the reports for more details):

- **Cellulosic ethanol commercial plant in Crescentino (Italy) by Versalis** – enzymatic hydrolysis of cellulosic biomass and fermentation to produce cellulosic ethanol using giant reed, wheat straw, rice straw, hardwood (TRL 9 – actual system proven in operational environment)
- **Crescentino biorefinery, PROESA™ (Italy) –** advanced biofuel refinery: pretreatment of lignocellulosic biomass, enzymatic hydrolysis & fermentation to ethanol; separation of lignin for use in a boiler; anaerobic digestion of sludges using agricultural residues (rice straw, wheat straw), energy crops (giant reed, switchgrass, woody crops), forestry residues/wastes (TRL 7 – system prototype demonstration in operational environment)
- **UPM Biofuels (Finland) –** process developed by UPM, based on hydrotreatment, produces renewable diesel from crude tall oil (CTO) (TRL 9 – actual system proven in operational environment)

Several companies were also highlighted with brief details in the report *Biofuels for the marine shipping sector* (Hsieh and Felby, 2017), some of which are included below.

Biofuel Provider. Neste Corporation (Finland) is a publicly traded oil refining and engineering company producing petroleum products and renewable fuels. Neste produces HVO in four state-of-the-art plants: two in Finland, one in The Netherlands, and one in Singapore. Neste is the market leader in producing renewable diesel from waste and residues with a superior quality compared to traditional biodiesels. The company is the largest producer of drop-in fuels from palm oil, though they have used over ten different raw materials. The production technology is marketed as NexBtL, and is used to make both diesel and aviation fuel.

Biofuel provider. Avril Group (France) is an international agro-industrial group focused on the development of oilseed and protein products from crops founded in 1983. They produce biodiesel from rapeseed oil under the brand Diester, and are the leading producer of biodiesel in Europe. The company incorporates biofuels in diesel blends between 5 and 30% in their company vehicles, while French diesel vehicles use 8%. It is also involved in developing second-generation biodiesel from non-edible plants and agricultural waste as well as animal fats and waste oil. The group participates in BioTfueL, together with Total, a program developing biodiesel and biokerosene from forestry waste. It was designed to transform lignocellulosic biomass and torrified material into biofuel by thermochemical conversion. Its aim is to produce 200,000 metric tons of biodiesel and biojet fuel per year from one million metric tons of biomass by 2020.

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[3] https://www.ieabioenergy.com/iea-publications/success-stories/
[4] https://datam.jrc.ec.europa.eu/datam/mashup/BIOBASED_INDUSTRY/index.html

Biofuel Provider. SunPine (Sweden) is a company specializing in the production of fuels and chemicals from by-products of the forestry industry. Founded in 2006, the company is focused on sustainable forestry practices and adding value to residual products from the pulp industry. Their production plant is located in Piteå Harbour in northern Sweden, and has been operational since 2010. At the moment, SunPine focuses on extracting tall oil from the pulp and paper industry as a raw material for their renewable products portfolio. Their crude tall oil (CTO) intermediate product is further processed at the Preem refinery to upgrade the tall oil diesel to a higher quality drop-in fuel, branded as green diesel, which can be blended with regular diesel fuel. SunPine also uses tall oil to produce bio-oil and resin.

Biofuel provider. Eni (Italy) is an energy company founded in 1953 with operations in 79 countries worldwide. Though mainly focused on oil and gas, Eni has expanded operations in a large number of fields including nuclear power, renewable energy, mining, chemicals, and plastics. Eni has converted its refinery in Porto Marghera, Venice, to the production of biofuel from vegetable oil and biomass[133]. The plant produces green diesel, naphtha, and LPG from palm oil, but plans to expand their feedstock base to second generation biomass. They use their trademarked Ecofining process, developed together with Honeywell-UOP in the San Donato Milanese laboratories, for the production of biofuels using the catalytic hydro-desulphurization section of a traditional refinery. The biodiesel produced has been used by the Italian Navy's offshore patrol vessel Foscari.

Fuel Technology & Fuel Provider. BetaRenewables (Italy) was established in 2011 as a joint venture between Biochemtex (Italy), Texas Pacific Group (USA), and Novozymes (Denmark). BetaRenewables owns the PROESA technology, a patented process to produce second generation biofuels and biochemicals at a commercial scale. The company has tested their technology on various lignocellulosic biomass, including energy crops, woody biomass, and agricultural residues for bioconversion to ethanol. At the end of 2012, BetaRenewables, partnered with Biochemtex, completed the first commercial 2nd generation bioethanol plant in Crescentino, Italy to showcase their PROESA technology. The bioethanol produced is derived from wheat straw and giant reed, which are locally available within a 70 km radius from the plant. PROESA first involves a biomass pretreatment step, followed by saccharification and fermentation of C5 and C6 sugars to ethanol. BetaRenewables is still actively developing the biorefinery process, and future plans include fermentation to other C5- and C6-derived chemicals such as butanol, fatty alcohols, and ethylene glycol[92].

As shown in Figure 12, some countries may have thriving bioenergy industries that are focused on specific crops and production processes. Note that the types and proportions of biomass and bioproduct have likely changed since the year of publication.

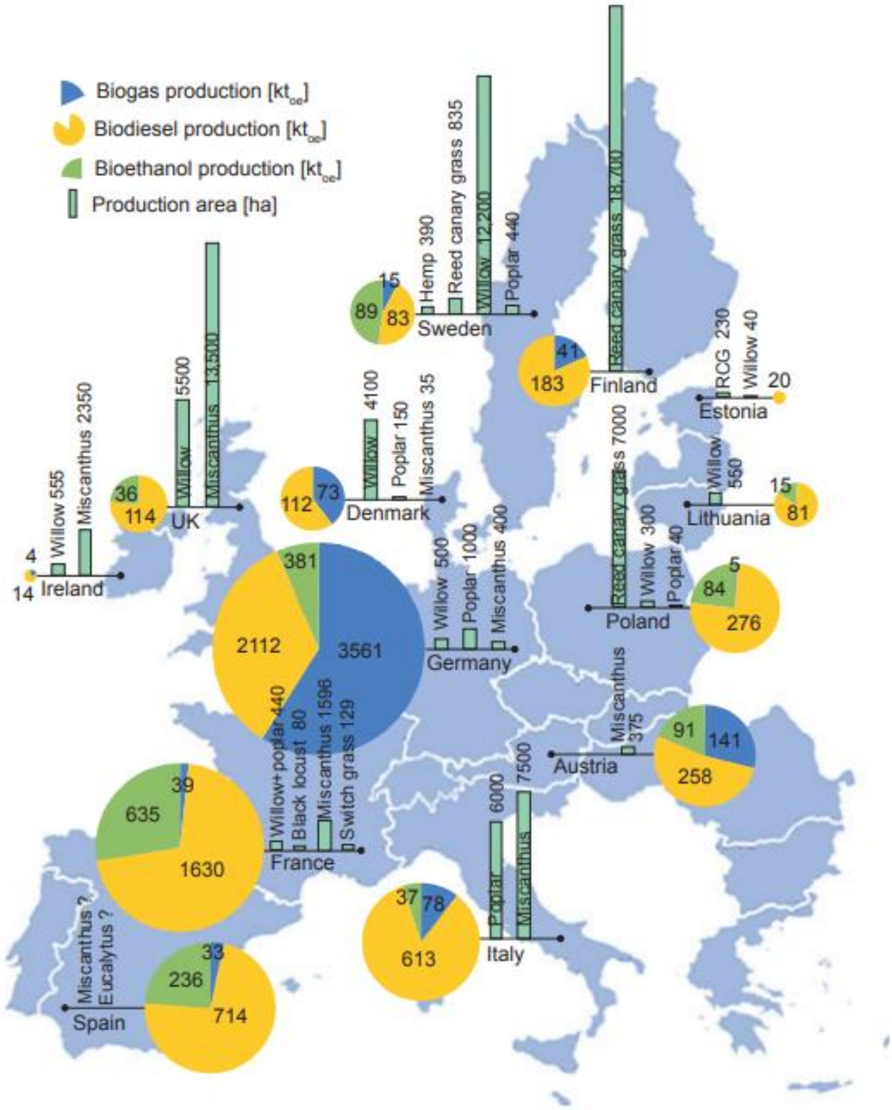

Figure 12. Energy crops in Europe at time of publication: production area (ha) of dedicated energy crops and energy production (ktoe) of conventional energy crops, from (Don et al., 2012).

4 Selected plants' potential for phytoremediation and production of biofuels

Depending on the end product and type of bioenergy, different plant species and biomass compositions are required. For example, the 4F Crops European Commission project was created to expand upon and identify the most influential bioenergy crops used in Europe to contribute to a bio-based economy (EC, 2010). The project resulted in a list of 15 non-food crops that were categorized in five groups: oil crops for biodiesel production (rapeseed, sunflower, Ethiopian mustard), sugar and starch crops for bioethanol (sweet sorghum and sugar beets), fibre crops (hemp and flax), lignocellulosic crops (giant reed, miscanthus, switchgrass, reed canary grass), and short rotation forestry crops (willow, poplar, eucalyptus).

In general, biofuels for transport rely mainly on annual oil and starch or grain energy crops (e.g., corn, soybean, rapeseed, sugar beet, and cereals) while electricity and heating on perennial herbaceous and woody plants (e.g., miscanthus, switchgrass, reed canary grass, willow, and poplar) as well as waste biomass. However, the use of different crops for producing bioenergy has evolved over time and is generally separated into different generations. First-generation bioenergy crops are typically oilseed and starch/grain crops that were originally used to develop biofuels like ethanol, and are still used today, though there are many controversies regarding growing them to produce fuel on fertile agricultural land instead of food crops. Some of these, such as wheat and rye, have particularly high environmental impacts, and the gains using those crops would be small, while the potential impacts on the land and soil would be of concern (Y Andersson-Sköld et al., 2014). An important consideration in the second and successive generations is that they are non-food crops that do not contribute to indirect-land use change (ILUC), i.e., in competition with other uses of the land that exacerbate conflicts in the 'food-water-energy' land use nexus. Lignocellulosic biofuels are fuels made from non-food crops or agricultural/wood residues, which can be more expensive and complicated than using starch- or sugar-rich feedstocks (like corn) because it is harder to access the plant's sugar and break down the tissues. However, lignocellulosic biofuels are generally considered to be more environmentally and socially sustainable. These new types of bioenergy crops would replace first-generation crops such as corn and sugarcane that are often produced using intensive agriculture (high impact) on high value agricultural land that could otherwise be used to produce food. Indeed, second generation bioenergy crops are better suited for marginal, contaminated, and/or degraded land, without high input requirements. Many projects have lately focused on the production of industrial, non-food crops on marginal lands in Europe, e.g., MAGIC and PANACEA projects (Alexopoulou et al., 2018; Monti and Zanetti, 2017), see Figure 13.

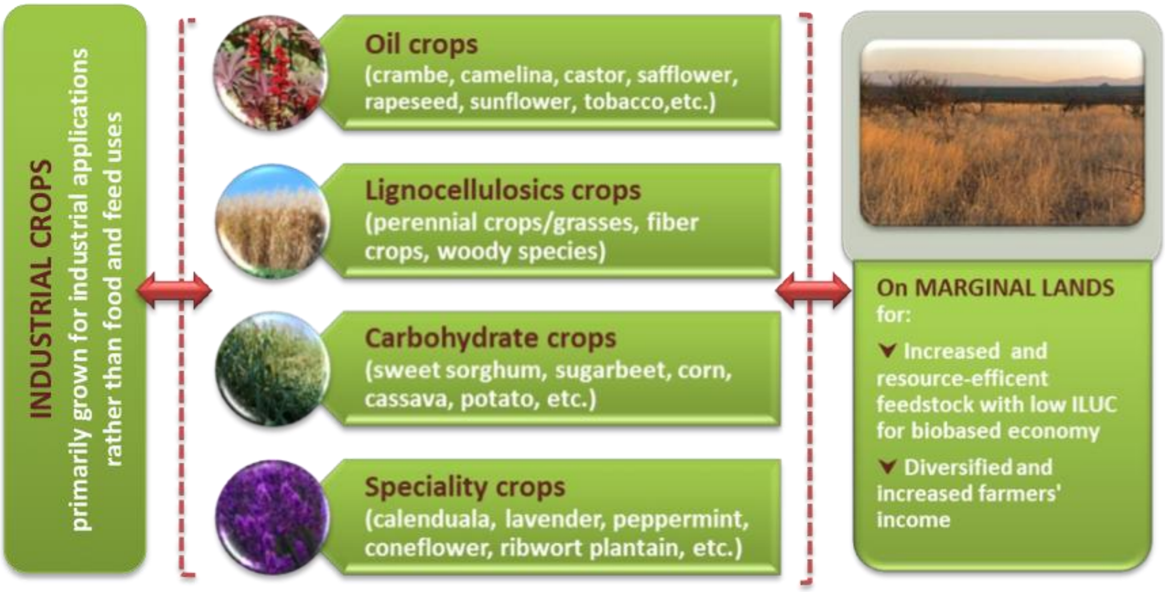

Figure 13. Types of crops that may be suitable for cultivation on marginal lands in European climate zones, from https://magic-h2020.eu/.

Climate is one of the most important considerations when decided which plants to cultivate (Figure 14). For example, willows, as well as herbaceous crops such as giant reed or miscanthus, are appropriate crops for growing in both warmer and cooler temperate climate conditions ranging from Sweden, Ukraine, Germany and Italy. Water availability is also important where, for example, willow can be also grown under temporarily or permanently water-saturated soil conditions (Panoutsou et al., 2022).

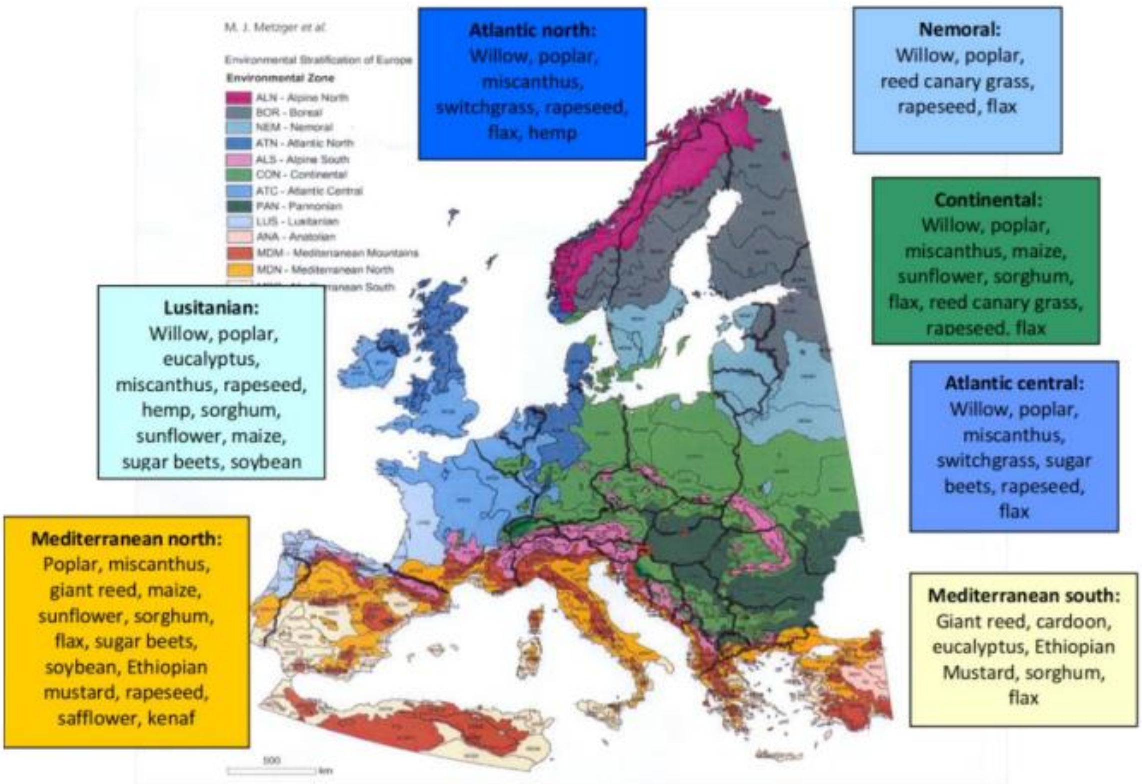

Figure 14. Recommended bioenergy crops per climatic zone, from (Panoutsou et al., 2017).

Regarding specifically biofuels, biomass crops for sustainable biofuel production can be generally separated into two main categories: oil and lignocellulosic (Panoutsou et al., 2022). Descriptions of the different plants are provided in the following sections, see e.g., (Alexopoulou et al., 2018; Andersson-Sköld et al., 2013a; Mehmood et al., 2017; Monti and Zanetti, 2017; Moreira et al., 2021) for more information. Brief details about the climate/growth conditions and approximate biomass yield are provided.

4.1 Oil crops – annual, flowering species

Sunflower (*Helianthus annus*) – *solros*

Annual spring crop belonging to the Asteraceae family. Native to central America it's widely grown in whole southern Europe, where it is the most widespread oilseed species. Characterized by very high drought tolerance it could grow under rain fed conditions in southern Europe. The oils of high oleic sunflower hybrids represent a valuable raw material for many oleochemical processes (Monti and Zanetti, 2017).

- Climate/Growth conditions: temperate climates, may not be well-suited for northern (or central) climates, grows well in clayey and sandy soils
- Approximate biomass yield: Average oil yield ca. 0.67 t/ha/yr (National Sunflower Association, n.d.), of which about 80% can be extracted via mechanical extraction.

Canola/Rapeseed (*Brassica napus*) – *raps*

Belonging to the Brassicaceae family, rapeseed has high oil content and produces high quality oil which is commonly used to produce biodiesel that is very efficient in powering heavy machinery and other vehicles. HEAR, defined as high erucic acid rapeseed, is a type of rapeseed oils that can be used in many non-food applications. HEAR is very similar to rapeseed in terms of agronomic needs and seed production. The majority of HEAR varieties are winter type and they are well adapted to continental Europe climate, where they can achieve oil production > 2 Mg/ha (Monti and Zanetti, 2017).

- Climate/Growth conditions: temperate climates but wide climate tolerance, can require good quality agricultural soil for high yield, somewhat high input and management requirements; An effective break crop in cereal rotation because it results in higher-yielding cereal crops and weed control
- Approximate biomass yield: Seed yield 2-4.5 t/ha/yr; biodiesel production 392 L/ton biomass

Camelina (*Camelina sativa L.*) – *oljedådra*

Annual C3 crop native to Eurasia. Plants are erect (0.8-1.2 m tall). Each branch terminates in a raceme with yellow flowers typical of Brassicaceae family. Up to 10-12 seeds are enclosed in a "pear-shape" silique. Individual seed weight is below 1.5 mg. Both spring and winter biotypes are available in the market. Seeds contain up to 42% of oil and up to 30% of protein. Camelina oil is very rich in polyunsaturated fatty acids, with a composition like flax (Alexopoulou et al., 2018; Monti and Zanetti, 2017; Panoutsou et al., 2022).

- Climate/Growth conditions: Fast-growing crop, double cropping (catch crop), wide climate tolerance and soil tolerance, native to Europe
- Approximate biomass yield: Seed yield 0.5-3 t/ha/yr, 38-42% oil content

Mustard (*Brassica carinata, B. juncea*) – *senap*

Belonging to the Brassicaceae family, Indian/Ethiopian mustard is a low input crop, very tolerant to different biotic and abiotic stresses, and to seed shattering. Plants are highly vigorous, and they can present both white and yellow flowers. Despite being a spring crop in mild environments, it could be grown also as a winter crop. Seeds contain up to 35% in oil and up to 30% in protein. The oil is rich in erucic acid (C22:1>40%) (Monti and Zanetti, 2017).

- Climate/Growth conditions: temperate climates, grows well in sandy to heavy clayey soils, shallow soils, grown as a spring crop in areas with cold winters due to low tolerance to frost and cold climates, water stress tolerant, pH tolerance (5.5-8.0)
- Approximate biomass yield: Seed yield 1.5-3 t/ha/yr, oil content ca. 40%; biodiesel production 370L/ton biomass

Crambe (*Crambe abyssinica* L.) – *oljekål eller oljekrambe*

Belonging to the Brassicaceae family, crambe is the species with the highest content of erucic acid in its oil (>55%). Crambe is a low-input spring crop well suited to drought environments. Plants are up to 1.2 m tall, and the seeds are singly enclosed in their pods, which are indehiscent. Crambe seeds are very rich in glucosinolates. Vegetable oil can be extracted from crambe seeds to produce biodiesel – oil has higher calorific value and oxidative stability compared to soybean oil biodiesel (Alexopoulou et al., 2018; Monti and Zanetti, 2017; Panoutsou et al., 2022).

- Climate/Growth conditions: grown as a spring crop in areas with cold winters, water stress tolerant, wide tolerance, pH tolerance (5.0-7.8)
- Approximate biomass yield: Seed yield 0.5-3 t/ha/yr, oil content ca. 54%

Cardoon (*Cynara cardunculus* L.) – *tistel*

Perennial C3 plant belonging to the Asteraceae family, native to Mediterranean region. It is a good candidate to be grown in the dry lands of the Mediterranean region as a multipurpose crop since from the harvested biomass it is possible to obtain lignocellulosic feedstock, while from the seeds it is derived a valuable oil with many non-food applications (Alexopoulou et al., 2018; Monti and Zanetti, 2017; Panoutsou et al., 2022).

- Climate/Growth conditions: Herbaceous perennial plant, high temperate, low rainfall, drought and salinity tolerant
- Approximate biomass yield: 7.4-14.6 t/ha/yr, seed yield 1-3 ton/ha, oil content ca. 25%

4.2 Lignocellulosic – grasses and trees

Willow (*Salix* spp.) – *sälg, vide, pil*

Genus of deciduous woody plants includes 350-370 species. Most willow species can be easily reproduced with winter cuttings. For energy feedstock, fast-growing cultivars of shrub willows (*Salix viminalis* in Europe and *S. eriocephala* in North America) are considered most suitable as biomass crops. Compared to most other trees of the temperate zone, willows can achieve a greater photosynthetic rate and light-use efficiency when well supplied with water and nutrients, and fast-growing willow varieties are able to utilize a greater part of the growing season for growth. A specific feature of many willows is their ability to re-sprout from stumps or stools even after repeated cuts or biomass harvesting. Willow does not necessarily require nutrient-rich soil, it can grow in low-fertile and acidic soils but requires moisture at least during a significant portion of the growing season. However, site conditions favourable for plant growth are important to achieve high biomass yield also for willows, and warmer climate along with fertile soils may generate higher yields than cold climate and infertile soils. In regions with extended seasonal droughts, plantations of biomass willow should be established in the areas of adequate moisture, floodplains, and other places with high levels of groundwater where drought conditions are common (Monti and Zanetti, 2017). Willow trees consist of about 45% cellulose, 20% hemicellulose and 25% lignin, and, like other lignocellulosic plants, have an inherent resistance to destruction. This biomass recalcitrance can be overcome, which has been demonstrated by selecting specifies varieties of *S. viminalis* and pretreatment processes that can improve efficiency for both enzymatic hydrolysis and anaerobic digestion pathways (Ohlsson, 2021).

- Climate/Growth conditions: Moist soils in cool- to warm-temperate regions, wide tolerance and can establish on soils of poorer quality though fertilization is still recommended, most often cultivated in short-rotation coppice (SRC)
- Approximate biomass yield: 5-15 t/ha/yr

Poplar (*Populus* spp.) – *poppel*

Similar to willow, poplar has a high growth rate already at a young age, requires relatively low fertilizer input, produces a clean feedstock for biorefineries and sugars are relatively easy to extract – they can be used for both phytoremediation and are tolerant to poor conditions on marginal/contaminated land. However, poplars also produce more biomass under more favourable conditions for growth. Populus is a genus of 25–35 species of deciduous flowering woody plants in the family Salicaceae, native to most of the Northern Hemisphere. It is a widely adaptable and fast-growing species, normally propagated by cuttings. Plants can grow up to 50 m tall. For biomass purposes it is often grown as short-rotation coppice(SRC) with harvests every two to five years for up to 20-

25 years, with multiple stems and able to achieve very high yield of lignocellulosic biomass, depending on the environmental conditions (Alexopoulou et al., 2018; Monti and Zanetti, 2017). Poplars (and willows) are more desirable for biofuels than many other woody crops because of their fast growth already in a young age, their ability to produce a significant amount of biomass in a short period of time, and their high cellulose and low lignin contents (Farm Energy, 2019), see Figure 15. Recent advances have extracted sugars from poplar wood chips and fermented to produce bioethanol (Farm Energy, 2019).

- Climate/Growth conditions: often wetlands or riparian trees, circumpolar subartic and cool- to warm-temperate, prefers loamy soils with stable moisture levels, wide tolerance, often cultivated in short-rotation coppice (SRC)
- Approximate biomass yield: 5-15 t/ha/yr

Note: can be considered invasive/exotic in parts of Europe.

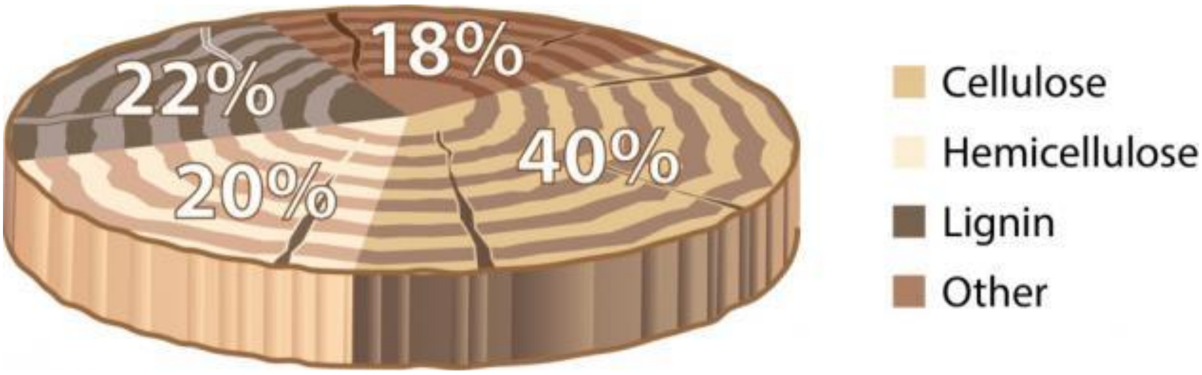

Figure 15. General composition of poplar wood showing estimates of average cellulose and lignin content, from Advanced Hardwood Biofuels Northwest (Farm Energy, 2019).

Miscanthus (*Miscanthus x giganteus*) – *elefantgräs, miscanthus*

Miscanthus is a perennial rhizomatous C4 grass, native to East Asia, with high biomass yield potential, fast growth, high tolerance, and low input requirements that makes is a dedicated bioenergy crop with high potential (Monti and Zanetti, 2017; Yadav et al., 2019). *Miscanthus* x *giganteus* is presently the only commercially grown miscanthus genotype, which is a triploid, sterile hybrid between *M. sinensis* and *M. sacchariflorus*. It's commonly vegetative propagated with rhizomes. Miscanthus biomass consists of about 38% cellulose, 24% hemicellulose and 25% lignin, and has many valuable applications in different end-uses, mainly related to energy production via combustion, gasification and pyrolysis conversion pathways (Figure 16). Other research exploring simultaneous saccharification and fermentation of pretreated miscanthus resulted in experimental ethanol yields of 0.13-0.23 g/g-raw biomass (Lee and Kuan, 2015).

- Climate/Growth conditions: Perennial, C4-pathway (efficient water use), suitable for various climates – grows well in warm-temperate climates although spring frosts can damage yields, does not grow below 6°C, low to medium grade agricultural soil, prefers well-drained soils but wide range of tolerance,
- Approximate biomass yield: 10-20 t/ha/yr

For phytoremediation, Miscanthus can be considered a metal excluder, with a capacity to accumulate more metals in roots and limit transfer to shoots, promote degradation of organic contaminants, and improve soil quality at contaminated sites. Miscanthus is a suitable crop for combining biomass production and ecological restoration of contaminated and marginal land (Nsanganwimana et al., 2014). Miscanthus has been shown to increase carbon inputs and promote microorganism diversity and activity, which are important in soil particle aggregation and rehabilitation processes (Técher et al., 2011).

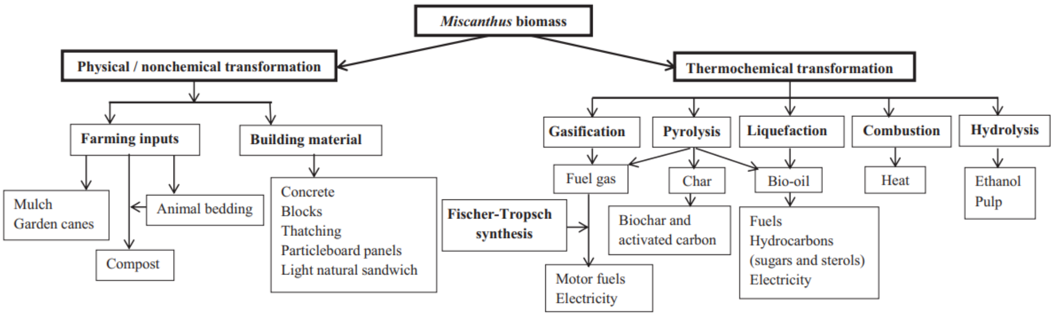

Figure 16. Miscanthus biomass transformation pathways and products, from (Nsanganwimana et al., 2014)

Switchgrass (*Panicum virgatum*) – *rödhirs, präriehirs*

Switchgrass is a perennial, herbaceous C4 warm-season grass native to Northern America that is commonly cultivated on marginal and degraded lands and generally has low nutrient and water requirements to produce high yields (Monti and Zanetti, 2017; Yadav et al., 2019). Erect and bushy plant, 1-3 m tall. Depending on their latitudinal origin, cultivars of switchgrass can placed into two distinct ecotypes: upland and lowland. Upland ecotypes are better adapted to the drier and colder habitats, while lowlands types tend to thrive in warmer, wetter habitats (Monti and Zanetti, 2017).

- Climate/Growth conditions: Perennial, adaptive to versatile growth conditions, C4-pathway (efficient water use), temperate regions, drought-resistant, wide tolerance
- Approximate biomass yield: up to 22 t/ha/yr

Note: can be considered invasive, may also be difficult to source high-quality seeds.

Sorghum (sweet/biomass/fiber) (*Sorghum bicolour*) – *durra*

Sorghum is a C4 grass with high sugar content belonging to the Poaceae family. *Sorghum bicolour* is a multipurpose species, native to Africa and able to grown worldwide in mild environments. It is a very drought tolerance species, characterized by low nutrient and water requirements thus making it well suited to marginal land, but it may be sensitive to low temperatures. Some varieties have been selected to produce sugar (sweet sorghum), others to produce high amount of lignocellulosic biomass (biomass sorghum and fiber sorghum) (Monti and Zanetti, 2017; Yadav et al., 2019). The global production of bioethanol from sorghum ranges from 3-9 m^3/ha (or 3740-5610 L/ha) and sorghum based bioethanol is considered more economical than that of based on sugarcane (Mehmood et al., 2017).

- Climate/Growth conditions: Higher abiotic resistance, under diverse climates, suitable for growing in dryland conditions), wide cultivation range but cold sensitive
- Approximate biomass yield: 9-28 t/ha/yr

Sorghum has been shown in numerous studies to have a significant potential for accumulating different metals, which may even lead to effective phytoextraction in the long-term due to high biomass production (e.g., (Ofori-Agyemang et al., 2024)).

Note: Sorghum was highly recommended by Prof. Michel Mench during interview.

Giant reed (*Arundo donax*) **–** *italienskt rör, pålrör, käpprör, mm*

Perennial rhizomatous C3 warm-season grass native to Asia. Erect and caespitose plant, 2-5 m tall. Sterile plant, propagate exclusively by vegetative propagules (rhizomes, stem cuttings, node cuttings). It can thrive in hot, drought prone environments, as well as wetter habitats, under salinity, steep slopes, poor soil texture and contaminated soil (Monti and Zanetti, 2017). Can be used to produce high amount of biogas during anaerobic digestion, and recent study demonstrated its high potential for producing sustainable aviation fuel via a pyrolysis pathway (Zongwei et al., 2025).

- Climate/Growth conditions: Perennial, C3-pathway (less efficient water use), subtropical and tropical regions, Mediterranean climate, high tolerance to poor quality soil
- Approximate biomass yield: up to 36 t/ha/yr

Note: potentially invasive, especially in wetland areas.

Reed canary grass (*Phalaris arundinacea*) **–** *rörflen, randgräs*

Reed canary grass is a native species growing in Europe as well in North America and Asia. The C3 grass is a sod- forming, productive, vigorous, perennial (up to 7 years rotation). Plants have dominantly basal broad and moderately harsh, erect leaves on coarse, erect stems. Height of 1,5 to 2 m. It is seed-propagated, well suited to wet soils that are poorly drained or subject to flooding, survives well in drought, and has excellent frost tolerance. It could be used as solid biofuels fresh biomass for biogas production. Regrowth after grazing and/ or mowing is very rapid on fertile sites and still can be high production on marginal land and in cooler climates (Andersson-Sköld et al., 2013a; Monti and Zanetti, 2017; Yadav et al., 2019).

- Climate/Growth conditions: Perennial bunch grass, suitable to cool- and warm-temperate regions, wet soils flood plains
- Approximate biomass yield: ca. 15 t/ha/yr

Note: potentially invasive, especially in wetland areas.

Industrial hemp (*Cannabis sativa*) – *hampa*

Hemp is a C3 annual warm-season plant belonging to the Cannabaceae family, adapted to a wide range of environments. It is a typical multi-purpose crop being able to produce lignocellulosic biomass and oil from the seeds. Naturally it is dioecious, with the male plants that are taller and that come to flower earlier that the female ones. Monoecious varieties have been recently selected to reduce some agronomic problems such as an efficient mechanization for harvesting the seeds, and the lower fibre quality and yield losses encountered when harvesting dioecious varieties at seed maturity (Andersson-Sköld et al., 2013a; Monti and Zanetti, 2017). Biodiesel produced from hemp seed oil presents physicochemical properties comparable to values reported in the fuel standard specifications for biodiesel fuel blends, i.e., ASTM D6751 (Edgar et al., 2021).

- Climate/Growth conditions: Prefers loamy soils; tolerant of high metal concentrations, requires a mild, humid climate and highly fertile soil
- Approximate biomass yield: ca. 12-15 t/ha/yr, seed yield 850-1500 kg/ha/yr

A summary of the agronomic characteristics of some of the plants mentioned above are provided in Figure 17.

Characteristics[a]	*Miscanthus* sp.	*Sorghum bicolor*	*Panicum virgatum*	*Arundo donax*	*Populus* sp.	*Salix* sp.	*Eucalyptus* sp.	*Cannabis sativa*	*Brassica carinata*
Biomass yield (t DW ha^{-1})	15–30	5–30	10–25	14–45	7–28	10–30	10–25	12–23	2.6–4
N requirement (kg ha^{-1})	0–100	56–224	0–70	40–60	110–450	80–150	60–125	100–220	80–170
Nutrient use efficiency	+++	++	+++	+++	++	+++	+++	+++	++
Nutrient recycling	+++	+	+++	+++	+++	+++	+++	+	+
Water needs (P_{mm})[b]	700–800	300–700	450–750	380–650	>350	1,000	870–1,100	400–600	
Water use efficiency	+++	++	+++	++	+	++	++	++	++
Pest resistance	+++	+++	+++	+++	++	++	++	+++	++
Noninvasiveness	++[c]	++	+++	++[d]	++	++	++	++	++
Ecological benefits[e]	+++	+++	+++	+++	+++	+++	+++	+++	+

[a] Favorable characteristics and effects are indicated by +, with +++ being the most favorable.
[b] Ranges of annual rainfall needed for optimal productivity.
[c] Nonhybrid *Miscanthus* species such as *M. sinensis* can become invasive outside their native distribution ranges.
[d] *Arundo donax* is an aggressive riparian invasive in nonagricultural ecosystems.
[e] The ecological benefits mainly refer to the plant's potential to improve soil and water quality, to grow on and add value to marginal land, and to reduce greenhouse gas emissions during its life cycle.

Figure 17. Agronomic characteristics of the most frequently used bioenergy crops in Europe, from (Nsanganwimana et al., 2014).

4.3 Plant potential

From the different types of plants, produced biomass and potential for biofuel production, a subset of plants emerge that are the most promising for achieving the project aim. Different biomass conversion processes have different **Technology Readiness Levels** (Monti and Zanetti, 2017), which can be divided into the following groups:

- TRL <3: basic research data available
- 3 < TRL < 5: from research to product development
- 5 < TRL <7: production available at demo scale
- TRL > 7: industrial production already available at commercial scale

A summary of the suitability of different types of plants for phytoremediation and production of biofuels, including TRL for both Large-scale agricultural production methods (P) and Biomass conversion pathway maturity to produce biofuel (B) is presented in Table 2.

4.4 Viable biofuels in the short- and long term

Based on the presented information, the most feasible pathways for phytomanagement and biofuel production are likely a combination of a short-term and a long-term strategy:

Short-term: First-generation biofuels (e.g., bioethanol, biodiesel) produced using oil crops like rapeseed, sunflower, and mustard or fermentation of sugar-rich crops like sorghum. The primary reason for proposing these crops in the short-term is the maturity of the existing market to produce biofuels from vegetable oils and sugars, i.e., high TRL, >7).

Long-term: Second-generation biofuels produced using lignocellulosic biomass, which is still under development but developing rapidly as evidenced by the many ongoing research projects and companies engaged in this field. Overall, the net benefit of using perennial, lignocellulosic crops to produce biofuels is greater; however, the market and bioenergy industry are likely not yet mature enough, i.e., lower TRL of 3-5 – with some exceptions.

Table 2. Suitability of different types of plants for phytoremediation and production of biofuels. TRL is for both Large-scale agricultural production methods (P) and Biomass conversion pathway maturity to produce biofuel (B). Approximate biofuel production provided where estimates were readily available, derived from e.g., (Addison, 2001; Johnston et al., 2009; Kurki and Morris, 2006; Lee and Kuan, 2015; Mehmood et al., 2017).

Plant Type	**Common name** (Latin)	**Swedish name**	**Remediation potential** (Removal)	**Bioenergy uses and additional benefits** (Fuel production potential)	**References** (Projects)	**TRL** (P/B)
Lignocellulosic, grass (annual)	Biomass/Sweet Sorghum *(Sorghum bicolour L.)*	*Durra*	Inorganics – Medium Metal accumulator: Cd, Zn, Pb Organics – Medium Degradation of PAHs, BTEX	Biofuel production (bioethanol) or in other bio-products (biogas); large biomass quantity; well-suited for rotation with deep-rooted crops (Ethanol: 402 L/ton biomass or 3740-5610 L/ha)	(Ionata et al., 2024; Kidd et al., 2015; Mehmood et al., 2017; Ofori-Agyemang et al., 2024; Pandey et al., 2016; Zegada-Lizarazu and Monti, 2011) (GOLD)	P: 5-7 B: >7
Lignocellulosic, grass (perennial)	Reed canarygrass *(Phlaris arundinacea)*	*Rörflen, randgräs*	Inorganics – Medium Extraction of As, Sn, Cd, Cr, Cu, Ni, Pb, Zn; highly tolerant to pollution Organics – Medium Degradation of PAHs and pesticides	Biofuel and bioenergy; carbon sequestration, soil restoration, large biomass quantity; drought tolerant - suitable for warm regions	(Andersson-Sköld et al., 2013a; Lord, 2015; Mehmood et al., 2017; Pandey et al., 2016) (CERESIS)	P: 5-7 B: 3-5
Lignocellulosic, grass (perennial)	Giant perennial silvergrass, miscanthus or elephant grass *(Miscanthus x giganteus)*	*Miskantus/ Elefantgräs*	Inorganics – Low Stabilisation (metal excluder); highly tolerant to pollution Organics – High Degradation of PAHs, hydrocarbons (increases degrading microbes) and pesticides	Biofuel and bioenergy; carbon sequestration, soil restoration, large biomass quantity; (*M. giganteus*) non-invasive genetic mutant; resistant to pests and disease; increases carbon storage, and microorganism diversity and activity; prevents erosion and runoff - dense, fibrous root system; habitat provisioning (Ethanol: 0.13-0.23 g/g-raw biomass)	(Andersson-Sköld et al., 2013a; Kidd et al., 2015; Mehmood et al., 2017; Nsanganwimana et al., 2014; Pandey et al., 2016; Tripathi et al., 2016) (GOLD, Phy2Climate, CERESIS)	P: 5-7 B: 3-5
Lignocellulosic, grass (perennial)	Switchgrass (*Panicum virgatum)*	*Rödhirs, präriehirs*	Inorganics – Low Stabilisation (metal excluder); highly tolerant to pollution Organics – Medium Low uptake of DDT; degradation of atrazine and PAHs	Biofuel and bioenergy; carbon sequestration, soil restoration, large biomass quantity; drought tolerant - suitable for warm regions	(GREENLAND, 2014; Lewandowski et al., 2003; Paul et al., 2015)	P: 5-7 B: 3-5
Lignocellulosic, grass (perennial)	Giant reed (*Arundo donax*)	*Italienskt rör, pålrör, käpprör, mm*	Inorganics – Low Stabilisation (metal excluder); highly tolerant to pollution Organics – Unknown	Biofuel and bioenergy; carbon sequestration, soil restoration, large biomass quantity; drought tolerant - suitable for warm regions	(GREENLAND, 2014; Lewandowski et al., 2003)	P: 5-7 B: 3-5

Lignocellulosic, grass (perennial)	Industrial hemp (*Cannabis sativa*)	*Hampa*	Inorganics – Medium Extraction of Cd, Cr, Cu, Ni, Pb, and Zn Organics – Medium Degradation of PAHs and pesticides (tested for PFAS uptake)	Biofuel production (biodiesel), bioenergy or in other bio-products as fibre; large biomass quantity and fast growing; natural control of pests/weeds (Biodiesel: 363 L/ha)	(Pandey et al., 2016; Tang et al., 2012; Zegada-Lizarazu and Monti, 2011)	P: 5-7 B: 3-7
Lignocellulosic, tree (perennial)	Willow (*Salix viminalis, S. alba, S.* spp.)	*Sälg, Vide, Pil*	Inorganics – High Extraction of Cd, Cr, Mn, Fe, Ni, Cu, Zn, Pb, Rb, Sr, Ti, Co; Stabilisation (depends on clone) Organics – Medium Degradation of chlorinated solvents, PAHs, and POPs; low uptake of DDT;	Biomass, biogas, plywood, biochar; fast growing, high biomass quantity; carbon sequestration, increases faunal biodiversity - extensive testing of clones and hybrids (properties vary with clone e.g., Klara, Inger, Tora) - deep rooting and phreatophytic	(Andersson-Sköld et al., 2013a; Delplanque et al., 2013; GREENLAND, 2014; Ionata et al., 2024; Kidd et al., 2015; Licht and Isebrands, 2005; Mehmood et al., 2017; Pandey et al., 2016; Tripathi et al., 2016)	P: 5-7 B: 3-5
Lignocellulosic, tree (perennial)	Poplar (*Populus alba, P. deltoides, P.* spp.), Hybrid aspen (*P. tremula x P. tremuloids*)	*Poppel*	Inorganics – High Extraction of various metals Organics – High Degradation of PAHs; TNT, TCE, VOCs and POPs	Biomass, biogas, plywood, biochar; fast growing, high biomass quantity; carbon sequestration - extensive testing of clones and hybrids - deep rooting and phreatophytic	(Andersson-Sköld et al., 2013a; Chalot et al., 2012; GREENLAND, 2014; Kidd et al., 2015; Licht and Isebrands, 2005; Mehmood et al., 2017; Pandey et al., 2016; Tripathi et al., 2016)	P: 5-7 B: 3-5
Oil crop (annual)	Sunflower *(Helianthus annus L.)*	*Solros*	Inorganics – High Extraction of Cd, Cr, Pb, Ni, As, Fe, Zn, Hg Organics – Medium Degradation of PAHs and atrazine; degradation and uptake of DDT/DDE and POPs	Biofuel production (biodiesel, bioethanol, biogas), charcoal; land reclamation, drought resistant; efficient use of soil resources; large biomass quantity; natural control of pests/weeds (Biodiesel: 418 L/ton biomass or 952 L/ha)	(GREENLAND, 2014; Kidd et al., 2015; Thijs et al., 2018; Tripathi et al., 2016; Zegada-Lizarazu and Monti, 2011)	P: 5-7 B: >7
Oil crop (annual)	Rapeseed *(Brassica napus)*	*Raps*	Inorganics – High Extraction of As, Sn, Cd, Cr, Cu, Ni, Pb, Zn Organics – Medium Degradation of PAHs and PCBs	Biofuel production (biodiesel) and bioenergy (biogas); Soil restoration, large biomass quantity (Biodiesel: 392 L/ton biomass or 1190 L/ha)	(Ionata et al., 2024; Lacalle et al., 2018; Witters et al., 2012a, 2012b; Zegada-Lizarazu and Monti, 2011)	P: >7 B: >7

Oil crop (annual)	Indian Mustard (*Brassica juncea L.*), Ethiopian Mustard (*B. carinata*)	*Senap*	Inorganics – High Extraction of Cd, Zn, Pb, Ni, Hg Organics - Unknown	Biofuel production (biodiesel) and bioenergy; carbon sequestration, land reclamation - use as green manure (Biodiesel: 370 L/ton biomass or 572 L/ha)	(Ionata et al., 2024; Zegada-Lizarazu and Monti, 2011)	P: 5-7 B: >7
Oil crop (annual)	Camelina (*Camelina sativa* L.)	*Oljedådra*	Inorganics – Medium Extraction of Cd, Ni and other metals Organics – Medium Degradation of PAHs and atrizine	Biofuel production (biodiesel) or in other bioproducts as fiber (similar to flax); large biomass quantity; well-suited for rotation with deep rooted crops (Biodiesel: 583 L/ha)	(Panoutsou et al., 2022)	P: 5-7 B: 3-7
Oil crop (annual)	Crambe (*Crambe abyssinica* L.)	*Oljekål, oljekrambe*	Inorganics – Uknown Organics – Unknown	Biofuel production (biodiesel)	(Panoutsou et al., 2022)	P: 5-7 B: 3-7
Oil crop (annual)	Cardoon (*Cynara cardunculus* L.)	*Tistel*	Inorganics – Medium Extraction of As, Cd Organics – Unknown	Biofuel production (biodiesel)	(Mehmood et al., 2017; Panoutsou et al., 2022)	P: >7 B: 3-7

5 Production of biofuels with contaminated biomass

One of the main constraints in using bioenergy crops grown on contaminated land is the real, or perceived, negative effects that the contaminants would have during the conversion process to heat, biofuels or other bio-products (Bert et al., 2017). Certain elements such as excess Ca, Si, Mg or K can be a concern for bioenergy production, and metal(loid) contaminants may induce operational problems such as 'slag' formation, damage to catalysts or corrosion in the facility (Moreira et al., 2021). There are not yet many regulations and standards for established contaminant thresholds (Bert et al., 2017). Excess metal(loid)s can, however, negatively impact the quality of the biomass and the resulting end product such as the heavy hydrocarbons present in the tar, ash content of biochar, yield of bio-oil, and lignin content in woody biomass (Edgar et al., 2021; Moreira et al., 2021), which may limit their valorisation. Ordinary biomass combustion technologies without precautions are unsuitable for processing contaminated biomass (Kovacs and Szemmelveisz, 2017), and specific requirements for facilities, e.g., filters and ash or digestate management, are likely required for safe use of biomass.

These concerns, which primarily apply for thermal conversion processes and metal(loid) contaminated biomass, could be a significant barrier that could compromise much of the economic and environmental value of phytomanagement. Two ways of managing these issues can be distinguished: i) ensuring safe and effective utilisation of biomass produced during phytoextraction with elevated contaminant concentrations, and/or ii) cultivating plants that do not take up contaminants into their biomass, i.e., phytoexclusion and stabilisation of contaminants in the soil rather than extraction.

5.1 Contaminant fate during conversion processes

Depending on the type of contaminant and fate in the plant, the bioenergy production process should be carefully selected since contaminants could be released into the environment. This aspect represents the first barrier to facilitating incorporation of phytoremediation biomass into bioenergy conversion where the safety and regulatory aspects are not yet well-established (Edgar et al., 2021).

In general, the fate of metal(loid)s during the (thermal) conversion processes is a complex and multifactorial process, which varies depending on the type of contaminant and temperature of the thermal conversion process (Edgar et al., 2021; Kovacs and Szemmelveisz, 2017; Moreira et al., 2021). Depending on the process, the contaminants can ultimately accumulate in the bottom ash (or char), other process ashes, or the fly ash and flue gas. Different contaminants have different volatilization temperatures; however, higher thermal conversion temperatures have been generally shown to increase the fraction of metals in the fly ash and flue gas. Oxide-forming elements and refractory compounds are often found in ashes and tars (Edgar et al., 2021; Moreira et al., 2021). Capture of the more volatile contaminants, e.g., Cd and As, depends on the quality of the filter in the particular facility.

Depending on the process, contaminants such as metals can be captured in the solid product of the biomass conversion process, thus mitigating spreading and damage to equipment, etc. High-temperature thermal conversion via combustion and gasification may require costly flue gas filters and treatment to avoid re-emission of metals into the atmosphere (Chalot et al., 2012). Recent studies examining high-temperature combustion (ca. 800-1000C) of metal-enriched woody biomass produced from phytoremediation showed that metal(loid)s accumulate in different ash fractions (Chalot et al., 2012; Delplanque et al., 2013), see Figure 18. Cu, Cr, and Ni tend to concentrate in the bottom ash, heat exchanger ash, and cyclone ash fractions. Conversely, As, Cd, Pb, and Zn are significantly recovered in the emission fraction, which can exceed regulatory limits in the absence of an effective filter. The combustion of metal-enriched poplars, willows and other biomass in boilers equipped with high-quality filters is thus recommended to minimize air pollution and comply with regulatory thresholds. Metals such as Pb and Zn have wide combustion temperature ranges where they can be largely (>90%) captured in the solid phase(220-900 °C), but other metal(loid)s like As and Cd have low transition temperatures, so there is an increased risk of these metals transferring to the gas phase and potentially being captured in the syngas product or leaving the system as gas emissions (Edgar et al., 2021). Metal contamination in the biomass can also be transferred to the liquified products during hydrothermal liquefaction (Dastyar et al., 2019).

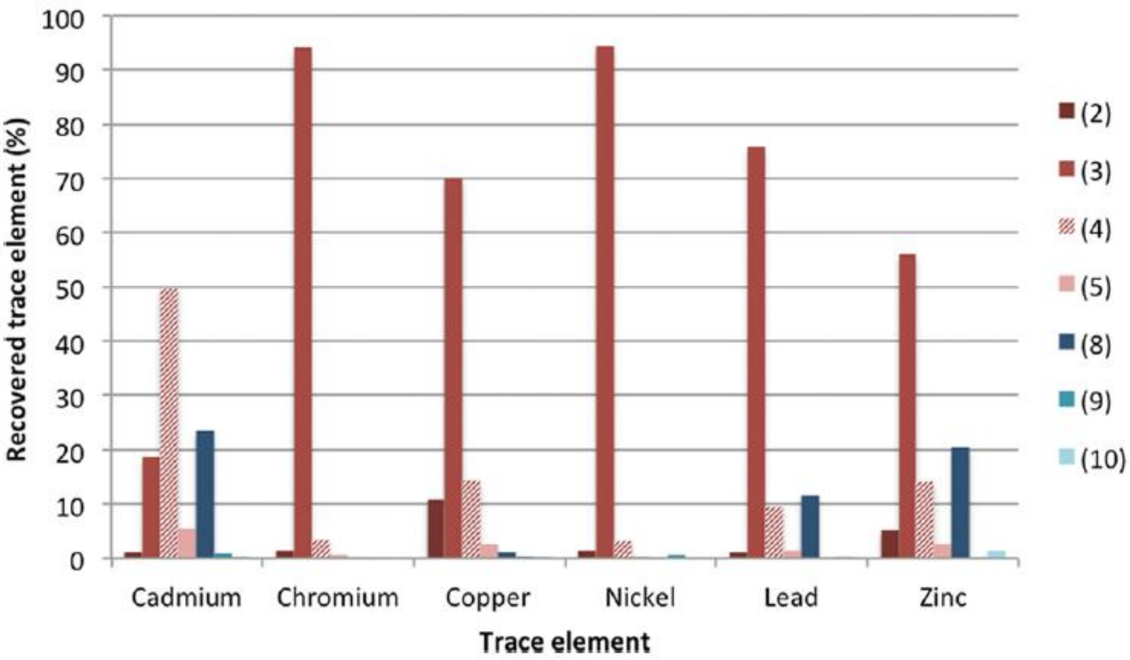

Figure 18. Distribution of major trace elements in ash and emission fractions from phytoremediation wood [at an approximate temperature of 800C]. Data are expressed as % of recovered trace elements in various fractions: 2) bottom ashes, 3) furnace ashes, 4) heat exchanger ashes, 5) cyclone-fly ashes, 8) filter-fly ashes, 9) particulate fraction downstream the filter, 10) gas fraction downstream the filter. From (Chalot et al., 2012)

Since pyrolysis temperatures are typically lower, fast/flash pyrolysis at low temperature (300-500 °C) prevents metal volatilization and may be a more advantageous and economically profitable method for valorising biomass produced during phytoextraction to produce a metal-free bio-oil as well as large-scale electricity and heat recovery (Dastyar et al., 2019; Edgar et al., 2021; Kovacs and Szemmelveisz, 2017; Kuppens et al., 2015, 2010). This is similar to the approach taken in the Phy2Climate project where a

Thermo-Catalytic Reforming (TCR®) process is used as a first step to convert biomass into higher energy density, storable intermediates that captures contaminants in the solid char, or bio-coke, while also producing high-quality bio-oil and syngas (Kick et al., 2024). An important note, however, is that this process is not yet commercially viable and an important objective in the Phy2Climate project is to develop the process from TRL 3 to TRL 5. The CERESIS project has also explored this pathway for metal contaminated biomass and concluded that pyrolysis using screw reactor is a viable technology (TRL 4-5) where the most critical parameters affecting the bio-oil yield and quality are temperature, heating rate, and carrier gas flow rate with temperature being the most important for bio-oil contamination (Giudicianni, 2024).

Regarding gasification (high temperature, high pressure), pressure, temperature and the concentration of metals present in the biomass greatly affects the interaction and behaviour of metals during gasification (Jiang et al., 2016). As, Cd, Zn and Pb tend to transform to their gaseous forms at relatively low temperatures (<1000 °C), therefore their potential emission is of significant concern, and may also concentrate the produced syngas (Kovacs and Szemmelveisz, 2017). Operating at high pressure significantly increases the starting temperature for phase transformation of heavy metals. To avoid gaseous emission of these metals, it is possible to maintain gasification temperatures below the phase transformation threshold, and higher pressure may improve product yield while increasing volatilization temperatures (Jiang et al., 2016).

Regarding biochemical conversion, many studies have shown that the potential negative effects of contaminants in the biomass can be controlled and validated the viability of biochemical conversion processes for fermentation of sugars and transesterification of fatty oils to produce bioethanol and biodiesel from biomass harvested during phytoremediation (Edgar et al., 2021). For anaerobic digestion, however, contaminants present in the biomass would likely have minimal impact on produced biogas, with the possible exception of Hg, but are expected to accumulate in the digestate that may need to be treated before use (Edgar et al., 2021). This has been noted to be a significant concern for facility operators that discourages the use of biomass produced during phytoextraction (Bert et al., 2017).

5.2 Pre- and post-treatment

Several pre-treatments can separate the metal(loid)s from the biomass fraction of interest, prevents their release during the process, or limits their bioavailability in the biochars produced (Dastyar et al., 2019; Edgar et al., 2021; Ionata et al., 2024; Kovacs and Szemmelveisz, 2017), see Table 3. These include pre-mixing with chemicals (e.g., $MgCO_3$, $FeCl_3$ and $Fe(NO_3)_3$, CaO) before biomass pyrolysis; composting (except the methylation of Hg-compounds); for anaerobic digestion and fermentation, pre-treatment with NaOH enhances the release of biogas during anaerobic digestion and metals from straw; biomass pre-treatments with either ethanol organosolv, soda or dilute acid and steam explosion to release metals before bioethanol production.

Table 3. Pretreatments on biomass from phytoremediation, advantages and disadvantages, from (Ionata et al., 2024) – see paper for references.

Pretreatment		Biomass	Advantages	Disadvantages	Ref
Physico-chemical	Steam explosion–sulfuric acid	Willow, Napier grass	Cellulose enrichment. Lignin transformation. High rate of metals removal	High operating temperature. Generation of toxic compounds.	[112]
	Nitric acid	*P. vittata*	Lignin solubilization. Cellulose crystallinity reduction	Cost associated with acids and recovery	[105]
	Sulfuric acid	*N. tabacum* L., *S. viminalis*, *B. pendula*, *B. juncea* L., Sweet sorghum bagasse	Efficient extraction of the metals (80% As, up to 90% Cd). Glucan enrichment.	Hemicelluloses degradation. Formation of inhibitors, lignin breakdown products. Cost associated with acids and recovery	[115,117,118]
	Sodium hydroxide	*N. tabacum* L., *S. viminalis*, *B. pendula*, *P. vittata*, *B. juncea* L.	Lignin removal (up to 80%). Easy sugar recovery.	Low metal extraction. Expensive	[105,115,117]
Chemical	Sodium hydroxide + Sulfuric acid	*B. juncea* L.	Complete metal (Cd) release (99%). Cellulose crystallinity reduction	High costs	[117]
	Ethanol extraction	*P. vittata*	Low soluble carbon reduction. Efficient Metals extraction (As 93%).	Expensive	[114]
	Ethanol organosolv	*N. tabacum* L., *S. viminalis*, *B. pendula*,	High rate of lignin solubilization.	Metals extraction is low. High production costs.	[115]
	Deep eutectic solvent (DES)	*S. alfredii*	Lignin (90%) and hemicellulose removal. Cellulose enrichment.	Low cellulose-rich pulp obtainment. High viscosity at room temperature. Toxicity.	[118]
	IonoSolv	*Miscanthus*	Biomass enriched in cellulose. Lignin removal. Effective extraction of HMs	Degradation of hemicelluloses. Costly solvents.	[121]
	Organosolv (formic acid + hydrogen peroxide)	Poplar	Complete removal of lignin. Obtainment of a clean cellulose pulp. Dissolution of metals	Xylan removal. Not be applied to softwoods. External energy requirement.	[122]
Biological	*C. versicolor*	Sweet sorghum bagasse	Low cost. Environmentally friendly. No formation of inhibitors	Not usable with high HM content. Long treatment. Low hydrolysis rate.	[124]

Post-treatment of conversion products and platform chemicals is also an option (e.g., sorption of arsenicals by Fe hydroxides after solvolysis of *Pteris vittata* fronds). Various leaching methods can be used to extract and recover potentially valuable metals from ashes (Edgar et al., 2021), which can also improve the financial viability of phytoremediation (Jiang et al., 2015).

The CERESIS project has also seen success for cleaning the bio-oil produced from pyrolysis of metal contaminated biomass via microfiltration (Giudicianni, 2024).

5.3 Waste and residue management

An important aspect of any bioenergy conversion process is the management of the waste and residue products. For example, if an oil crop or a sugar-rich crop is used for bioenergy production wherein the oil or sugars are extracted, the remaining biomass, that may be contaminated with metals, will still need to be managed. Depending on the facility and national regulations, the residual biomass can be used as a resource in another application such as combustion for energy production, anaerobic digestion, etc., but it may instead be classified as a waste to be sent to a landfill or facility for incineration as an additional cost.

Another difficulty concerns ash management and valorisation resulting from biomass conversion to energy. The main risk is associated with the reincorporation of contaminants into the soil due to inappropriate management and disposal since clean ashes and digestate are frequently spread on agricultural and forest soils. According to Bert et al., (2017), ash valorisation is an important component of the bioenergy value chain and is an important consideration for facility operators. Following combustion of metal enriched wood or other biomass, Cd and other metals may be dissipated to the environment through ash recycling in field application (Delplanque et al., 2013; Witters et al., 2012a). This would contradict the phytoextraction goal of removing harmful pollutants from soils. Depending on the conversion process used (e.g., combustion, pyrolysis, gasification), volatilization temperatures of metals and equipment used for filtration, a significant fraction of a metal-free ash may be obtained, either the bottom ash, the cyclone ash or the fly ash. The different types of ashes may need to be separated depending on the resulting concentrations and managed accordingly. In the study performed by Delplanque et al. (2013), French regulations, which compared the contaminated wood with commercial wood, classified the produced biomass not as a potential fuel but as a waste. Co-combustion of the biomass with another fuel source (e.g. fossil based) would likely be more acceptable to regulators. Ideally, bottom ash resulting from combustion would be used as a basic mineral amendment to boost soil quality, but this would depend on the classification of the ash as a valid soil amendment fertilizer.

5.4 Contaminant exclusion

A significant advantage of using oil crops like sunflower, rapeseed, hemp and most Brassicaceae species for phytoremediation and biomass production is that the accumulated metals do not transfer to the seeds, so the extracted oil is not affected by the high metal content in the biomass (Moreira et al., 2021). This may also apply for high sugar content crops such as sorghum where the sugars are extracted and have low contaminant concentrations.

However, for thermochemical conversion pathways using lignocellulosic crops where the aboveground biomass is utilised, the contaminant uptake into plants will be an important factor that could limit their use. In some cases, instead of phytoextraction, phytostabilization may be preferable. For many facility operators, plants used in phytostabilization or phytoexclusion were thought to be less risky and, consequently, benefited from a better theoretical acceptance than those issued from phytoextraction (Bert et al., 2017). Many concerns related to national regulations and the regulatory gap concerning the status of the plant biomass produced on contaminated land. The general acceptance of biomass from phytoremediation was, however, high under certain prerequisites where there was less uncertainty. Plants cultivated during phytostabilization could be accepted as input in aerobic digestion facilities if metal content proved to be low or close to background levels. However, from the operators' point of view, the use of metal enriched plants could involve more disadvantages than advantages (Bert et al., 2017).

6 Expected development of the land and co-benefits over time

A main, frequently cited advantage of GRO is the potential for multifunctionality: to potentially both manage risks and improve (or at least not reduce) soil functionality to provide ecosystem services (Burges et al., 2018; Cundy et al., 2016; Drenning et al., 2022). Cultivating bioenergy crops on marginal land can provide added value in terms of co-benefits like carbon sequestration, improving soil health, increasing biodiversity, and other ecosystem services. For example, a thorough review by (Nsanganwimana et al., 2014) shows the feasibility for phytomanagement using *Miscanthus* spp. to restore ecosystem services; which, owing to the perennial growth and its ability to stabilize trace elements and degrade some organic contaminant, could potentially limit contaminant transfer into different environmental compartments by reducing i) contaminant leaching from the root zone and groundwater contamination, ii) contaminant run-off (water erosion) and surface water contamination, iii) dust emission into the atmosphere due to wind erosion and seasonal soil tillage, and iv) contaminant transfer into plant above-ground parts and thus transfer into food chains.

Some of the main co-benefits of phytomanagement are described in brief below.

6.1 Carbon sequestration

Bioenergy crops tend to produce large amounts of biomass that contributes to removal of atmospheric CO_2, some of which is sequestered in the soil by the roots for short-/long-term storage. For example, perennial energy crops have the potential to sequester additional carbon in soil biomass if established on former cropland with estimates of approximately 0.44 Mg soil C /ha-yr for poplar and willow and 0.66 Mg soil C/ha-yr for miscanthus (Don et al., 2012). Similarly, a meta-analysis study showed soil organic carbon storage for herbaceous perennials (miscanthus and switchgrass) of between 1.14 to 1.88 mg C ha/year and for woody perennials (willow and poplar) a range from 0.63 to 0.72 mg C ha/year (Agostini et al., 2015). More recent research has shown that the carbon sequestration effect of willow can be even higher, ranging from 0.27-1.47 Mg soil C/ha-yr for different *Salix* varieties, with carbon modelling projecting increases over 50 years of cultivation (Kalita et al., 2021). The carbon sequestration effect, however, can vary depending on fertilization conditions and *Salix* variety (Baum et al., 2020; Kalita et al., 2021). In general, the effect of perennials on building up soil organic carbon is particularly large in marginal land which usually has low organic carbon levels (Panoutsou et al., 2022).

The carbon sequestration potential of phytomanagement for bioenergy production can be converted into economic terms (Börjesson, 1999a; Witters et al., 2012a). For example, (Witters et al., 2012a) used a life cycle analysis approach to show for the studied crops (willow, energy maize, and rapeseed) and carbon savings converted to monetary terms using a marginal abatement cost of CO_2 (€20/ton), the external benefit of CO_2 abatement when of phytomanagement and bioenergy production ranges between €55-501 per hectare. (Börjesson, 1999a) estimated that the environmental benefits, including carbon sequestration and others like water purification, of willow and reed canary grass for bioenergy ranged from US$1-5 (in 1999) per GJ of produced bioenergy.

6.2 Improved biodiversity and soil health

Soil biodiversity will likely be improved through bioenergy crop cultivation on degraded land (Yadav et al., 2019). However, this may depend, at least in part, on the plant species and whether the crops are grown in monoculture (worse) or polyculture (better). For example, a diversity of willow genotypes in SRC was shown to improve diversity of the soil arthropod community, which may promote ecosystem services within these plantations (Müller et al., 2018). Willow and poplar SRC have been generally shown to have many positive effects on soil ecology, including increasing soil microbial colonisation and activity and the abundance and diversity of soil fauna such as earthworms (Baum et al., 2009). In general, lignocellulosic plants can improve biodiversity by providing habitat for many birds and invertebrates, which provide many valuable ecosystem services like pollination, especially compared to annual crops due to less tillage and pesticide use (Börjesson, 1999b; Nsanganwimana et al., 2014; Yadav et al., 2019). Willow and poplar plants likely sustain more biodiversity compared to perennial grasses due to longer life cycles and creation of habitat for birds, vertebrates and flora (Langeveld et al., 2012); however, the overall effect of these crops on biodiversity may be negligible due to regular harvesting (Yadav et al., 2019).

The overall health of the soil and delivery of ecosystem services is expected to improve over time with cultivation of bioenergy crops on marginal land due to improvements in soil structure, soil organic carbon, decrease in toxic pressure, etc. This is especially true if good agronomic practices (agroecology) and nature-based solutions are implemented (Blanco-Canqui, 2024; Drenning, 2024; Drenning et al., 2024b; Panoutsou et al., 2022).

6.3 Agroecology

Best practices for successful phytomanagement that incorporate agroecological principles have been developed and optimised in large-scale European projects (e.g., GREENLAND and PhytoSUDOE), including (Fagnano et al., 2020; Garbisu et al., 2019; Gómez-Sagasti et al., 2018; GREENLAND, 2014, 2014; Kidd et al., 2015; Mench et al., 2019; Moreira et al., 2021, 2019), including:

- Enhancing standard phytoremediation strategies with soil amendments and/or bacterial inoculates and mycorrhizal fungi;
- Creating tree plantations based on short-rotation coppicing of woody plants such as poplar and willow;
- Using high-biomass annual or perennial herbaceous species (e.g., rapeseed, sunflower, tobacco, bioenergy grasses, maize, etc.).

Schröder et al. (2018) developed a useful framework for mobilising marginal lands for biomass production, see Figure 19.

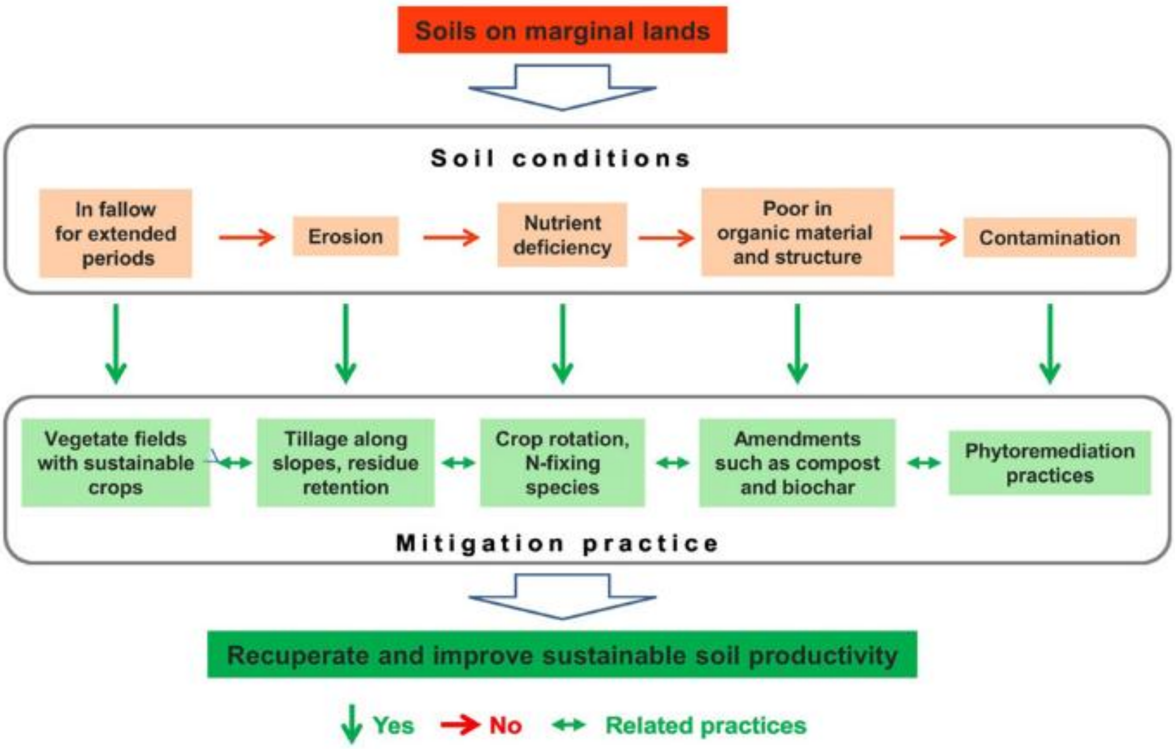

Figure 19. Flowchart for improving and optimising the productivity of soils on marginal lands, from (Schröder et al., 2018).

According to agricultural projections, good agronomic practices are expected to increase yields by 15-25% on average (Panoutsou et al., 2022). Including the above, a few main agroecological practices should be considered to improve agricultural production during phytomanagement, described below.

Crop rotations, intercropping, and cover cropping

Crop rotation refers to the temporal alternation of different crops or crop types (mown vs lifted, monocots vs dicots, annual vs perennial) on a piece of farmland. Intercropping refers to the cultivation of two or more species on the same piece of land a crop grown amidst a main crop or in between the planting rows of that main crop and intended to be harvested or to be supportive of the harvest of the main crop. Similar to crop rotation, cover cropping refers to a crop grown in between two main crop seasons (Panoutsou et al., 2022). For all of these applications, the inclusion of leguminous, nitrogen-fixing crops (e.g., alfalfa, common vetch, fava bean, clover) as components of the crop rotation or intercrop are often favoured.

Many crops that are well-suited for biofuel production are annuals that are typically grown in crop rotation with other crops that could either be used to restore the soil in between growth seasons or be used to produce other crops. In general, considering that phytomanagement is generally expected to be of a long duration, single species monoculture is unlikely to be effective in the long term and may even degrade the agricultural soil (Kidd et al., 2015). An advantage with crop rotations is that it can preserve soil quality (nutrients, etc.) and be used to produce other useful products in between seasons (Kidd et al., 2015; Zegada-Lizarazu and Monti, 2011). Intermediate grain crops in a rotation, like wheat and barley, could also be used to produce biomass for bioenergy. Integrating legumes into a crop rotation with annual crops such as sorghum, sunflower and rapeseed could enhance nitrogen and carbon sequestration, improve soil moisture retention, soil fertility, and overall lead to increased yields of the desired bioenergy crop (Fagnano et al., 2020; Kidd et al., 2015; Moreira et al., 2021; Tang et al., 2012; Zegada-Lizarazu and Monti, 2011). Cropping with legumes is likely especially important on marginal soils which may not be fertile enough to support high crop yields. For example, intercropping legumes (*Trifolium pratense, T. repens*) with the bioenergy crop *Sida hermaphrodita* was shown to significantly increase the yield on marginal soil (Nabel et al., 2018).

Crop rotations and intercrops must be adapted to the local climate and value chain landscape, and some rotations have been proposed for different climate zones that can incorporate the bioenergy and phytoremediation plants with greatest potential. For example, an appropriate crop rotation for the Nemoral climate zone could be a rotation of rapeseed – cereal (wheat, barley, oat) – cereal – rapeseed, and for the Continental zone it could be wheat (legume) – maize – sunflower – sorghum – fallow (EC, 2010). Willow could also be included as a four-year coppice followed by wheat – rapeseed – maize – rapeseed, or possibly as a longer 8-10 year rotation. Zegada-Lizarazu and Monti (2011) propose bioenergy crop rotations for different climate zones, such as a bioethanol chain, that rotates crops like maize, sugar beet (or wheat), and sorghum, which all have the potential to produce feedstock for fermentation and they can be grown in a rotation. For oilseed crops to produce biodiesel, the sequential growth of soybean, Ethiopian mustard and sunflower are another option, provided the areas of implementation are free from diseases (Zegada-Lizarazu and Monti, 2011). Yilmaz Balaman et al. (2023) propose a 2-year grass-clover ley period within the typical barley-oat-wheat-rapeseed rotation in Sweden to maximise the environmental benefits of the agricultural production while harvesting the produced biomass as lignocellulosic feedstock for a biorefinery.

Regarding phytomanagement, rotation of annual crops typically intended for phytoextraction (e.g., tobacco, sunflower, rapeseed) is likely necessary to ensure soil quality and effectiveness over time (Kidd et al., 2015). Some studies have shown that a three-year rotation of sunflower – tobacco – corn or a two-year rotation of sunflower – tobacco followed by winter fodder pea have been effective in maintaining extraction over time (Herzig et al., 2014).

In general, perennial plants have the greatest overall potential for improving soil ecosystem services and have been noted to accumulate 2-10 times more soil carbon than annual row crops and cover crops (Blanco-Canqui, 2024).

Agroforestry

Agroforestry, as a specific type of intercrop system, involves land-use systems and practices where woody perennials (e.g., poplar, willow) are deliberately integrated with row crops and/or animals on parcels with the same land management, without the intention of establishing a permanent forest stand (Panoutsou et al., 2022). Agroforestry systems include alley cropping, riparian buffers, hedgerows, shelterbelts or windbreaks, intercropping, crop-tree rotations, agrosilviculture, and agrisilvopastoral (trees, crops, and livestock) (Blanco-Canqui, 2024) Agroforestry systems may be potentially beneficial to maximize ecosystem services such as carbon sequestration, reducing erosion, water and air quality purification, biodiversity, etc. (Barrios et al., 2013; Blanco-Canqui, 2024;

Fagnano et al., 2020; Mehmood et al., 2017) Soil carbon storage may be especially high in agroforestry systems with estimates up to 1.0 Mg C/ha-yr in some cases (Blanco-Canqui, 2024).

Amendments

Approaches to restore the functionality of degraded sites should be based in on 'eco-agricultural' (or regenerative agriculture, agroecology, etc.) practices that entail applying organic matter in the form of crop residues and other wastes or compost or, in the later years, also biochar, to enhance biogeochemical nutrient cycling, stimulate soil biodiversity and its proliferation effectively (Schröder et al., 2018). Soil amendments play a key role in phytomanagement on marginal land to improve soil fertility by using organic amendments like compost and biochar to e.g. adjust the soil pH, increase soil nutrient content and retention capacity and improve the microbial community abundance and activity (Schröder et al., 2018; Touceda-González et al., 2017b, 2017a).

In many cases, soil amendment may be a necessary expense to ensure that the soil can support vegetation and produce sufficient yields.

Organic amendments like compost and biochar as well as different types of chemical fertilizers are commonly applied according to best agricultural practices. Increasingly, bioinoculants/biostimulants are added with plants to improve the effectiveness of phytomanagement as well as biomass production, which could include mycorrhizal fungi, fulvic/humic acids, or various types of plant growth promoting rhizobacteria (PGPR) (Kidd et al., 2015; Moreira et al., 2021). For example, recent experiments using commercial products have shown that biostimulation with humic substances (Lonite) and mycorrhiza (Symbivit) resulted in a significantly higher biomass of sorghum, but did not affect the uptake of metals in the above-ground parts (Peroni et al., 2024).

6.4 Food production

An interesting question is whether it will be possible to grow food crops on previously contaminated land that is or has undergone phytomanagement. Over time, this may be possible, but possible human exposure due to plant intake necessitates caution and more in-depth risk assessment when food crops are considered for cultivation in, previously or currently, contaminated soil. Haller and Jonsson (2020) explored the possibilities for combined phytoremediation and food production (CPFP), which showed there is potential but there are challenges with the remediation and post-harvest technologies and inadequate soil governance. They conclude that, although large scale CPFP has not yet reached technological maturity, appropriate combinations of soil types, plant species/cultivars, and agronomic practices together with thorough monitoring of the pollutants' pathways can potentially allow for safe food production on polluted soil that restricts the transfer of a number of pollutants to the food chain while the soil pool of pollutants is gradually reduced (Haller and Jonsson, 2020). It may, for example, be possible to safely cultivate food crops in contaminated soils by i) selectively cultivating crop varieties or clones that exclude (i.e., do not take up) contaminants from their edible biomass; ii) pre-cultivating or co-cropping contaminant accumulating (i.e., extractive) species with non-accumulating or excluding food crop varieties (e.g., Cd- excluders) to further reduce plant uptake in food crops; and/or iii) pre-cultivating contaminant accumulating species to strip the bioavailable fraction and reduce contaminant uptake (e.g., of Cd in subsequent wheat crop) in subsequent crops (GREENLAND, 2014; Greger and Landberg, 2015; Kidd et al., 2015; Tang et al., 2012).

Most likely, however, cultivating food crops on previously contaminated agricultural soil may not be recommendable until after phytoremediation is deemed complete according to regulators.

7 Contaminated or marginal land that may be suitable – possibilities and scaling potential

In the European Union, the proportion of contaminated land that is estimated to be impacted by metal(loid)s is more than 37%, followed by 33.7% with mineral oil contamination, 13.3% with polycyclic aromatic hydrocarbons contamination, and other contaminants to a lesser degree (EEA, 2021). Metal(loid)s are, by far, the most common contaminants in contaminated land, and the accumulation of metal(loid)s (e.g., Cd, As, Cu, Hg, Pb, Cr, Zn) in agricultural soils, due primarily to atmospheric deposition, is considered to be one of the most significant obstacles to sustainable development and achieving global food security (Hou et al., 2020). Cadmium, in particular, is a common concern in agricultural soils due to its widespread prevalence from fertilisation and high relative bioavailability for plants.

Globally, it is estimated that 385-472 million hectares of abandoned land are unsuitable for food production due to contamination but may be suitable for bioenergy crop production (Campbell et al., 2008). In Europe, there are millions of hectares of contaminated land that may be amenable for producing bioenergy crops (Figure 20), and biomass production on this land could amount to 10-52 % of current world liquid fuel consumption using second-generation bioenergy crops (Cai et al., 2011). A recent investigation within the GOLD project estimated the potential suitable land in the European Union for phytoremediation as the proportion of the total area of potentially contaminated land (due to military training activities, industrial activities, mining and landfills), of which less than 40 % is sealed, as ca. **2 million ha** (Römkens et al., 2022). Of the total of 20,708 mines the authors considered relevant for phytoremediation, almost half (10,206) are located in areas with agricultural land use, which suggests a potential for biomass production in these areas. France, Germany, Spain and UK have the largest total areas of all types of potentially contaminated sites, amounting to more than 150,000 ha in each of the countries (Römkens et al., 2022). Some authors report country-specific estimates of contaminated land that may be suitable for bioenergy crop production, including approximately 900,000 ha of brownfield land in Romania (Y Andersson-Sköld et al., 2014), 750,000 ha of the total contaminated/potentially contaminated land area in Sweden (Andersson-Sköld et al., 2009), 10,000 ha of agricultural land in Germany taken out of food production because of contamination with metals (Lewandowski et al., 2006), and 39,000 ha of marginal land in England that requires treatment to bring it back into beneficial use (Gomes, 2012). More recent and accurate country-specific estimates are difficult to acquire, but could be the subject of a more detailed investigation using GIS tools.

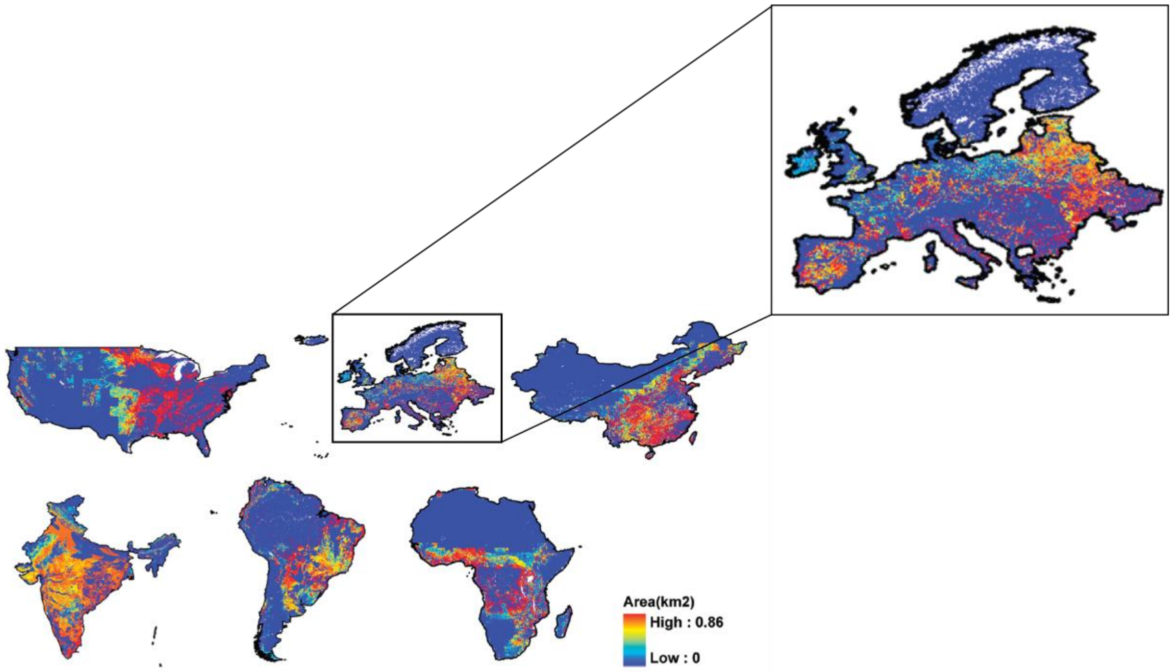

Figure 20. Maps of land available for bioenergy crop production, modified from (Cai et al., 2011).

Identifying the best opportunities in Europe for phytomanagement of marginal or contaminated lands with bioenergy crops for biofuel production involves evaluating the best opportunities in different regions of Europe according to: i) availability of marginal/contaminated land (ideally abandoned agricultural land of decent quality) and ii) proximity to existing biorefineries. Ongoing efforts at mapping existing bioenergy facilities may be of use to locate the type of facility that is needed in a particular region, such as shown in Figure 21 and Figure 22. Other mapping tools from the MAGIC project including the MAPS, CROPS, and DSS GIS databases could be useful references (available at: https://magic-h2020.eu/).

In general, it appears that clusters of potential in terms of contaminated land in relatively close proximity to an existing bioenergy industry may be in certain regions of central and eastern Europe, northern Italy, eastern Germany, and northern France. In northern Italy, for instance, there seems to be both a significant bioenergy industry with several facilities capable of producing biofuels from lignocellulosic biomass and large tracts of contaminated agricultural land that may yet be good quality for growing bioenergy crops. These areas combine the availability of marginal lands with proximity to biorefineries and supportive policies within the EU, offering opportunities for cost-effective and sustainable biofuel production.

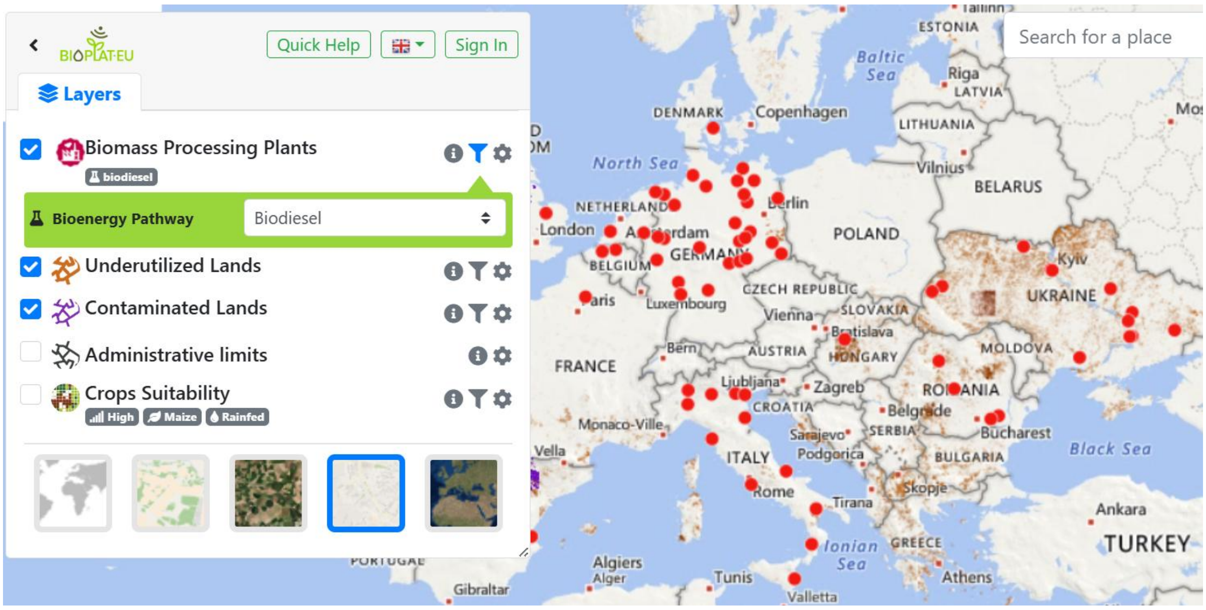

Figure 21. Screenshot of the online platform BioPlat.Eu showing a map of biodiesel facilities in Europe and underutilized or contaminated lands, from https://webgis.bioplat.eu/#/map.

Figure 22. Distribution of bio-based industry for liquid biofuels in Europe, screenshot from https://datam.jrc.ec.europa.eu/datam/mashup/BIOBASED_INDUSTRY/index.html.

8 Discussion

There is high potential for phytomanagement of contaminated land to remediate soils and produce biomass for biofuels. However, there remain numerous challenges that must be addressed and overcome for such a project to become truly feasible both technologically and financially. The biggest challenges in adopting biofuels in shipping are the high biomass and production costs, which makes them less competitive with fossil fuels, and limited availability of resources. Experts argue that first-generation biofuels such as vegetable oil-based biodiesel or bioethanol can compete against conventional fuels when oil prices rise to at least USD$60 per barrel, but, given the current state of technology, second generation biofuels may not become economically competitive until oil prices reach around USD$100 per barrel (Hsieh and Felby, 2017). Thus, biofuels are attractive in markets where biofuel costs are low relative to total operational costs and clean air (reducing shipping emissions) and other environmental benefits are seen as advantages. However, it is important to note that non-food biomass production will likely face competition in different markets due to an increasing demand for the same or similar feedstock for different bioproducts, e.g., willow and poplar in the wood products market, oilseed crops in food or other chemicals markets, which makes future prices difficult to predict

An efficient energy production chain and biomass valorisation is crucial to the overall feasibility and sustainability of large-scale application of phytomanagement (Fagnano et al., 2020; Vigil et al., 2022, 2015). Minimising transportation distances between biomass production, pre-treatment and processing facilities is an important factor. Recent life-cycle analyses have shown that production of a useful product like biofuels or biogas can offset the negative impacts of the production process and transportation up to a distance of approximately 200-300 km between the site and the processing facility (Vigil et al., 2015). However, the maximum transportation distance for maintaining a net benefit has also been noted, in specific cases, to be as little as 25 km for producing bioethanol from maize, 255-415 km producing biodiesel from rapeseed, or up to 267 km producing biogas via anaerobic co-digestion of grasses (Vigil et al., 2022). Biomass processing may also have significant environmental impacts, e.g., pre-processing miscanthus biomass into pellets may have a greater impact than briquettes (Murphy et al., 2013).

Considering financial feasibility, there are a few main considerations to ensure a profitable project. Jiang et al. (2015) developed a model to determine the financial feasibility of integrating phytoremediation with biomass valorisation (Figure 23), which is based on a stochastic approach using probability distributions and Monte Carlo simulations to consider uncertainties in important parameters that influence the overall profitability and project risk – i.e., income from biomass valorisation (e.g., biofuels, heat and electricity) and possible metal recovery against costs of biomass production and processing. Overall, their economic model suggests that prioritising high biomass yield with guaranteed valorisation can significantly increase the confidence of achieving financial return from the project (Jiang et al., 2015).

In terms of an overall business model, results from the Phy2Climate project showed that developing a business model requires a balance of broader social aspects (stakeholders, acceptance), legal aspects (regulatory, national/EU, cross border), technical aspects (plant selection, biomass processing, product production) and economic aspects (OPEX/CAPEX, logistics, revenues) simultaneously while considering the individual parts of a phytomanagement project, including remediation effectiveness, biomass production and harvest, biorefinery to produce biofuels, and generating added value like ecosystem services and restoring land value (Kick et al., 2024). In general, the most critical overarching components of the value chain that have the greatest and often most variable impact on cost generation are the site assessment (sampling, analysis), land preparation, monitoring, harvesting, and pretreatment of biomass for conversion. The interaction between product generation and energy input in the biorefinery also plays a significant role. Another key factor is the long period of time required for this process, which is up to ten times longer than conventional methods. This is precisely where the added value from various products, along with the increasing appreciation of the land over time, contributes to making this process financially feasible. Added value can be generated in several areas: on the product side, where different biofuels (petrol, diesel, marine diesel) or biocoke can be profitably produced, and through carbon sequestration, increased land value, soil restoration and many associated positive side effects for society that can potentially be valued (Kick et al., 2024).

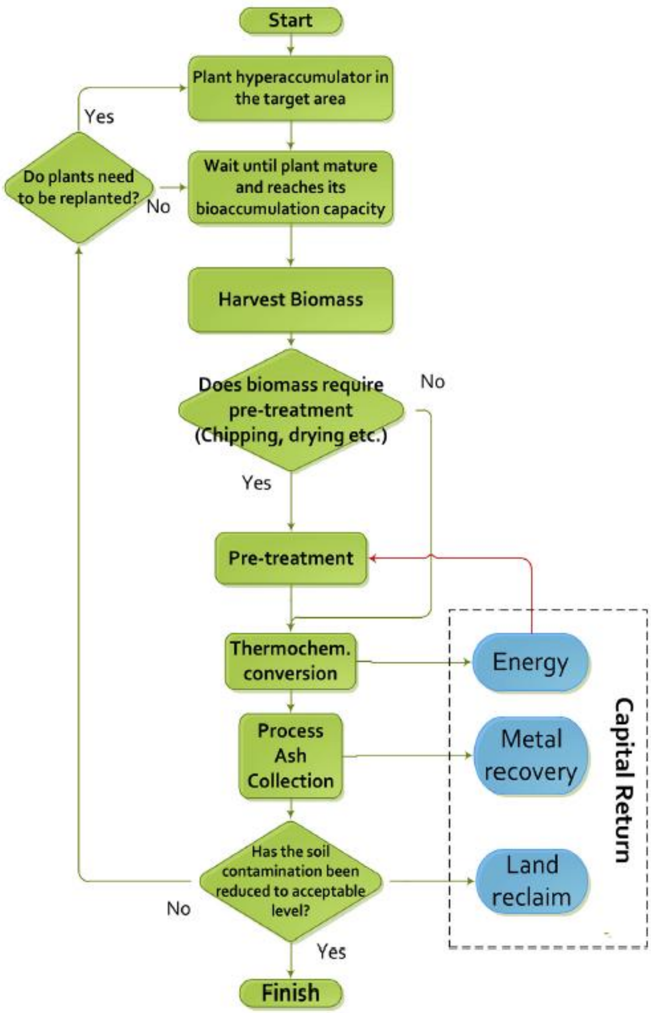

Figure 23. Logic flowchart of an integrated phytoremediation project with biomass valorisation, from (Jiang et al., 2015).

A potential phytomanagement project can be broken down into a series of steps where each step has several aspects to consider for maximising the possibility of project success and financial feasibility. During a workshop in Stockholm in February 2025, a short-term business case was explored, see Figure 24. The most promising short-term case was discussed which is summarised briefly below in terms of a series of steps and main points to consider.

- **Underutilised land & biomass production**: Agricultural land taken out of food production due to contamination, but otherwise of good quality, was identified as the most promising type of underutilised land in the short term. Here, 1st generation bioenergy crops for vegetable oils (e.g., rapeseed, mustard) or sugar-rich crops for fermentation (sorghum) could be cultivated and optimised for both soil health improvement and risk reduction with crop rotations. Such land areas should ideally also be close to an existing biorefinery. There needs to be a viable business model for landowners and farmers who want to invest in bioenergy crops to ensure that they can sell their products. A possibility is to extend the utilised land area to also include productive agricultural land. Traditional agricultural practices could be developed to implement crop rotation for the purpose of increased soil health. If there is a market for biofuels, non-food crops in such rotation schemes can then also provide income. The total land area contributing to the production of biofuels could then be a combination of contaminated and clean agricultural soils. In a longer perspective, when the technologies for producing biofuels from lignocellulosic crops such as *Salix* are more market-ready, rotational schemes should include *Salix* as it effectively improves the soil structure, can increase carbon storage and contributes positively to biodiversity.

  Example of stakeholders: landowners, farmers, controlling authorities for permits, and biorefinery owners.

- **Pretreatment of biomass:** Depending on the type of biomass (and conversion process), pre-treatment is likely necessary and should be optimised to limit costs by e.g., minimising transportation and energy use. There needs to be an adequate system in place for handling contaminated biomass as a residual waste product. If the residual product of biomass is used for incineration, e.g., for energy production, proper filters and handling of ashes need to be in place in such facilities nearby.

  Example of stakeholders: landowners/farmers if pretreatment at the site of crop production, owners of pretreatment facilities, or biorefinery owners if pretreatment takes place at the biorefinery, owners of incineration plants for energy production, landfill owners, and controlling authorities for permits.

- **Production of biofuel and upgrading/refining:** Biofuel production facilities need to be in close proximity to the crop production and the pretreatment facility. Different biorefineries can make use of different types of biomass and produce different products and they thus need to be identified to understand their specifications and technical capacity and plant quality and quantity requirements. An important question is whether the conversion process and upgrading/refining are combined to take place at the same facility or whether a separate plant is needed for the upgrading and refining of the biofuel. The potential effects of contaminants in the biomass used in the process need to be considered. How can existing biorefineries guarantee that they will buy products produced on contaminated land? From a business model perspective, the size or the production capacity of the biorefinery needs to be large enough to be profitable, and thus the land area from which the crops are bought needs to be large enough. If there is a variation in types of crops due to crop rotation systems, this also calls for several different types of biorefineries, and the size of the land area need to be even larger.

Example of stakeholders: owners of biorefineries, buyers of biofuel, and controlling authorities for permits.

- **Reach end user:** The end users are the ships, and thus the biofuel facility should ideally be located close to a harbour to minimise transportation. The transportation distance will influence the price of the product as well as the quantity produced. The final price needs to meet the price an end user would be willing to pay.

  Example of stakeholders: ship owners, biofuel producers, and controlling authorities for permits.

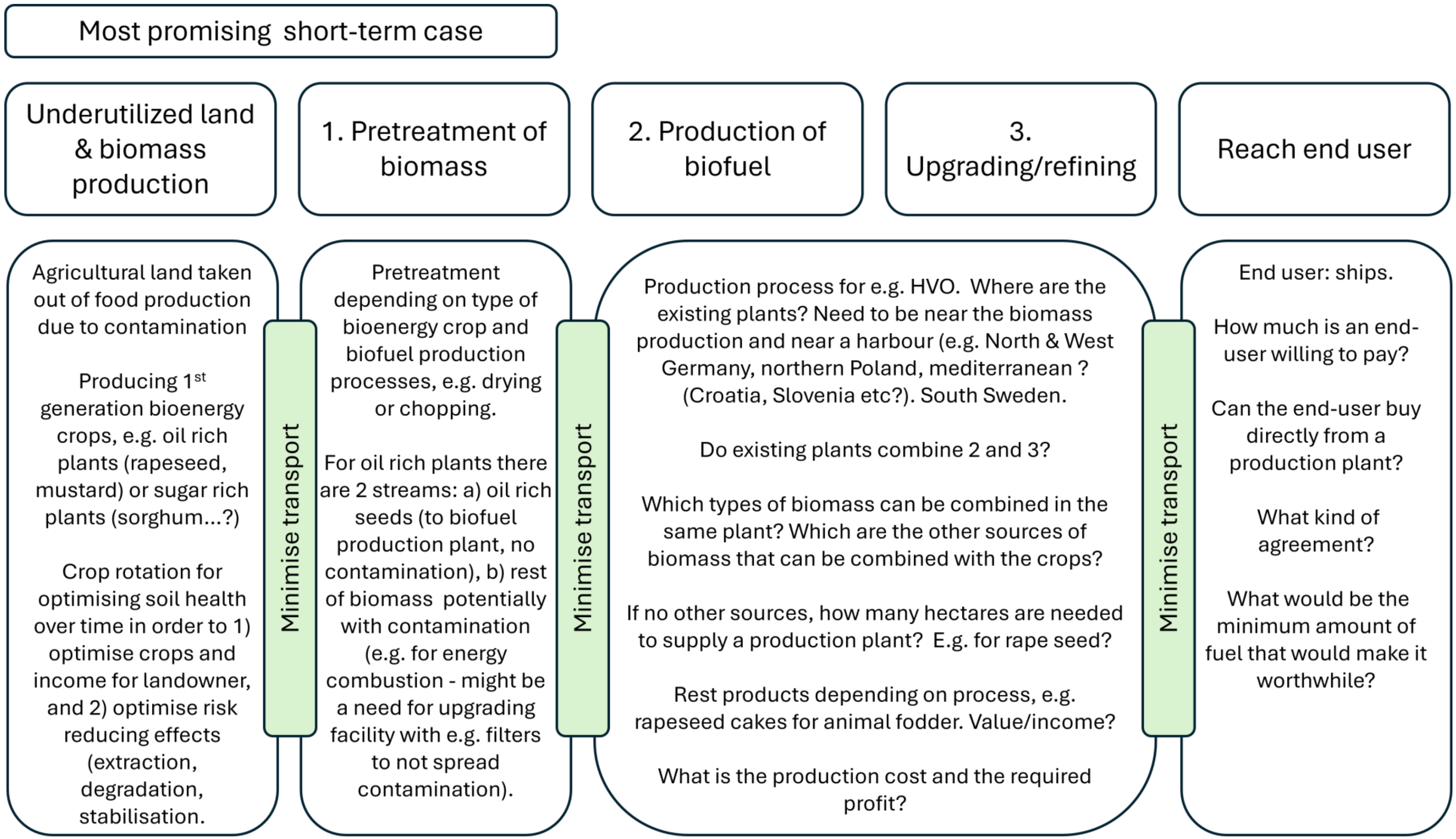

Figure 24. Summary of the workshop in Stockholm on February 21, 2025.

9 Conclusions and recommendations

The proposal of phytomanagement of contaminated land to remediate soils and produce biomass for biofuel production at competitive prices is technically feasible though there are important considerations to ensure short- and long-term financial feasibility. The many potential environmental benefits and potential for good return on investment make for a strong case to invest in phytomanagement for biofuel production, particularly if regulatory policies and government subsidies are supportive. For the maritime shipping sector, sector analysis indicates that the transition to biofuels or biofuel blends will likely be led by 'forward thinking' shippers, large freight shipping companies, and shipping companies with high-end customer profiles such as ferry and cruise companies (Hsieh and Felby, 2017). There are thus opportunities to be on the front end of the transition to biofuels while the market develops. A short-term and a long-term strategy are recommended. A **short-term** strategy utilises primarily first-generation energy oilseed crops like rapeseed, sunflower and mustard (biodiesel/HVO) and sugar-rich crops like sorghum (bioethanol) for phytomanagement and biofuel production most likely on abandoned agricultural land, due to the well-established markets, high TRL >7 and high soil quality. A **long-term** strategy employs second-generation biofuels produced from lignocellulosic biomass (grasses and trees), which has a greater net benefit but is not yet a mature technology (TRL 3-5), but can be more advantageous when the technology has sufficiently developed and with a higher potential to upgrade degraded land also in terms of soil quality, not only contamination.

There remain, however, important limitations and obstacles that will need to be addressed in any potential phytomanagement project. Phytoremediation as a source-removal technology has some challenges, e.g., phytoextraction can be limited in effectiveness and may take a long time, but phytomanagement as a land management strategy can be effective to manage risks while providing useful biomass and many co-benefits like carbon sequestration and other ecosystem services. The biomass produced during phytomanagement, however, may require specific pre-treatment procedures or careful process design during the conversion steps to produce biofuels to ensure that the facilities and intermediate/final bioproducts are not negatively affected. The requirements differ depending on the type of biomass, conversion process, etc. but there are generally advantages to using oilseed crops where the contaminants do not accumulate in the seeds and the extracted vegetable oil, and it may be worth considering phytostabilization to prevent contaminant uptake in plant biomass where this may be an issue. Agricultural production on marginal lands may also pose challenges such as requiring additional inputs to improve soil fertility to maximise biomass yields, which could impact cost-effectiveness. This can be avoided or overcome by primarily targeting higher quality agricultural soils that have been abandoned for food production due to contamination issues and employing best agronomic practices like crop rotations, intercropping and applying soil amendments. Major challenges relate to further developing the entire supply chain and business case for the different stakeholders involved and identifying potential bottlenecks and project risks, e.g., for farmers who take a significant risk growing a crop such as willow that may generate revenue until after a few years.

The overall feasibility of the proposal is supported in this study illustrating several possible ways forward (Figure 24), but there are important details that could not be covered here that may be the subject of future studies, including:

- GIS-based investigation to determine the contaminated lands in Europe with the greatest potential for a successful phytomanagement project (e.g., higher quality agricultural land taken out of production, proximity to biofuel production facility, etc.).
- More detailed financial calculations to gather approximate cost information for different scenarios and apply a probabilistic approach to determine financial feasibility and the most important cost parameters (e.g., Jiang et al., 2015). This would also be useful information to develop an overall business model for phytomanagement and determining financial viability for different stakeholders. An important next step is to explore the different business models in the full chain in more detail, from farmers and landowners to the ship owners as end users, to better understand the scale and to identify new innovative models and partnerships.
- More detailed stakeholder analysis starting with identifying a potential biofuel production partner that understands the conversion process in more detail.
- Exploration and application of the various identified decision-support tools (Appendix A) would be a useful starting point to better develop a phytomanagement project plan.
- Finally, considering the new European soil monitoring law and the current focus on European land management and soil health, a broader perspective on combining efforts to improve soil health on contaminated land and agricultural land by phytomanagement should be explored.

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Appendix A: Considerations for future pilot projects

From interviews with experts, two primary considerations emerged (Michel Mench, *personal communication*):

1. Team building: the biomass production (phytoremediation) must align with the biomass processing (local value chain) – the Germany company Fraunhofer Umsicht (https://www.fraunhofer.de/) seems to be a leader in this field and is active in several large-scale EU projects, including Phy2Climate and Seafairer (see the report (Collard et al., 2023) for more information about their TCR process).
2. Pilot scale studies: different plants should be tested in small-scale plots before any large-scale effort

Questions to answer in an initial pilot-scale phytoremediation trial

- How effective are the different plants?
- Which are most suitable to the site conditions?
- Which enhancements should be used and how can they be applied?

In terms of degradation effectiveness for organic contaminants, OVAM (OVAM, 2019) recommends a feasibility analysis for natural degradation (without amendments) by assessing the abundance of degrading microorganisms (by e.g. quantitative PCR or DNA fingerprinting); maintaining that fewer than **10^5 microorganisms per gram of soil** (or mL of groundwater) will result in too slow of a degradation for practical purposes.

As shown in Figure 25, there are many factors that affect the effectiveness of GRO. In brief, an initial feasibility assessment concerning the type of contaminant, concentrations, **bioavailability**, soil properties and other important factors are essential to determine the viability of GRO. To improve the chances for success, the GRO strategy can be enhanced through well-informed plant selection, well-designed planting systems, **agronomic practices** like intercropping and crop rotations, the use of **soil amendments** including compost and biochar, and biostimulation or bioaugmentation to improve the microbial community.

Tripathi et al. (2016) listed several problem areas for which suitable strategies must be framed: 1) enhancing the growth and yield of selected bioenergy crops under varying agroclimatic conditions, 2) limiting the transfer of pollutants into the end products, 3) ensuring the safety of stakeholder involved in such activities, 4) identifying the potential markets of such bioproducts, 5) proper certification of bioproducts, and 6) ensuring the overall safety and sustainability of such coupled systems (i.e., .phytoremediation and bioenergy production).

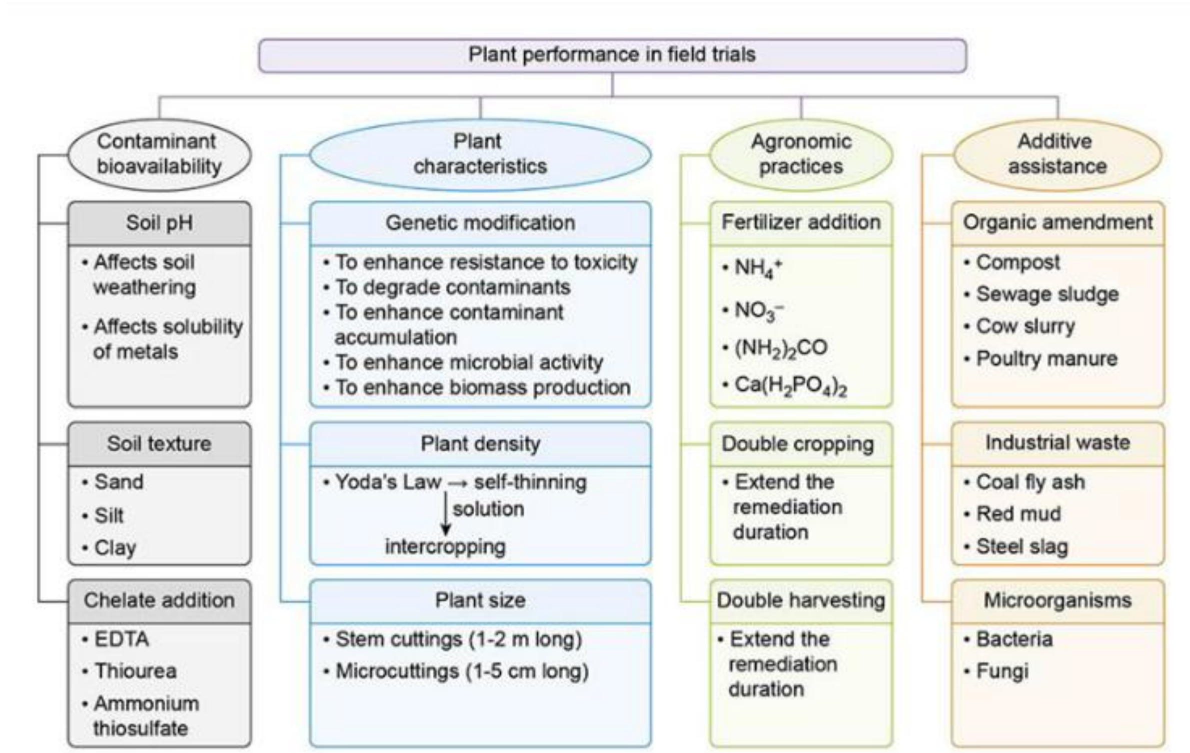

Figure 25. Factors determining the performance of plant-based remediation technologies in field trials, from (Wang et al., 2019).

Several other critical issues are addressed in brief detail below:

Water availability
Since bioenergy crops could modify the water and nutrient dynamics of soils, their water usage pattern should also be taken into consideration before field plantation. Depending on the land type, a suitable bioenergy crop should be recommended. Water scarcity may be a major limitation for growing certain crops in some climates, especially considering climate changes making heat and drought more common in some areas. Some bioenergy crop species are deep-rooted, drought tolerant (e.g., Miscanthus) and well-suited to areas where this may be the case.

Climate
In temperate and warm regions, C4 grasses outyield C3 grasses due to their more efficient photosynthetic pathway. However, the further north perennial grasses are planted, the more likely cool season grasses are to yield more than warm season grasses. Low winter temperatures and short vegetation periods are major limits to the growth of C4 grasses in northern Europe. With increasing temperatures towards central and southern Europe, the productivity of C4 grasses and therefore their biomass yields and competitiveness increase.

Input requirements
Marginal and/or contaminated land may be in a degraded or depleted state that will require inputs to produce biomass. It is important to consider the nutrient requirements (N and P deficiencies are common) for the intended plant species and whether soil amendments such as compost, biochar, or bioinoculants are needed, and from where they will be sourced.

Plant selection

Selecting the right cultivar or clone is crucial to the success of phytomanagement, whether contaminant uptake or exclusion is preferred. There have been extensive tests and selective breeding programs to optimise certain traits, even contaminant uptake for some species such as willow (Kuzovkina and Volk, 2009; Rönnberg-Wästljung et al., 2022), Miscanthus (http://www.miscanthusbreeding.org/miscanspeed.html), sunflower (Herzig et al., 2014) and tobacco (Herzig et al., 2014).

Stakeholders

The Phy2Climate project has made investigations into the various stakeholders involved in this type of project, visualisations of which are shown in Figure 26 and Figure 27.

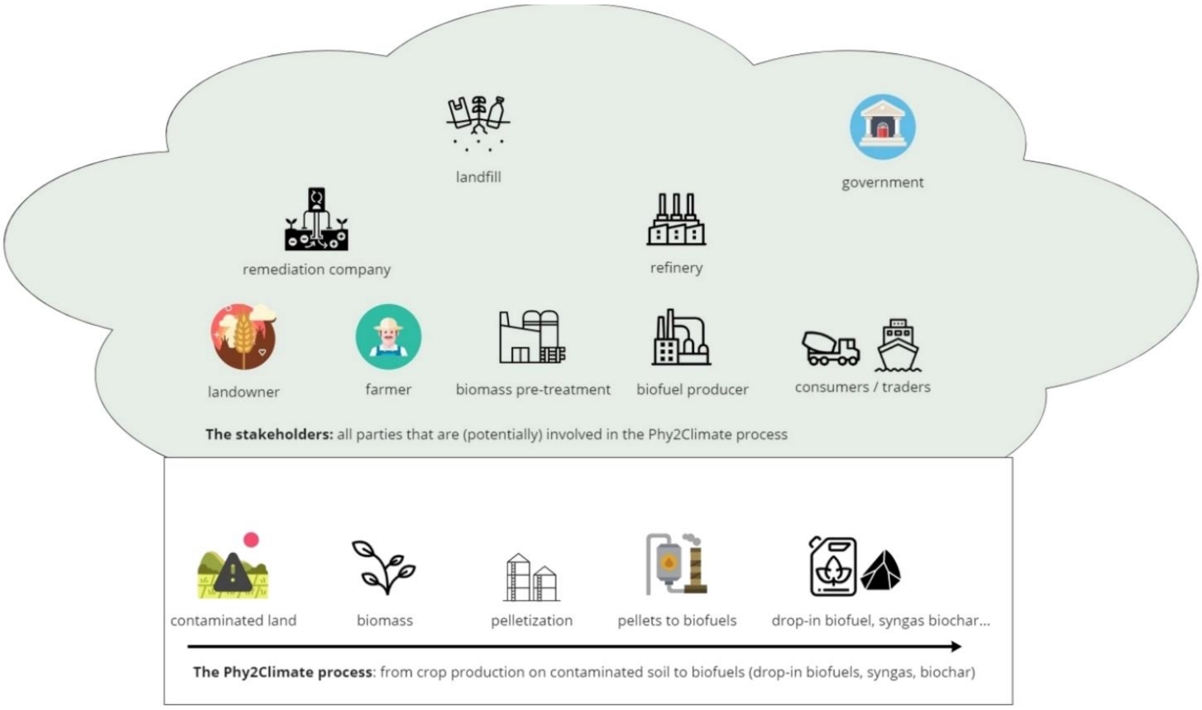

Figure 26. Stakeholders involved in the process from phytoremediation to biofuel production, from https://www.phy2climate.eu/.

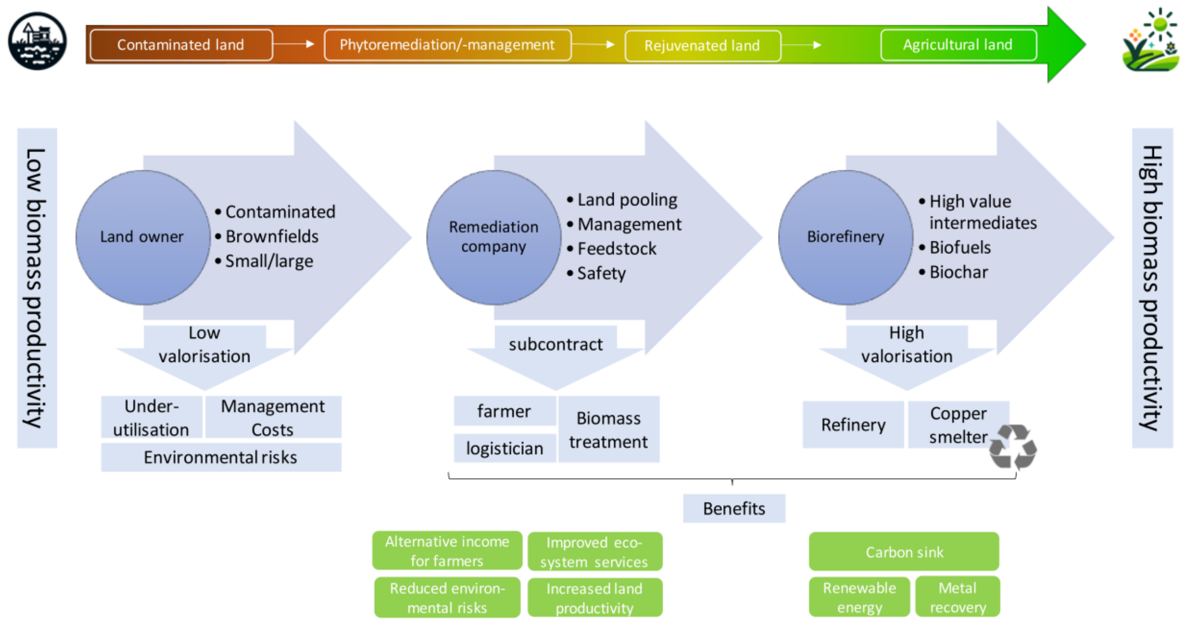

Figure 27. Overview of the value chain with key stakeholders, highlighting the transformation of unproductive contaminated land into productive land and outlining the most significant benefits, from (Kick et al., 2024).

Regulatory aspects

An important challenge is that current legislation and practice in soil remediation are based on the total concentrations of the contaminants left in the soil and not on soil functionality or risk-based land management, which can be a barrier to the use of phytoremediation as it is typically a slow remediation process. During an interview with Yvonne Andersson-Sköld, regulatory aspects were highlighted as a key challenge in the Rejuvenate project for widespread application of bioenergy production on contaminated lands. Sweden was noted as being particularly risk averse, and that the regulatory environment may be more favourable in other countries.

Favourable policies and subsidies

There may be favourable policies and subsidies within the European Union that make cultivation on contaminated land more economically advantageous. For example, the Renewable Energy Directive (RED II) encourages the cultivation of bioenergy crops on contaminated/marginal/abandoned agricultural land to prevent indirect land use change (ILUC) (Fermeglia and Perišić, 2023; Panoutsou et al., 2022), and there may be subsidies available to support these kinds of projects. Presently, the Energy Efficiency Design Index (EEDI) and RED II can incentivise and promote advanced biofuels: EEDI encourages the ship owners/operators to use more energy efficient and low-carbon technologies to power their ships, and RED II may provide an obligation to deliver biofuels to the market (Hsieh and Felby, 2017).

Decision-support tools

A few projects have created decision-support tools or systems to facilitate the implementation and identification of suitable plants, conversion processes, and more, including:

- **CERESIS**: https://ceresis.eu/ - developed a Decision Support System (DSS) which supports stakeholders & policy makers in assessing the suitability of integrated pathways of energy crops production in contaminated land to

conversion to clean biofuels. It includes techno-economic analysis of pathways, LCA & LCC, supply chain optimization, and multi-criteria assessment.
Available at: https://dss.ceresis.eu/ -

- **MAGIC**: https://magic-h2020.eu/ - developed several GIS databases and tools to facilitate cultivation of non-food, industrial crops on marginal lands:
    - MAGIC-MAPS – The MAGIC MAPS application characterises and analyses current and future marginal land in Europe facing natural constraints.
    Available at: https://iiasa-spatial.maps.arcgis.com/apps/webappviewer/index.html?id=4fd1be89d2304f8987ce42ae30f86159
    - MAGIC-CROPS – The MAGIC-CROPS database provides a description of 37 industrial crops suitable for growing on marginal land in Europe.
    Available at: https://iiasa-spatial.maps.arcgis.com/apps/webappviewer/index.html?id=431205b041fb4da0824782496721c1b7
    - MAGIC-DSS – The MAGIC decision Support System (DSS) provides users with guidelines for industrial crops growing under marginal conditions in Europe.
    Available at: https://iiasa-spatial.maps.arcgis.com/apps/webappviewer/index.html?id=96bec7f4c7ee49df8e4fd24a82039ea3
    - Bio2Match Tool - The Bio2Match tool collects information on conversion technologies for various biomass crops growing on marginal land in Europe.
    Available at: https://magicmatch.wenr.wur.nl/
- **Rejuvenate** – Useful guides were created in the Rejuvenate project for phytomanagement with the purpose to grow biomass for bioenergy (Andersson-Sköld et al., 2013a; Y. Andersson-Sköld et al., 2014; Bardos et al., 2011). A checklist-based methodology was developed for designing and implementing profitable biomass production on marginal land while effectively managing risks by stabilising the contaminants using plants. The method to develop a project entailed four stages considering the 1) biomass crop, 2) site management, 3) project value and 4) project risks (Figure 28).

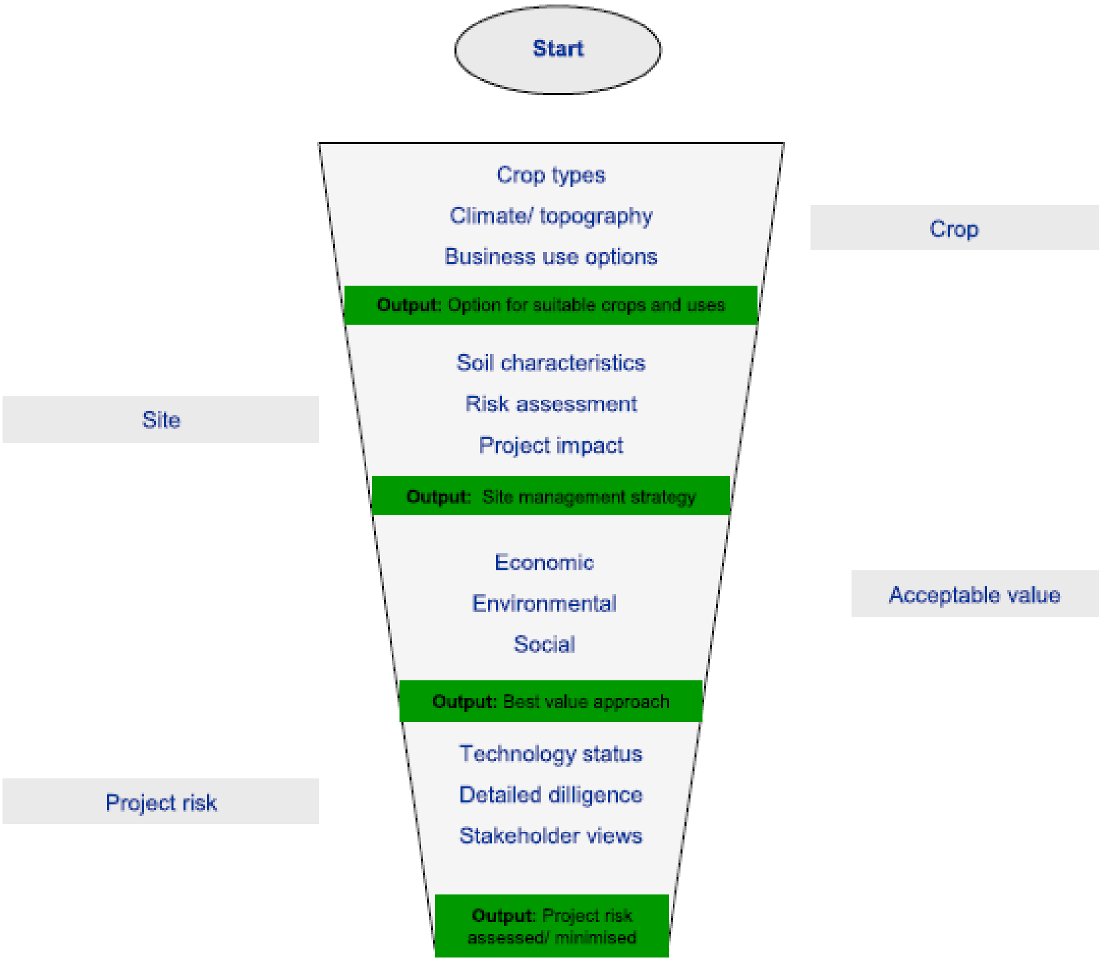

Figure 28. Rejuvenate DST stages and funnelling process, from (Andersson-Sköld et al., 2013a).

Appendix B: Short overview of good examples

Table 4. provides a short compilation of good examples of field trials and reference projects of phytoremediation where the produced biomass was used to bioenergy/biofuel production. See e.g., (Edgar et al., 2021; Ionata et al., 2024; Moreira et al., 2021; Pandey et al., 2016) for more comprehensive reviews of relevant studies and good examples.

Table 4. Compilation of relevant studies and good examples of field trials of phytoremediation and bioenergy production, EX = phytoextraction; ST = phytostabilization; PD/RD = phyto/rhizodegradation.

Location	Contaminants	GRO	Plant Species	Remediation Effect	Biomass use	Reference (Project)
England	PAH, Metals	EX, ST	Reed canarygrass, Miscanthus, Willow	Reed canarygrass had the highest biomass yield, lowest cost for establishment, time to maturity, and lowest contaminant levels (4-7 ton dw/ha)	Estimated energy yield from reed canarygrass of 97 GJ/ha (4-7 ton dw/ha-yr) at contamination levels acceptable for domestic pellets	Lord (2015) (*BioReGen*)
Sweden	Metals	ST	Willow	Effective stabilisation: Chemical toxic presssures were found to be in the same range or lower than initial values, no leachate inhibitory effects were found in Microtox tests and nematode analysis indicated improved ecological conditions - no risk to grazing animals was found	Yield: 5.4 ton dw/ha-yr Energy: 4.4kWhr/ton dw Revenue: €70/ton dw (better with subsidies)	Enell et al. (2016) (*Rejuvenate*)
Belgium	Metals	EX	Willow, Maize, Rapeseed	Generally low uptake of contaminants (Cd),which likely resulted in long remediation times	Maize: anaerobic digestion producing estimated 30,000-42,000 kWhr in CHP Rapeseed: Cold pressing + esterification for biodiesel Willow: Co-combustion	Witters et al. (2012a, b); Meers et al. (2010)
Sweden	Metals, Dioxin, PAH	ST, PD/RD	Poplar, Willow, grasses	Decreased ecological risks according to TRIAD ecological risk assessment	Bioenergy generation via combustion, ethanol production, wood chips, and other biofuels	Andersson-Sköld et al. (2013; 2014) (*Rejuvenate*)
France	Metals, Organics	ST, PD/RD	Polar, Willow, Miscanthus, Grasses	Decreased ecological risks according to TRIAD ecological risk assessment	Biofuel production, wood chips for use in local boilers to produce energy via combustion	Andersson-Sköld et al. (2013; 2014) (*Rejuvenate / Phytopop)*

France	Metals, Organics	ST, PD/RD	Poplar (tested 14 genotypes) and Alder (*Alnus glutinosa*)	Decreased metal availability over time - improvement in soil quality - large variation in other genotypes: Vesten most productive and accumulated least metals, Trichobel genotype accumulated most metals - isolated bacteria exhibited plant-growth promoting traits and resistance to toxicity and possible degrading genes - poplar biomass production significantly enhanced by mycorrhizal inoculation	Higher metal content of bark tissues concentrated in branches led to conclusion that only stem wood be harvested, instead of the whole tree, which will enable a reduction in the risks encountered with TE-enriched biomass in valorization process	Chalot et al. 2020; Ciadmidaro et al. 2017; Foulon et al. 2016; Kidd et al. 2021 (*Biofiltree, Phytopop*)
Italy	Metals, PCBs	EX, ST, PD/RD	Hybrid poplar (*Populus generosa x nigra*) cv. Monviso	A significant decrease in PCB congeners (up to 90%) and heavy metal reduction observed where poplar trees were present - lighter congeners were detected in leaves but most contaminants were absorbed into roots	Gasification (no effect on syngas due to metal accumulation in roots), presence of Ca can have catalytic effect	Ancona et al. (2017, 2019, 2021)
France	Metals	EX	Sorghum	Significantly decreased exchangeable (bioavailable) concentrations of Cd, Pb, and Zn due to extraction with Sorghum	Potential bioethanol yield for sorghum biomass (11.5-15.9 ton dw/ha) of 4627-6388 L/ha	Ofori-Agyemang et al. (2024) (*GOLD*)
Lithuania	TPH	PD/RD	Herbaceous grass mix	Significant decrease of TPH after 2 years	Thermochemical conversion using developed biorefinery concept to produce bio-coke and bio-oil that can be upgraded to higher quality biofuel	Kick et al. (2024) (*Phy2Climate*)
Serbia	Metals	EX, ST	Rapeseed	Significant decrease in maximum concentration of all metals: Ni (43%), Cu (27%), Zn (23%), Pb (21%)		Kick et al. (2024) (*Phy2Climate*)
UK	Metals	ST	Reed canarygrass, Miscanthus, Willow	Generally high yield and low uptake of metals in bioenergy grasses	Thermochemical conversion based on pyrolysis to produce biochar and bio-oil that can be upgraded to biofuel	Lord et al. (2023); Guidicianni (2024) (*CERESIS*)
Italy	Metals	ST	Reed canarygrass, Giant reed, Switchgrass	Generally high yield and low uptake of metals in bioenergy grasses		Lord et al. (2023); Guidicianni (2024) (*CERESIS*)
Ukraine	Metals, Pesticides, TPH	ST, PD/RD	Reed canarygrass, Miscanthus	Generally high yield and low uptake of metals in bioenergy grasses, some degradation of organics		Lord et al. (2023); Guidicianni (2024) (*CERESIS*)
Italy	Metals	EX	Giant reed, Switchgrass	Giant reed accumulated significant amounts of Zn, Cu and Cd	Anaerobic digestion to produce biogas or combustion, high yield of 19-33 ton/ha	Danelli et al. (2015)

Appendix C: Useful references for phytoremediation and bioenergy crops

Many research projects relating to phytoremediation and/or the production of biomass on contaminated/marginal land for bioenergy have been carried out. Below is a short compilation of projects and other useful information relating to the proposed project.

- **GOLD** – *Growing energy crops on contaminated land for biofuels and soil remediation.* Available at: https://www.gold-h2020.eu/
- **Phy2SUDOE** - *Advancing in the application of innovative phyto-management strategies in contaminated areas of the SUDOE space.* Available at: https://www.phytosudoe.eu/en/
- **Phy2Climate** – *Clean biofuel production and phytoremediation solutions from contaminated lands worldwid*e. Available at: https://www.phy2climate.eu/
- **CERESIS** – *Contaminated land remediation through energy crops for soil improvement to liquid biofuel strategies.* Available at: https://ceresis.eu/
- **Dendromass** – *Securing sustainable dendromass production with poplar planations in European rural areas.* Available at: https://www.dendromass4europe.eu/
- **MAGIC** – *Cultivation of industrial land to avoid competition with food production.* Available at: https://magic-h2020.eu/
- **PANACEA** – *Non-food crops for a EU bioeconomy.* Available at: https://panacea-crops.net/
- **S2Biom** – *Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe.* Available at: https://www.s2biom.eu/
- Seafairer - https://www.seafairer-project.eu/the-project/
- **GREENLAND** – *Best Practice Guidance for Practical Application of Gentle Remediation Options (GRO) and Appendices*. Available at: GREENLAND (Gentle remediation of trace element contaminated land) (europa.eu)
- **ITRC** – *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised.* Available at: Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised (itrcweb.org)
- **ITRC** – *Phytotechnologies for Site Cleanup, Fact Sheet.* Available at: Phytotechnologies for Site Cleanup (clu-in.org)
- ***Phyto****: Principles and resources for site remediation and landscape design*, Routledge. Available at: Phyto: Principles and Resources for Site Remediation and Landscape Design (routledge.com)
- **OVAM** – *Phytoremediation: Code of Good Practice.* Available at: Phytoremediation (ovam.be)
- **Rejuvenate** – *Crop-based systems for Sustainable Risk-based Land Management for Economically Marginal Degraded Areas.* Available at: Rejuvenate 2 (swedgeo.se)

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