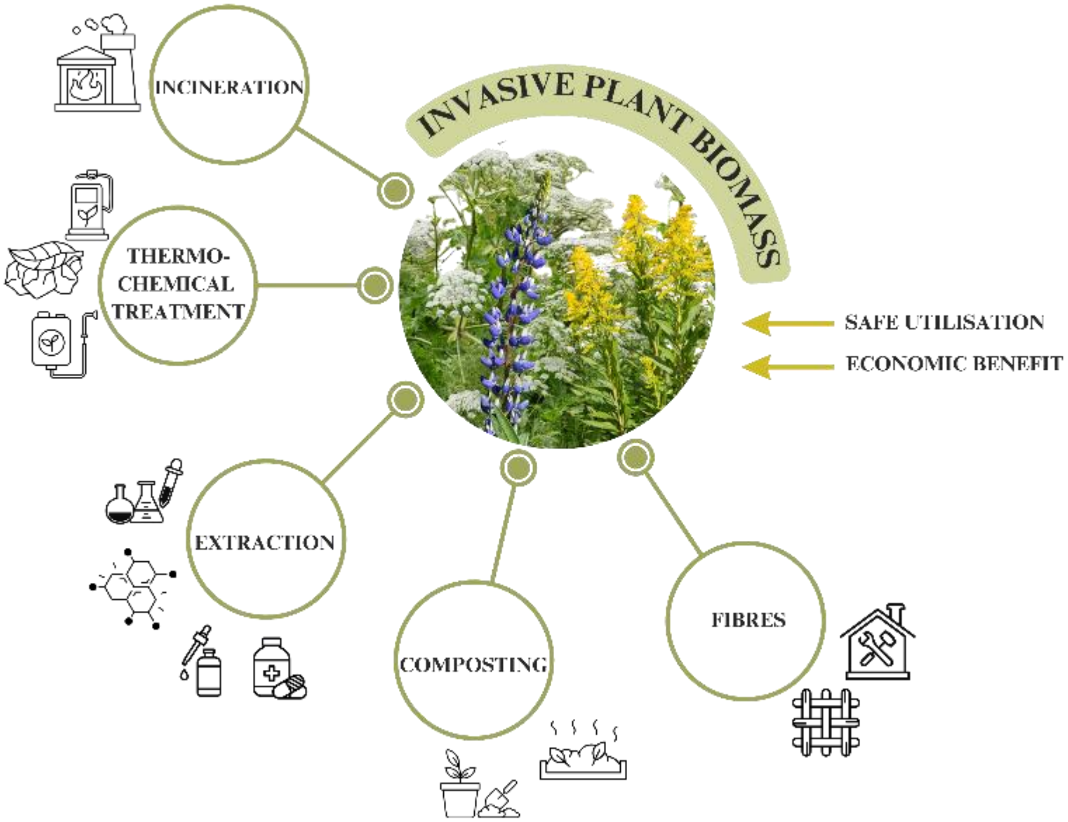
Biomass of Invasive Plants as a Resource for the Development of the Bioeconomy

Maris Klavins,* Oskars Purmalis, Laura Klavina, Evelina Niedrite and Linda Ansone-Bertina

* *Corresponding author: maris.klavins@lu.lv*

DOI: 10.15376/biores.19.4.Klavins

GRAPHICAL ABSTRACT



Biomass of Invasive Plants as a Resource for the Development of the Bioeconomy

Maris Klavins,* Oskars Purmalis, Laura Klavina, Evelina Niedrite, and Linda Ansone-Bertina

The global spread of invasive plants is an important environmental problem and a real threat to biological diversity, with significant impacts on agriculture, forestry, and human and animal health. Invasive plant eradication produces large amounts of plant biomass, which should be safely utilized. The study reviews possibilities for using biomass of invasive plant species in the bioeconomy to safely convert them to items of value. Invasive plant biomass can be used as fuel or for energy production applying either biochemical or thermochemical processing technologies. The biomass of invasive plants also can be used for energy production or isolation of biologically active components. Invasive plants contain many groups of substances providing their defense potential against predators; these substances participate in metabolic regulation processes and others. Amongst the substances of interest for bioeconomy are lipids, polyphenols, alkaloids, carbohydrates, plant fibers, and essential oils. In the development of invasive plant biomass utilization strategies, the bio-based value pyramid and the waste hierarchy should be considered. Scientific sound strategies of invasive plant management will limit their spread and provide economic benefits *via* their eradication.

DOI: 10.15376/biores.19.4.Klavins

Keywords: Invasive plants; Bioeconomy; Extraction; Biofuel; Biochar; Biomass; Biorefinery

*Contact information: Department of Environmental Science, University of Latvia, Raiņa Blvd. 19, Riga, LV 1586, Latvia; maris.klavins@lu.lv; laura.klavina@lu.lv; oskars.purmalis@lu.lv; Evelina niedrite; linda.ansone-bertina@lu.lv; *Corresponding author: maris.klavins@lu.lv*

INTRODUCTION

Invasive plants are an important environmental problem, producing threats to biological diversity as well as impacts on agricultural production, inland water quality, and forestry. Plant invasion is a pervasive economic problem as well. Because invasive plants are not native in the region affected, they are less demanding concerning soil quality, availability of nutrients, and water; thus, they outcompete local natural populations (Gioria *et al.* 2023). Invasive plants can exert direct and indirect adverse effects. For example, several invasive plants are toxic to humans and animals, but indirectly invasive plants affect ecosystem services, and in some cases they can fully destroy natural habitats (Rai and Singh 2020). Total costs to the economy and environment by invasive alien species in the EU and USA are estimated at several billions of USD per year (Haubrock *et al*. 2021), and a significant part of these costs can be related to impacts of invasive plants.

Human activities are largely responsible for the spread of invasive plants, as it takes place through global trade, transport, and intentional gardening. The spread of invasive plants is enhanced by climate change (Hellmann *et al*. 2008). In addition to being an economic need, there is social responsibility to control invasive plant populations. In the

European Union Biodiversity Strategy for 2030, the need to manage established invasive species and reduce the spread by 50% by 2030 (EU Biodiversity Strategy for 2030 2020) is set as a political target. A set of actions to be implemented in the EU concerning invasive alien species control is outlined in the Invasive Alien Species Regulation (2014). The Union List of Invasive Alien Species is the core component of the Regulation. The regulations and guidelines outlined in the Regulation apply to the species on this list and include limitations on the possession, import, sale, breeding, growth, and release of those species into the environment. Member States are obligated to manage species that are already widely distributed in their territory, take action on pathways of inadvertent introduction (*i.e.*, prevention), and take action for the early detection and swift eradication of these species. Similar actions are planned in other regions of the world (Grice *et al*. 2020). Amongst key factors limiting invasive plant eradication strategies are economic factors (Epanchin-Niell 2017).

Invasive plant management and eradication requires not only political will but also concrete actions and should be economically justified (Fletcher *et al*. 2015). Different control methods can be used to eradicate and limit the spread of invasive plants. Non-chemical methods are the most widely used (Weidlich *et al*. 2020). Mowing, prescribed fire as well as hand-pulling, cutting, and harrowing are the most popular (Weidlich *et al*. 2020). Chemical control methods include treatment with herbicides (the most common is the use of glyphosate, but also imazapic is used, as well as other herbicides). Recently several biological control methods have demonstrated their efficiency, and they might include the use of microorganisms (Hess *et al*. 2019; Shahrtash and Brown 2021), genetic biocontrol (Teem *et al*. 2020), the use of natural enemies, and others (Hoddle 2023). Despite success stories of invasive plant control, much should be done to achieve the set aims of their eradication and limitation of spread.

One of the main factors affecting the efficiency of elaborated and suggested methods of invasive plant control is the lack of knowledge of invasive plant ecology, their survival strategies as well as their phytochemistry, and allelopathic properties. Another factor affecting invasive plant control method efficiency is problems related to the utilization of removed invasive plant biomass, especially considering that this biomass for many species of invasive plants is high. Besides, some of the suggested invasive plant biomass utilization methods can support their spread, for example, composting; in addition, some eradication methods can be costly and labor-consuming (Hinz *et al.* 2019).

One of the conceptual directions of development of the European Union considers the reduction of the use of fossil materials, especially fuel. This can be achieved by replacing fossil materials with renewable biomass, *i.e.* bioeconomy (A sustainable bioeconomy for Europe 2018). The aim of a bioeconomy is to use any kind of renewable biological resources to produce food, materials, and energy (A sustainable bioeconomy for Europe 2018). Another direction of development is the integration of circular economy concepts in all types of production and life (A new Circular Economy Action Plan... 2020). The circular economy is one of the key elements of the EU Green Deal (The European Green Deal 2020). This legislation supports sustainable development aimed at the reduction of pressure on natural resources, and biological diversity, while promoting industrial and social development. According to these concepts, invasive plant biomass is not a waste, but a valuable resource, possibly supporting its rational use. However, to effectively and safely utilize invasive plant biomass, much more should be done to understand possibilities of its use and application as well as safe utilization possibilities. Considering the use of invasive plant biomass, it is very important to keep in mind 2 aspects: 1) the priority task is eradication and control of invasive plants, and any application should not promote their intended cultivation; 2) any processing should be elaborated in a way preventing propagation or renewed spread of plants and should be considered as utilization of invasive plant biomass. During the last decade, several new solutions for safe utilization of invasive plant biomass have been suggested, at first for bioenergy production, and then to obtain extracts from plants, fibers, and other materials (Fig. 1). Invasive plant biomass can be incinerated, and it has been used as feedstock to obtain biofuels (bioethanol, biogas, and others) and biochar as well as source of plant fibers. Plant biomass has been composted. By such means, the invasive plant biomass, after suitable processing, no longer can contribute to the spread of the undesired species. Instead, it can serve as a source of biologically active substances for food and pharmaceutical industry, as source of fine chemicals, pigments, and many other interesting applications. However, the results of these studies so far have not been summarized (Vera *et al.* 2022).

The present article reviews possibilities to use biomass of invasive plant species in the bioeconomy to achieve their safe utilization targets.

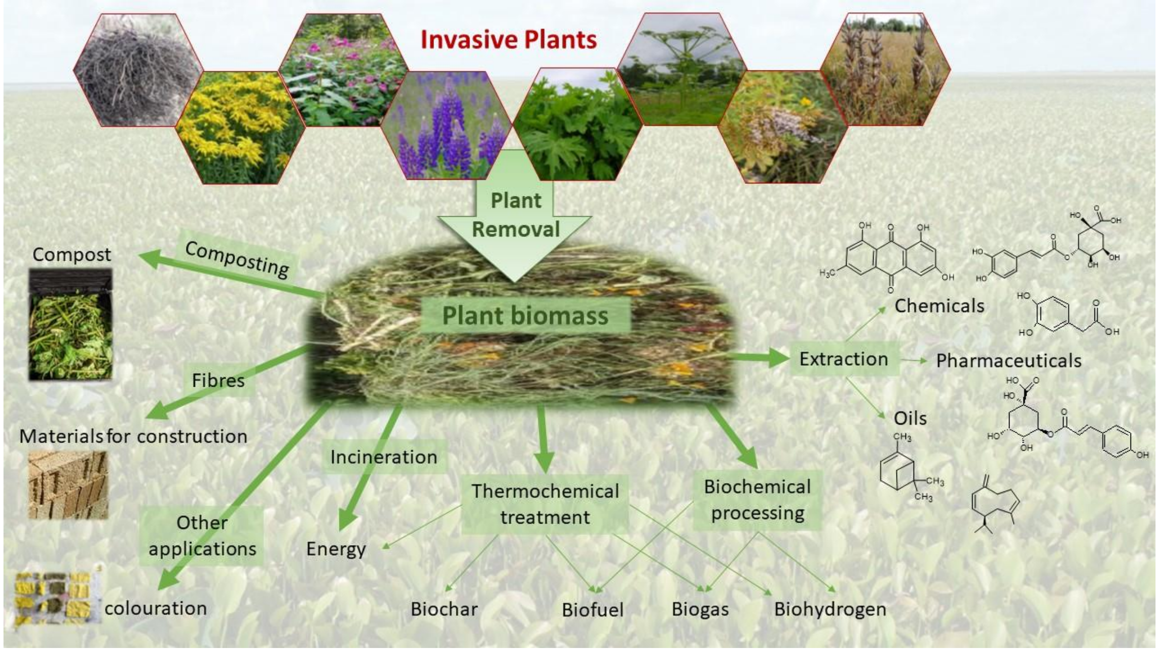


Fig. 1. Approaches for safe utilization of invasive plant biomass to achieve safe utilization and use in bioeconomy aims

INVASIVE PLANT BIOMASS AS FEEDSTOCK FOR BIOENERGY

Invasive plants, just as any other type of biomass, can be used for energy production. The waste obtained after the eradication of plants, which is a renewable material, can support the replacement of fossil energy sources. Many invasive plants have high biomass productivity, which can be at the same level as energy plants. For example, *Reynoutria japonica* and *Stapelia gigantea* have annual biomass yield of 8.6 t/ha, but *Impatiens glandulifera* and *Heracleum mantegazzianum* have biomass production yield of 5.8 and 6.0 t/ha (dry mass) (Van Meerbeek *et al*. 2015).

A feasible approach can be considered incineration of invasive plant biomass, for example, using granulation. The widely used plants *Heracleum sosnowskyi* and *Solidago canadensis* in the form of pelletized biomass together with binders (potato peel waste and spent coffee grounds) can be used as biofuel, and such mixtures have acceptable calorific values and application potential (Zihare *et al*. 2018). However, an obstacle is the need for drying of plant biomass to achieve optimal energy yields as well as optimization of the incineration process to reduce adverse impacts and achieve energy-efficient conditions of the process (Liang *et al*. 2023). There is a need to select the most appropriate processing technologies for invasive plant management. As a starting point, biomass life cycle assessment can be used to find the most viable and economically prospective approach (Joseph *et al.* 2020).

Processing of invasive plant biomass into energy can be achieved using either biochemical or thermochemical processing technologies. The use of invasive plants for biofuel production is associated with risks of further spreading of these species, as economic driving forces are very important. Thus, in the case of highly spreadable species, there needs to be careful planning. Provisions need to be made for plant eradication, transport, and other logistics to minimize the spread risk, and the use of biological control to reduce the invasiveness of alien species for the production of biofuel (Richardson and Blanchard 2011).

Thermochemical Processing of Invasive Plant Biomass

Biomass transformation into biofuel can be achieved using thermochemical processes including hydrothermal treatment, torrefaction, combustion, pyrolysis, gasification, and thermal liquefaction. Thermochemical treatment products are gaseous (syngas, hydrogen), liquid (oils, methanol and others), and solid (biochar) products, depending on the biomass type, treatment temperature, catalyst used, presence of oxygen, processing duration and conditions, as well as other factors (Canabarro *et al*. 2013). Thermochemical treatment has benefits, as it requires less complicated facilities, and usually it does not require biomass pretreatment in comparison to biochemical processing (Pisupati and Tchapda 2015). Thermochemical biomass processing can be considered highly productive, when considering capital and operating costs and energy efficiency; the technology can be regarded as robust, since mixtures of different biomass types can be applied (Lee *et al*. 2022).

Gasification involves the conversion of biomass into syngas through the partial oxidation of biomass at elevated temperatures. The process converts solid biomass into combustible gas mixtures (synthesis gas or syngas - main components carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and nitrogen (N_2) (Lapuerta *et al.* 2008). Biomass gasification includes a combination of exothermic oxidation and endothermic pyrolysis, depending on the availability of oxygen, and as byproducts also tars are formed (Canabarro *et al*. 2013). Pyrolysis is a biomass thermochemical transformation process at temperatures of approximately 1,000 °C in the presence of limited amounts of oxygen, resulting in solid, liquid, and gaseous substances. A balance between different pyrolysis products depends on heating temperature, heating rate, and other process factors.

Possibilities to apply thermochemical processing methods influence the elemental and biochemical composition of invasive plants. As the category “invasive plants” reflects the distribution of these plants and their ecological risks, there are no significant differences with other higher vegetation plant biomass, both with respect to their composition and considering the main groups of substances forming them. Carbon content in most widely found invasive plants is in the range from 42% up to 50%, with other elements at approximately H 5.2 to 6% and N 1.0 to 3% (Van Meerbeek *et al*. 2015; Fałtynowicz *et al*. 2015; Reza *et al*. 2019; Pérez *et al*. 2021). Correspondingly, the higher heating values (indicating the calorific value of biomass if incinerated after the removal of water) are in the range from 16 to 20 MJ/kg (Van Meerbeek *et al*. 2014; Fałtynowicz *et al*. 2015; Reza *et al*. 2019; Pérez *et al*. 2021; Łapczyńska-Kordon *et al*. 2022).

Invasive Plants as a Source of Biochar

Biomass of invasive plants can be processed into solid biofuel, namely hydrochar or biochar. Biochar is a carbonaceous material produced during the thermal treatment of biomass at low oxygen conditions at temperatures starting from 180 °C up to 1,200 °C (Weber and Quicker 2018). Thermochemical transformation processes of biomass can be described as hydrothermal carbonization, slow and fast pyrolysis, gasification, carbonization, and torrefaction (Parshetti *et al*. 2013). Biochar has a highly condensed structure, and the concentrations of other elements than carbon (H, N, S, O) depend on the treatment conditions, the highest temperature of the first stage of heating, and the heating rate. Biochar can contain also surface functional groups (for example, -OH, -COOH, -C=O, C-H, N-H, and others) (Aller 2016). Depending on the processing temperature, specific surface area of biochar particles increases and can reach up to a few square meters per gram. However, by using physical activation (with gas, for example, CO_2) or chemical activation (for example, using KOH, H_3PO_4 or other agents), surface areas up to 1,500 m^2/g can be reached (Sakhiya *et al*. 2020). With increasing pyrolysis temperature, the yield of biochar decreases (Ahmed *et al.* 2016). Biochar contains also inorganic elements present in plant material, such as Na, K, Ca, and Mn, as well as trace elements.

Biochar is a versatile material with diverse application possibilities and at first, it can be used as a solid fuel as during the pyrolysis process concentrations of other elements are removed and the major element forming biochar composition is carbon. Thus, biochar's highest heating value can reach even up to 40 MJ/kg in comparison with highest heating value (HHV) of invasive plant biomass < 20 MJ/kg (Aller 2016). Biochar obtained from invasive plants can be used not only as fuel but also as sorbents for the removal of pollutants, for example, trace metals from wastewater (Xiang *et al*. 2020). Other applications also have been demonstrated (Cha *et al*. 2016).

A prospective area of biochar application includes its use in agriculture. Several studies have demonstrated beneficial and long-term implications of the use of biochar as a sustainable soil amendment as it improves soil environment, improves water retention capacity, stabilizes pH, supports slow release of nutrients, and it reduces emissions of greenhouse gases as well as bioavailability of pollutants, such as heavy metals (Woolf *et al*. 2010; Amini *et al*. 2016). Major benefits of invasive plant biomass thermochemical processing are related to the basic transformation of organic substances of plants into inert carbon material. Thus, risks related to the propagation of seeds or vegetative spread are excluded using this approach, but at the same time the carbon and nutrients accumulated in the plant biomass are recycled to soils.

The use of invasive plant biomass as a feedstock for the production of biochar has been reviewed in recent studies (Liao *et al*. 2013; Feng *et al*. 2021; Yang *et al*. 2022) and convincingly demonstrates the benefits of this approach for the safe utilization of plants but at the same time possibilities to obtain chars with significant differences in structure, composition, and high adsorption capacities. Further application possibilities of biochars obtained from invasive plants can be found in areas such as environmental remediation and agriculture, wastewater treatment and others.

Pyrolysis of invasive plant *Cortaderia selloana* abundant in Spain has been studied at 750 °C and 850 °C using conventional and flash pyrolysis to obtain high calority biogas (17 MJ/kg), bio-oil with high yield (34%), and biochar with similar high calority (up to 29 MJ/kg). Using pellets from *Reynoutria sachalinensis* and pyrolysis at different temperatures with the subsequent activation resulted in activated biochar with a high specific surface area (768 m^2/g), but by using chemical (KOH) activation even surface area of 2,541 m^2/g was obtained (Fałtynowicz *et al*. 2015). The potential to use obtained activated biochars for gas storage, purification, and depuration of mixtures has been mentioned. Invasive plant biochars can find new applications, for example for the production of hard carbons (Lakienko *et al*. 2022). Using *Heracleum sosnowskyi* stems biochars can be obtained in a short time, including the pretreatment stage and further carbonization at 1,300 °C. Electrochemical properties of obtained biochars demonstrate high discharge capacity and thus are prospective material for sodium-ion batteries. Pyrolysis of *Acacia holosericea* provides the possibility to obtain biochar with a yield of 34%, bio-oil with a yield of 32%, as well as syngas (Reza *et al*. 2019). *Schinus terebinthifolius* and *Dioscorea bulbifera* (plants invasive in South America) have been subjected to pyrolysis to produce biochar and bioenergy with yields similar to traditional pyrolysis feedstocks. The development of the pyrolysis model supports the possibilities of developing cost-effective invasive plant biomass utilization technology (Liao *et al*. 2013). Goldenrod (*Solidago canadensis*, *Solidago gigantea*) biomass has been used for the production of biochar using torrefaction (250 °C and 275 °C, for 3 h) and possibilities to use obtained biochar as fuel have been discussed (Łapczyńska-Kordon *et al*. 2022). The invasive plant *Hovenia dulcis* was used to prepare activated carbon (surface area 898 m^2/g), and application of it was studied as a sorbent of herbicide atrazine as well as for purification of contaminated river water (Lazarotto *et al*. 2022). Another study proved the efficiency of activated carbon obtained from the same plant for the removal of pesticide diuron (Georgin *et al*. 2022). Biochar obtained from invasive species *Reynoutria* at temperatures of 350, 450, and 550 °C were tested as absorbents for Cd^{2+} and Pb^{2+} removal in aqueous solutions. Thus, invasive plant biochar is a tool to control invasive plants that also can be applied in environmental and other technologies as a versatile material (Lian *et al*. 2020). Similar results were provided in the study of Wang *et al*. (2021), where the biomass of 5 invasive plants was used to produce biochar found to be efficient for the removal of Cd^{2+} and Cu^{2+} from wastewaters. Another study demonstrated the application possibilities of invasive plant biochar for the absorption of cation dye methyl orange from wastewater (Nguyen *et al*. 2021).

The main strength of invasive biomass utilization using pyrolysis to produce biochar is in respect to the high safety of this approach. Biochar production can be done using existing facilities. This technology has been used since historic times to produce wooden biochar, and it can be easily upscaled and transformed for processing of other types of biomasses. Another main positive aspect of this technology is the versatility and high application possibilities of obtained biochar as it has been already demonstrated in several studies.

Processing of Invasive Plant Biomass into Liquid or Gaseous Biofuel

Considering the versatility of applications, liquid and gaseous biofuels obtained from invasive plants are preferable in comparison with solid biofuels. Conversion of invasive plant biomass into liquid or gaseous biofuels can be achieved using thermochemical or biochemical processing. Biochemical processing is based on the isolation of oil components from plant biomass or hydrolysis of polymeric carbohydrates (cellulose, hemicellulose, starch, *etc*.) following fermentation and isolation of the desirable biofuel.

The use of plant biomass for the production of gaseous or liquid biofuels is a well elaborated approach and is widely tested on different kinds of biomass (Demirbas 2011; Voloshin *et al*. 2016; Srivastava *et al*. 2021; Ramos *et al*. 2022). Depending on biomass type, pretreatment methods, and further processing from plant biomass it is possible to obtain hydrocarbons starting from methane up to high molecular condensed polyaromatics (tars), lower alcohols (methanol, methanol, butanol and others), hydrogen, and other substances, which can be used for energy production as well as for other purposes (Zhu *et al*. 2020; Ashokkumar *et al*. 2022).

Applicability of plant biomass processing into liquid or gaseous biofuel has been demonstrated in several cases using invasive plant biomass. Eastern redcedar (*Juniperus virginiana*) fast pyrolysis has been successfully used to produce gasoline and diesel and the production costs, and analysis of possible prices of products indicate that the conversion of invasive biomass into biofuel is economically feasible (Ramli and Epplin 2017). Also, invasive aquatic plants have been evaluated as a source of plant-based biofuel (Kaur *et al* 2019). As a result, this research provides a thorough analysis of the physicochemical characteristics of aquatic plants and their potential for biofuel generation as well as demonstrates possibilities to use various invasive aquatic plants to produce biofuel. The strategies for producing biofuel from aquatic plants that are practical for future energy production have also been presented (Alam *et al*. 2021). Several varieties of floating aquatic plants— *Azolla filiculoides* , *Salvinia molesta, Eichhornia crassipes, Lemna minor and others*—as well as the biofuel production processes associated with them—transesterification, pyrolysis, hydrolysis, and torrefaction—have been examined. The optimal biofuel production conditions for aquatic plants and their improvement techniques are also evaluated in the same paper (Alam *et al*. 2021). The qualities of conventional gasoline and aquatic biofuel are also examined. Findings indicate that compared to other aquatic plants, azolla (*Azolla filiculoides*) and water fern (*Salvinia molesta*) are superior aquatic plants that can generate high-quality (comparable to diesel) biofuels (Koley *et al*. 2023). This is based on calorific value and viscosity. Production of biofuel from aquatic plants including water fern, water lettuce, and duckweed is another less concentrated energy source. By employing sustainable methods to produce biofuel from aquatic plants, the expense of removing invasive aquatic plants from water can be turned into an investment (Koley *et al*. 2023).

One of the highest risks of the management strategy to control invasive plant spread is related to the germination of their seeds and conservation of germination possibility of seeds as well as of vegetative spread risks. A study of water hyacinth (*Eichhornia crassipes*) seeds survival demonstrates that the utilization of plant biomass using composting or biogas production is not completely safe, as a high proportion of seed survival was observed (Pérez *et al*. 2015).

Invasive plants abundant in Central and Eastern Europe (*Reynoutria*, *Solidago,* and *Spiraea* species) have been tested concerning the possibilities of using them as a raw material for the production of second-generation biofuel – bioethanol. Pre-treatment of plant biomass (alkaline hydrolysis with 1% sodium hydroxide) followed by simultaneous saccharification and fermentation provides possibilities to obtain bioethanol with a yield of 2.6 m^3 per hectare in the case of *Reynoutria bohemica* biomass. Thus, convincingly both environmental and economic benefits are demonstrated. Still, as a problem can be considered, there is a need for further optimization of technological processes and safe transportation strategies to exclude accidental spread of invasive species (Wiatrowska *et al*. 2022). Also, Sosnowsky's hogweed has been utilized to produce biofuel from it and technology for processing plants into ethanol is elaborated. At the same time, it is important to create a closed production line to prevent the uncontrolled spread of hogweed seeds and exclude risks from skin burns (Mezentsev 2023).

The need for safe utilization of invasive plant biomass is considered a tool of ecosystem service restoration. Many aquatic invasive plants (for example, *Phalaris arundinacea*, *Phragmites australis*, *Typha*) have a damaging impact on ecosystem services and thus their eradication can help not only restore natural habitats, restore biological diversity, but also reverse eutrophication. As it has been studied in the example of coastal wetlands of Lake Ontario, a single growing season's biomass of these invasive plants can reach 659,545 metric tons and removal of plant biomass means also removal of 10,805 and 1,144 tons of nitrogen and phosphorus, respectively (Carson *et al*. 2018). Other benefits, such as potential energy yield resulting from harvesting of plant biomass have been modelled including the costs (*e.g.*, harvesting, transportation, drying and condensing), as well as the ecosystem service benefits (*e.g.*, biodiversity recovery, nutrient pollution abatement, greenhouse gas reductions) to demonstrate the need of holistic approach in respect to methods of invasive plant eradication covering the economic, ecological, and societal value management.

In China invasive plants have been considered as highly prospective feedstock for biogas production, and co-fermentation technology has been proposed as a tool to increase the biogas production efficiency of mixtures to convert plant biomass into valuable resources. Invasive plant use for biogas production has been considered as a utilization of plant biomass energy and as a tool to control invasive plant spread (Rezania *et al*. 2015). Aquatic and terrestrial invasive plants (*Eichhornia crassipes*, *Spartina alterniflora*, *Alternanthera philoxeroides*, *Eupatorium adenophorum*) have been used applying co-fermentation for biogas production. Co-fermentation of invasive plants and livestock manure has been used as a tool to increase the transformation efficiency of biomass energy and increase biogas production efficiency. The main benefits of invasive plant use include rapid growth and proliferation and high biomass as well as low growth environmental requirements, low investment costs, no competition for land for food production, and no competition with humans and livestock for food (Lu and Gao 2021). Evaluation of the potential to use *Spartina alterniflora* as bioenergy feedstock demonstrated that in China alone the annual biomass of this plant reaches 2.53 Mt, producing 39 PJ bioenergy, equivalent to that of 1.33 Mt of standard coal (Lu and Zhang 2013).

Invasive species, common in Europe (*Reynoutria japonica*, *Heracleum mantegazzianum*, *Impatiens glandulifera*, and *Solidago gigantea*) were used for biogas production. Using anaerobic digestion methane concentration was 50%, which is similar for commonly used biomass range (48 to 65%) for energy crops. Non-catalytic and catalytic pyrolysis of invasive *Pennisetum purpureum* grass produced biochar, bio-oil, and syngas (Reza *et al*. 2023). Invasive *Cortaderia selloana* has been using conventional and flash pyrolysis to obtain gas with a heating value of 17 MJ/kg with high CO, CH_4, and H_2 concentrations as well as bio-oil with a yield of 33.58% and heating value 22.74 to 29.12 MJ/kg The obtained pyrolysis bio-oils composition was dominated by nonaromatic and monoaromatic hydrocarbons while bio-oils from flash pyrolysis were composed mainly of polycyclic aromatic hydrocarbons (Pérez *et al*. 2021).

INVASIVE PLANTS AS A SOURCE OF BIOLOGICALLY ACTIVE SUBSTANCES

Safe utilization of biomass of invasive plants can be achieved not only by using them for energy production but also by processing of biomass and isolating biochemical components of plants. Plant biomass processing can contribute to sustainable management, because biologically active, nutritionally valuable substances can be found in most invasive plants. Several studies have demonstrated that many invasive plants have high nutritional value and have significant potential to recover biologically active compounds present in their composition (Peter *et al*. 2021). Several reviews have been dedicated to phytochemistry, ethnomedical, and pharmacological applications of invasive plants, for example, European goldenrod (*Solidago virgaurea*) and Sosnowsky's hogweed (Fursenco *et al*. 2020; Andreeva 2020). Many invasive plants in the regions where they are native are used in ethnomedicine. For example, *Reynoutria* species are included in Chinese, Japanese, and Korean traditional pharmacopoeia (Nawrot-Hadzik *et al*. 2018), *Solidago* species flowers traditionally by indigenous people of North America have been used for the coloration of fibers (Budzianowski *et al*. 2021), and Sosnowsky's hogweed fresh sprouts are used in cooking (Matarrese and Renna 2023). Thus, the invasive plants in regions where they have been growing traditionally have found many applications and probably their use limited their spread. However, when these plants have been introduced or have been transferred to regions where their application potential is not known, they are considered only as a nuisance. Another problem related to eradication and management problems of invasive plants is related to limited knowledge of their phytochemical composition, as the number of studies of the majority of invasive plants is relatively scarce.

Thus, to develop invasive plant management and eradication strategies it is important to know: 1) the usage of invasive plants in regions where they are native; 2) the phytochemical composition of these plants.

Another aspect influencing interest in the phytochemical composition of invasive plants is related to their high competitiveness with respect to other plants: high stability for stress (drought, salinity, UV radiation and others), competitiveness in respect to other plant species, and ability to outcompete native plant species, forming dense populations (Zhu *et al*. 2021). In many invasive plants substances with allelochemical properties have been found, and such substances can suppress the growth of other plants, thus contributing to the ability to invade territories, occupied by other plants (Thiébaut *et al*. 2019; Kalisz *et al*. 2021). For example, extracts of the invasive plant *Chromolaena odorata* inhibited the germination, and growth of other plants and responsible for this allelopathic properties are pyrrolizidine alkaloids as well as flavonoids, phenolic acids, and terpenoids were also found in this plant (Kato-Noguchi and Kato 2023). Hence, understanding why invasive plants outcompete other plants can be of importance in developing plant eradication strategies.

Polyphenols of Invasive Plants

Polyphenols are a widespread group of substances found in higher vegetation (Quideau *et al*. 2011). Polyphenols are secondary metabolites of plants, participate in the chemical defense reactions of plants against stress, and predators and thus have antioxidant activities (Bhattacharya *et al*. 2010). Polyphenols have at least one benzene unit substituted with one or more hydroxyl groups as well as other substituents. Polyphenols can be divided into several classes: 1) phenolic acids (hydroxybenzoic acids and hydroxycinnamic acids),

2) flavonoids (flavonols, flavones, flavanols, flavanones, isoflavones, proanthocyanidins), 3) stilbenes, 4) lignans (Singla *et al*. 2019).

Polyphenols are the most studied group of substances in invasive plants (Peter *et al*. 2021). For polyphenol isolation extraction with lower aqueous alcohols (methanol, ethanol, *etc*.) as well as acetone and similar solvents have been used, and often acidification of solvents has been done, to stabilize structures of polyphenols (Radusiene *et al*. 2015). Recently intensive extraction methods have been tested for polyphenol isolation (Kraujalienė *et al*. 2017). For the characterization of polyphenol extracts' total phenol concentration, radical scavenging activities have been analyzed as well as individual polyphenols were identified using liquid chromatography with different detection methods. Searches of polyphenols at first were done in invasive plants with known ethnopharmacological applications.

Different extraction methods have been used to study polyphenols from invasive plants. Besides traditional, solvent-based extraction recent extraction with supercritical carbon dioxide and pressurized liquid extraction has been used to obtain polyphenolics (10 phenolics were identified) as well as lipids from *Solidago virgaurea* (Kraujalienė *et al.* 2017). From native, invasive, and hybrid Solidago species, a number of phenolic acids and flavonoids were isolated (Marksa *et al*. 2020). Chlorogenic acid and 3,5-dicaffeoylquinic acid are among the phenolics influencing the radical scavenging activities of Solidago species.

Using extraction with ethanol, methanol, acetone, water, and mixtures of organic solvents from *Solidago canadensis* and *Solidago gigantea* flavonoids and phenolic acids were isolated. In extracts chlorogenic acid, rutin, hyperoside as well as glycosides of isoquercetin, kaempferol, isorhamnetin, and quercetin were found (Zekič *et al*. 2020).

In regions of its native growth, invasive *Carpobrotus edulis* is used in traditional medicine (Mudimba *et al*. 2019; Akinyede *et al*. 2020). It has high concentrations of polyphenolics (total polyphenolics concentration 273 mg gallic acid equivalents (GAE)/g DW. *C. edulis* extracts contain a high diversity of polyphenolics such as phenolic acids, flavonoids, and coumarins, specifically coumaric acid, uvaol, vanillin, kaempferol-O-(rhamnosyl) hexosylhexoside, azelaic acid, and emodin, supporting applications of *C. edulis* fruits in food, cosmetics, agriculture, and pharmaceuticals (Castaneda-Loaiza *et al*. 2020). In another study luteolin-7-O-glucoside, salicylic and coumaric acids have been found in extracts supporting their anti-inflammatory properties application and strong radical scavenging activities (Pereira *et al*. 2023) as well as potential use of the *C. edulis* extracts against vitiligo (Trigui *et al*. 2023). The anticancer activity of *C. edulis* extracts has been mentioned (Fakudze *et al*. 2023).

Invasive plants can be a rich source of biologically active substances with potential applications in medicine, pharmacology, veterinary as food supplements and other fields. An example of invasive plants as a source of biologically active substances is the extraction of resveratrol and its glucoside from rhizomes of *Reynoutria japonica* (Kanda *et al.* 2021) or other knotweed varieties (Cucu *et al*. 2021). Resveratrol and its glycoside have high antioxidant activity and demonstrate antimutagenic activity, inhibit angiogenesis, and have an antiobesity effect (De La Lastra and Villegas 2005). Dimethyl ether resveratrol and piceid were obtained with a yield of 0.342 and 2.57 mg/g, respectively, thus suggesting *Reynoutria japonica* as a prospective source of these compounds. In extracts of *Reynoutria japonica*, derivatives of anthranoids (emodine and its glucosides, 8-hydroxylamine) (Fig. 2) have been identified (Jo *et al*. 2013).

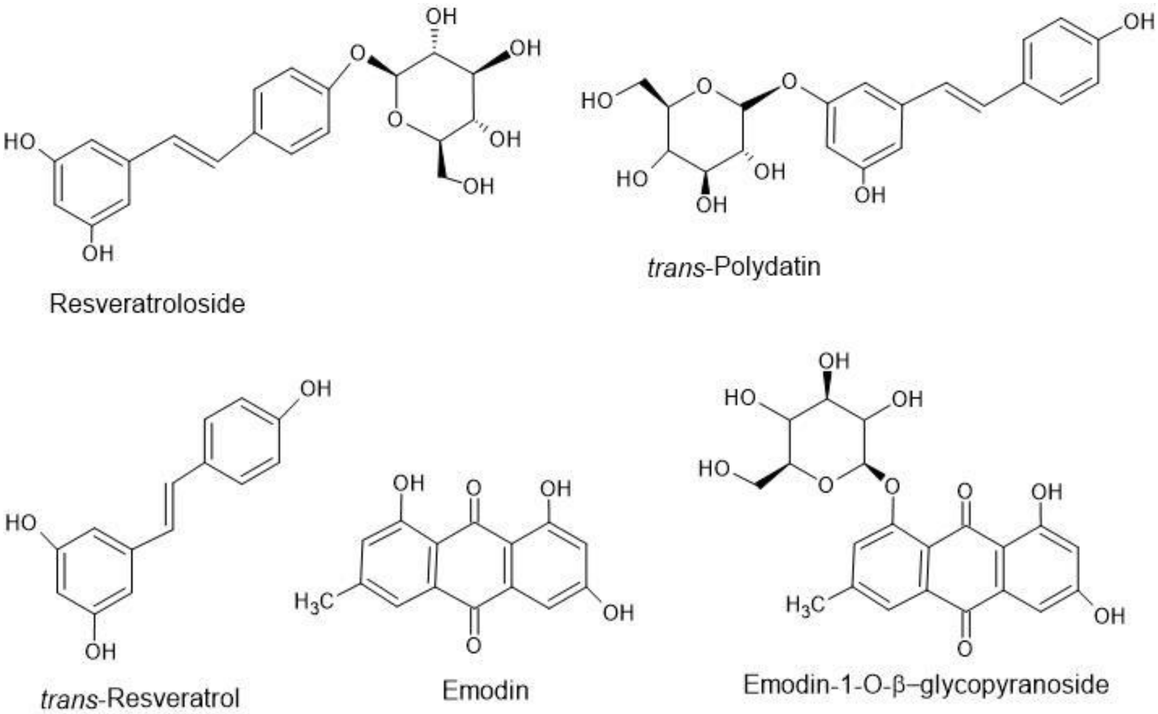


Fig. 2. Structures of polyphenols (resveratrol, emodin) and their glucosides (resveratroloside, emodin-1-O-β-glycopyranoside) found in extracts of rhizomes of *Reynoutria japonica*

As a part of the plant where the highest concentrations of polyphenols have been found, *Reynoutria japonica* rhizomes were identified (Cai *et al*. 2023). However, differences between species of plants of *Reynoutria* and plant parts have been demonstrated, suggesting use for food supplements and nutraceuticals production. It was found that *Reynoutria* leaves have the best potential food additives for health, due to high concentrations of polyphenols and triterpenoids, while at the same time high concentrations of stilbenes and polyphenolics in roots can be used to produce extracts for application in medical, pharmaceutical, and cosmetic industries (Lachowicz and Oszmiański 2019). The presence of biologically active substances has been found to be common also for other species of the same genus and antiaging, antioxidation, anti-inflammatory, anticancer, anti-hyperlipidemia, anti-hepatic fibrosis, and activity of extracts have been demonstrated (Song *et al*. 2019; Yang, and Kang 2020; Cai *et al*. 2023). In *Reynoutria japonica* rhizomes, high stilbene concentrations have been found (Alperth *et al*. 2021). Considering high concentrations of biologically active polyphenols in *Reynoutria* rhizomes, extraction and purification methods of pilot scale and industrial significance have been proposed (Beňová *et al*. 2010; Hren *et al*. 2023). Extraction of resveratrol and piceid from *Reynoutria japonica* rhizomes using dimethyl ether as the extrahent also is prospective for industrial-scale production of antioxidants from an invasive plant (Kanda *et al*. 2021).

Another aspect of the presence of polyphenols as well as other biologically active substances in *Reynoutria* species is an allelopathic activity of the plant: the ability to suppress other, especially native species (Mikulic-Petkovsek *et al*. 2022). The allelopathic effect of the *Reynoutria* extracts has been demonstrated in seed germination and growth tests (aqueous extracts of knotweed resulted in 38 to 48% lower seed germination and reduced growth of shoots and roots). Another study demonstrated the allelopathic effect of methanolic extracts in radish seed germination (Šoln *et al*. 2022). Allelopathic impacts are related not only to other plants but also to the surrounding environment as such, for example, *Reynoutria japonica* reduces soil microbial community biomass, thus indirectly affecting soil fertility (Stefanowicz *et al*. 2021). The effects on soil biota caused invasive plants thus may have implications if the restoration of invaded areas is planned (Stefanowicz *et al*. 2022). Invasion of *Reynoutria* species reduced also arbuscular mycorrhizal fungi spore number, species richness, and biomass (Zubek *et al*. 2022). Also, *Solidago canadensis* extracts inhibited the germination of rapeseed and ryegrass seeds, thus demonstrating the advantage of invasive plants through the inhibitory activity on germination of native plant seeds (Baležentienė 2015).

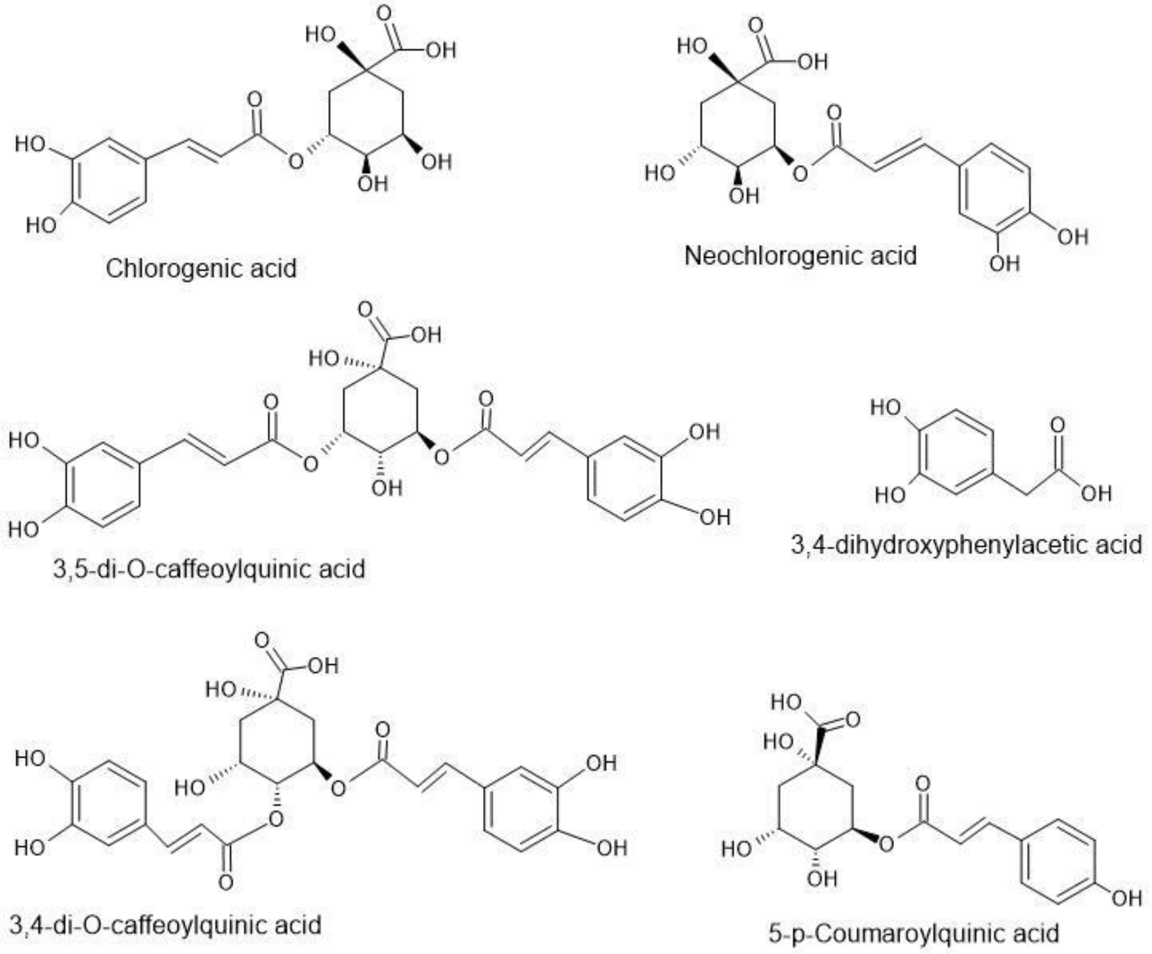
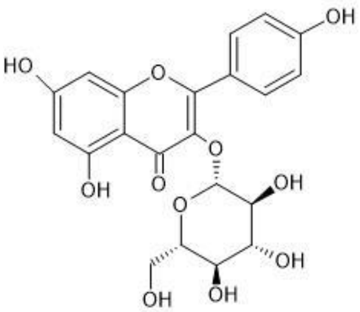
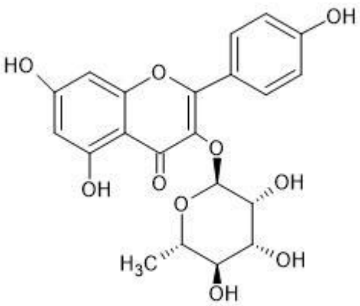

Chlorogenic acid
Neochlorogenic acid
3,5-di-O-caffeoylquinic acid
3,4-dihydroxyphenylacetic acid
3,4-di-O-caffeoylquinic acid
5-p-Coumaroylquinic acid

Fig. 3. Polyphenols found in *Solidago virgaurea* and *Solidago canadensis*

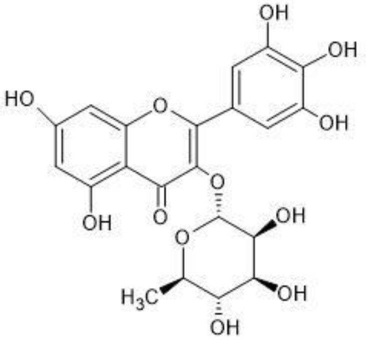
Also, black locust (*Robinia pseudoacacia*), an invasive tree, is a rich source of polyphenols and flavanols (catechin), flavonols (kaempferol glucuronyl rhamnosyl hexosides), as well as flavones, ellagitannins (luteolin dirhamnosyl hexosides and vescalagin), which have been identified in the plant extracts (Uzelac *et al*. 2023). In invasive plants, *Ambrosia artemisiifolia* and *Solidago canadensis* several polyphenols (Fig. 3) have been found: 5-O-caffeoylquinic acid, 3,5-dicafeoylquinic acids, and quercitrin with significant antioxidant activity and ability to inhibit lipase (Quinty *et al*. 2023). Thus, extracts of these plants are prospective to mitigate pathologies arising from oxidative stress, for example, obesity. Ethanolic extracts of *Solidago canadensis* contain hydroxycinnamic, cichoric, caffeic, chlorogenic, quinic, and ferulic acids (Suleymanova *et al*. 2019).



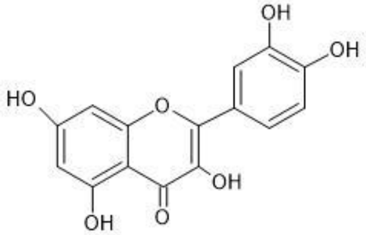
Kaempferol-3-O-glucoside (astragalin)



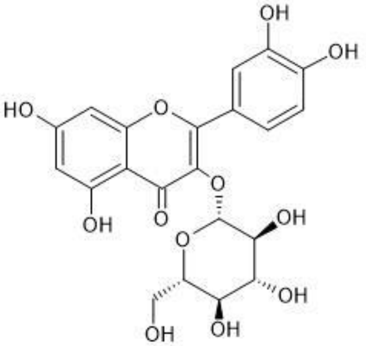
Kaempferol-3-O-rhamnoside (afzelin)



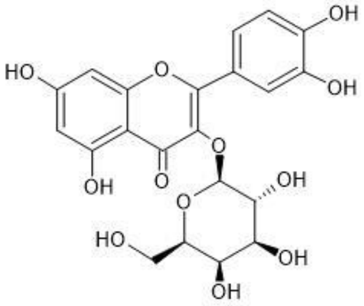
Myricetin 3-rhamnoside (myricitrin)



Quercetin



Quercetin-3-O-glucoside (isoquercitrin)



Quercetin-3-O-galactoside (hyperoside)

Fig. 4. Representative flavonoids from *Solidago virgaurea*

In *Solidago canadensis* and *Solidago gigantea*, quercetin glycosides and kaempferol rutinosides as well as over 20 diterpenoids were found (Fig. 4, 5); these are responsible for the inhibition of chemical mutagenesis thus indicating the chemopreventive potential of plant extracts (Woźniak *et al*. 2018).

B-type proanthocyanidins have been found in the leaves of Japanese knotweed and other varieties of knotweed (Bensa *et al*. 2020). All studied species contained (−)-epicatechin and procyanidin B2, while (+)-catechin was found only in Bohemian and giant knotweed. Concentrations of proanthocyanidins in Japanese, Bohemian and giant knotweed were found to be from 0.84 kg/t up to 2.36 kg/t DW; thus, biomass of knotweeds can be considered as a source of procyanidins of industrial interest (Bensa *et al*. 2020).

From biowaste obtained after eradication of *Tradescantia fluminensis* phenolic acids as well as flavonoids (sinapic acid, ferulic acid and others) were isolated (Míguez *et al*. 2022).

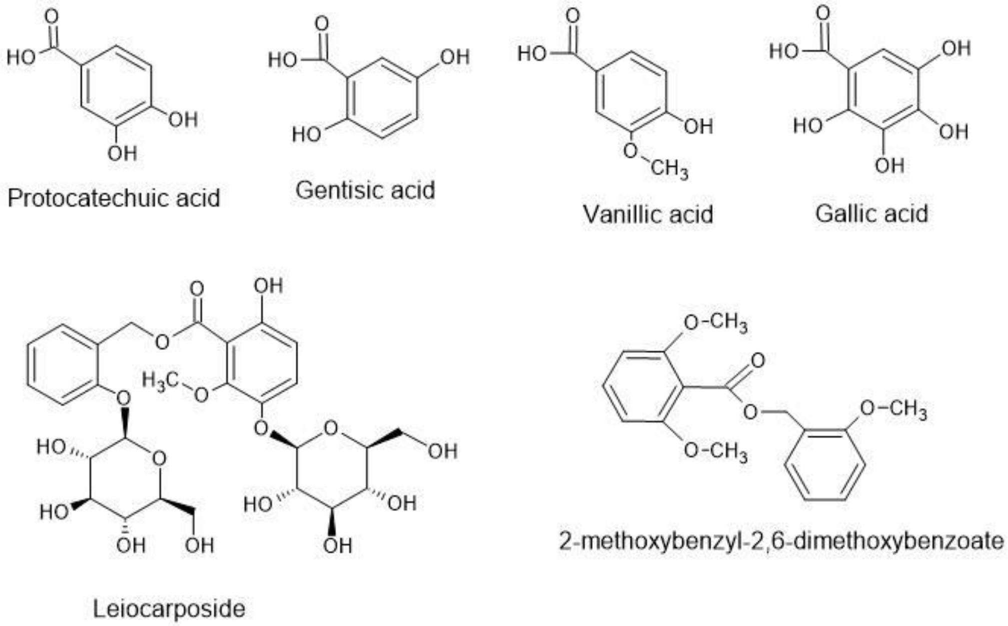


Fig. 5. Polyphenols found in *Solidago virgaurea*

Lipids, Alkaloids, and Other Biologically Active Substances in Invasive Plants

Invasive plants, just like other species of higher vegetation, have many groups of substances providing their defense potential against predators, allelochemicals, substances participating in metabolic regulation processes, and others. Amongst substances of interest for bioeconomy are lipids, alkaloids, carbohydrates, plant fibers, essential oils, and other groups of substances.

Essential oils can be used in medicine and healthcare, as food supplements due to their antimicrobial, antioxidant, insecticidal, or phytotoxic activities. In *S. canadensis* essential oil, 32 substances have been identified, and in the highest concentrations, germacrene D, limonene, α-pinene, β-elemene, and bornyl acetate have been found (Elshafie *et al*. 2019). In another study, several terpenes (Fig. 6) in essential oils isolated from *S. virgaurea* have been identified (Radušienė *et al*. 2022). Essential oils of *S. canadensis* demonstrated antimicrobial activities and thus are promising for use in therapies and health care (Baranová *et al*. 2022). Also, essential oils have repellent activities against aphids (Baranová *et al*. 2023).

In essential oils of *Solidago* inflorescences dominate monoterpene hydrocarbons, oxygenated sesquiterpenes as well as oxygenated monoterpenes and sesquiterpene hydrocarbons. As dominant substances α-pinene, bornyl acetate, spathulenol, isospathulenol, and caryophyllene oxide have been found. In leaves of studied *Solidago* o-cymene, β-cubebene, trans-pinocarveol, cis-verbenol, trans-verbenol, and γ-muurolene were found (Radušienė *et al*. 2022).

Different *Solidago* species contain significant amounts of lipids. In *Solidago canadensis*, the oil contents were 5.1% dry-weight plant material. Amongst them, saturated fatty, monounsaturated, and polyunsaturated fatty acids were found as dominant, but altogether 20 fatty acids were identified, dominated by four acids (linoleic acid, oleic acid, palmitic acid, linolenic acid) (Shelepova *et al*. 2019)

Biorefining of goldenrod (*S. virgaurea*) with differing polarity solvents (Fig. 6) produced a group of lipids with α-tocopherol as a main component (61.4 to 134 µg/g) (Kraujalienė *et al*. 2017). Also, possibilities to use *S. gigantea*. as a source of fatty acids have been studied using supercritical carbon dioxide extraction. Optimization of supercritical carbon dioxide extraction conditions provided possibilities to obtain a high yield of lipid fraction – 273 mg/g DM with fatty acid methyl esters as the main product demonstrating possibilities of the transfer of the extraction process to industrial scale (Wrona *et al*. 2019).

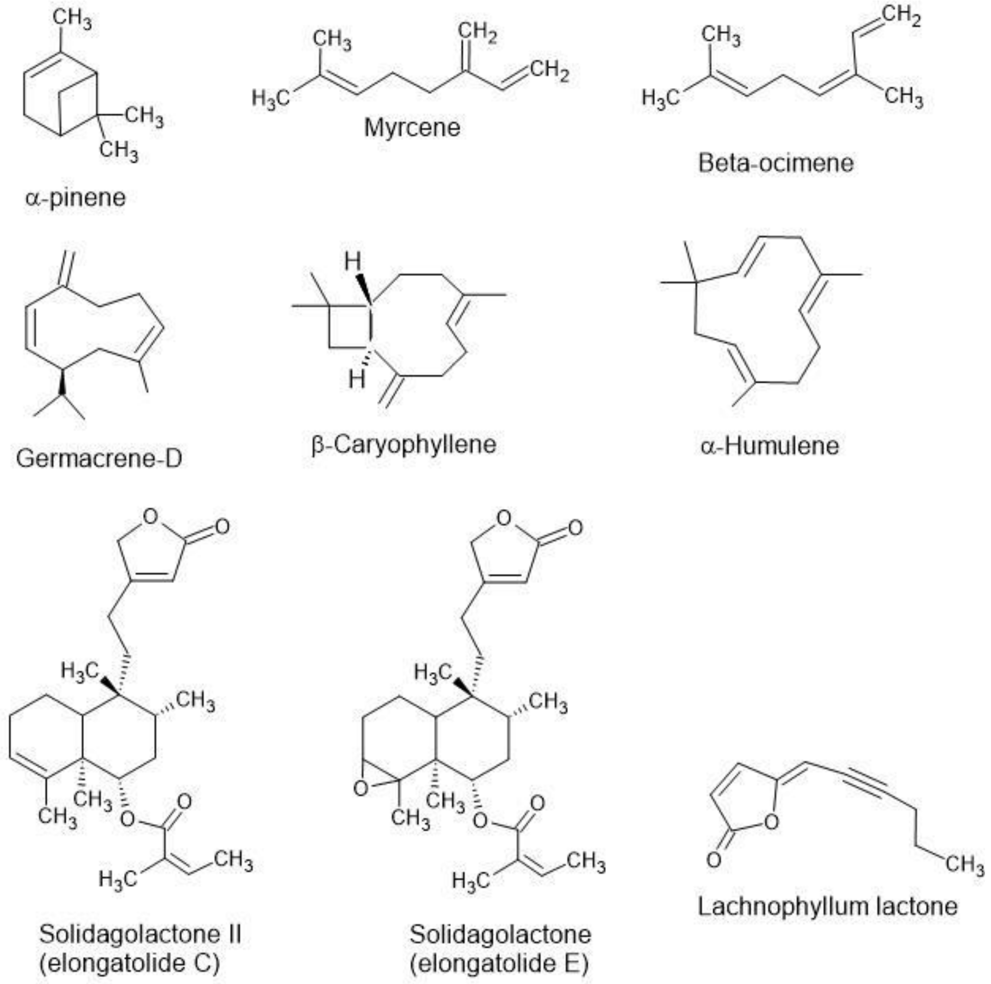


Fig. 6. Terpenes from *Solidago virgaurea*

Important lipid groups are waxes participating in defense against predators, drought stress, UV radiation and other impacts. Leaf epicuticular wax of the *Reynoutria japonica* consists of C16−C33 n-alkanes (up to 48.1% of the total wax mass), C9−C22 free fatty acids (Li and Ishikawa 2006).

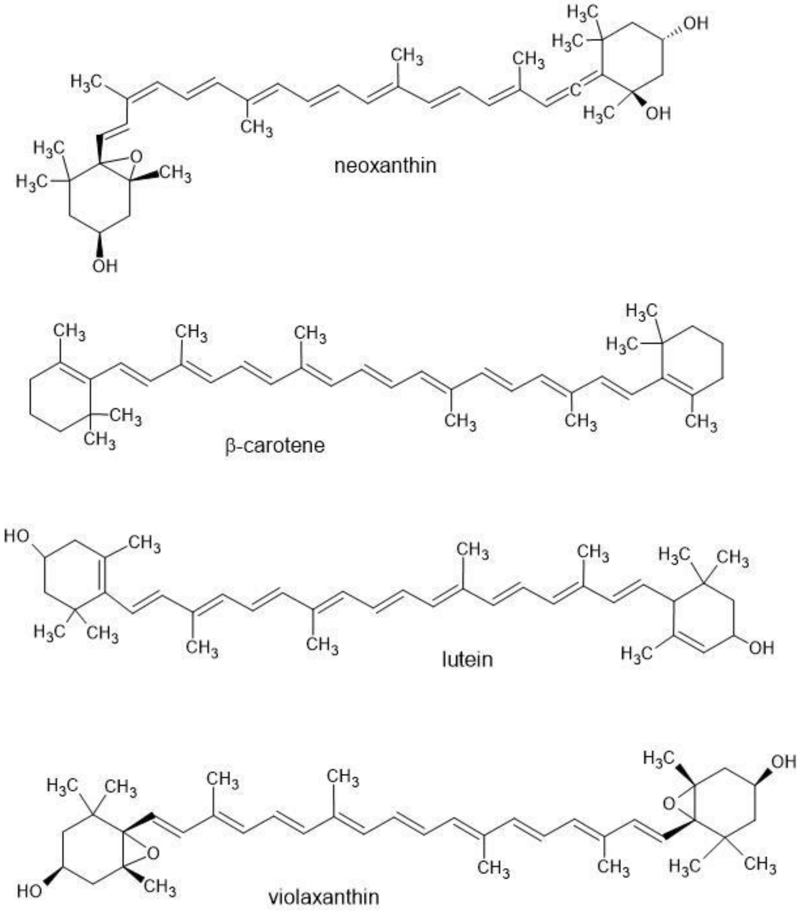


Fig. 7. Carotenoids found in green leaves of (*Reynoutria japonica*) and (*Reynoutria bohemica*)

Japanese and Bohemian knotweeds contain 11 carotenoids (Fig. 7) in their green leaves. The total carotenoid content was found as 378 and 260 mg of lutein equivalent /100 g dry weight – values which are comparable to carotenoid-rich foods. Thus, green leaves of knotweeds can be considered as a valuable and sustainable natural source of carotenoids. In another study, lutein was found in knotweed leaves (Metličar and Albreht 2022).

An important group of biologically active substances are alkaloids, which are usually participating in the defense of plants against predators and infections. Many invasive plants contain high concentrations of alkaloids and an example of the significance of this group of substances is Lupin species (Khan *et al*. 2015; Magalhães *et al*. 2017). In different species of Lupine quinolizidine, indole and piperidine classes of alkaloids were identified, and their concentration reached up to 0.5 g alkaloids/kg, DW. In the seeds of *Lupin albus* as the main alkaloids (Fig. 8) lupanin, hydroxyaphylline, albine, and multiflorine as well as sparteine, albine, and anagraine were found (Pereira *et al*. 2022). Alkaloids are responsible for the anti-inflammatory and antioxidant potential of Lupine extracts. The presence of alkaloids in Lupin is of importance considering the possible consumption of Lupin seeds, flours, and Lupin-containing food (de Cortes Sánchez *et al*. 2005; Reinhard *et al*. 2006; Resta *et al*. 2008). Alkaloids are a common component of invasive plants and this paper deals with the isolation of alkaloids, for example, in *Solidago canadensis* structural elucidation mannopyranosides of indole alkaloids have been isolated as substances responsible for analgesic and anti-inflammatory activities of a plant (Li *et al*. 2009).

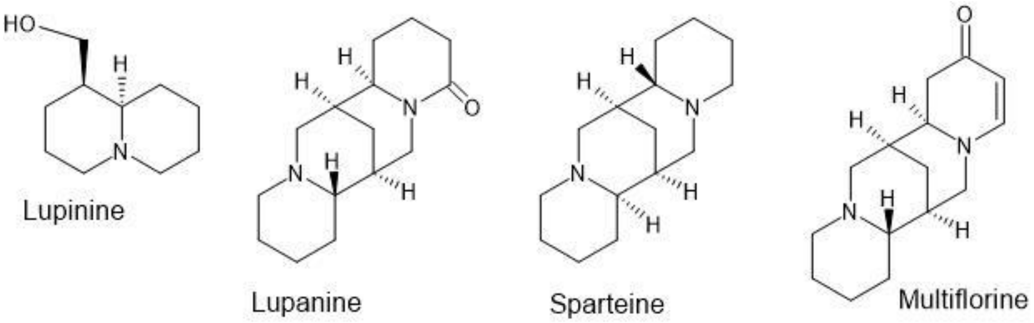


Fig. 8. Main alkaloids in seeds of *Lupinus albus*

Recently, quinolizidine alkaloids have been found in *Ulex europaeus*, a plant invasive in Chilean ecosystems (López-Rodríguez *et al*. 2023). In the shrub *Senecio pterophorus* invasive in Australia and Europe, a number of pyrrolizidine alkaloids have been found (Castells *et al*. 2014). A number of alkaloids have been found in aquatic invasive plants (Boppré and Colegate 2015).

OTHER APPLICATIONS OF INVASIVE PLANTS

Several invasive plant inflorescences, other parts, and rhizomes contain pigments that can be used for the coloration of fibers, paper, and other materials. For example, the orange extract of the Japanese knotweed rhizome has been used as a natural dye for screen printing inks. Study results confirmed the usefulness of the Japanese knotweed rhizome dye for printing, as intensive colors can be obtained, and the dye is resistant to fading (Klančnik 2021a). The dye obtained from the petals of the invasive plant *Impatiens glandulifera* (Himalayan balsam) has been used for screen printing on substrates such as woven fabrics, papers and other, recycled fibers (Klančnik 2021b). *Solidago canadensis* extracts also were used as concentrated solid plant dye and tested in standard dyeing experiments. The quality of coloring and color depth was found to be comparable with other plant extracts used for the colouring of natural fibers (Leitner *et al*. 2012). The roots of Japanese barberry (*Berberis thunbergii*), wineberry (*Rubus phoenicolasius*), oriental bittersweet (*Celastrus orbiculatus*) have been used as dyes, and the antimicrobial properties of colored fibers were tested (Flax *et al*. 2022).

Recently, invasive plant extracts have been source material for the synthesis of bio-nanoparticles (Nguyen *et al*. 2023). Several studies of invasive plant-mediated bio-nanoparticles have demonstrated excellent antibacterial, antifungal, anticancer, and antioxidant activities thus revealing new areas of invasive plant applications.

Japanese knotweed stems have been tested with respect to their mechanical properties and possibilities to use them for lightweight sandwich panels and other composite applications (Wunsch *et al*. 2022). Knotweed, goldenrod, and other invasive plant species have been studied as raw materials for papermaking, cooking, and textile production (Vrabič-Brodnjak and Možina 2022).

CONCLUSIONS: STRATEGIES FOR SUSTAINABLE MANAGEMENT OF INVASIVE PLANTS AS A RESOURCE FOR BIOECONOMY

Invasive plants worldwide are considered as one of the significant environmental problems, requiring actions to limit their spread. The character and significance of the plant invasion problem thus require actions to be taken to achieve progress in the management of invasive plants. At the same time, it is evident that the aims of invasive plant spread management will be more difficult to achieve without solving two problems: 1) in-depth knowledge of invasive plant phytochemistry and understanding of plant properties behind their invasiveness; 2) elaborating of invasive plant safe utilization methods, considering plant biomass as a resource. Innovation in invasive plant studies and their utilization methods is needed to advance understanding of their properties and develop economically rational processing approaches.

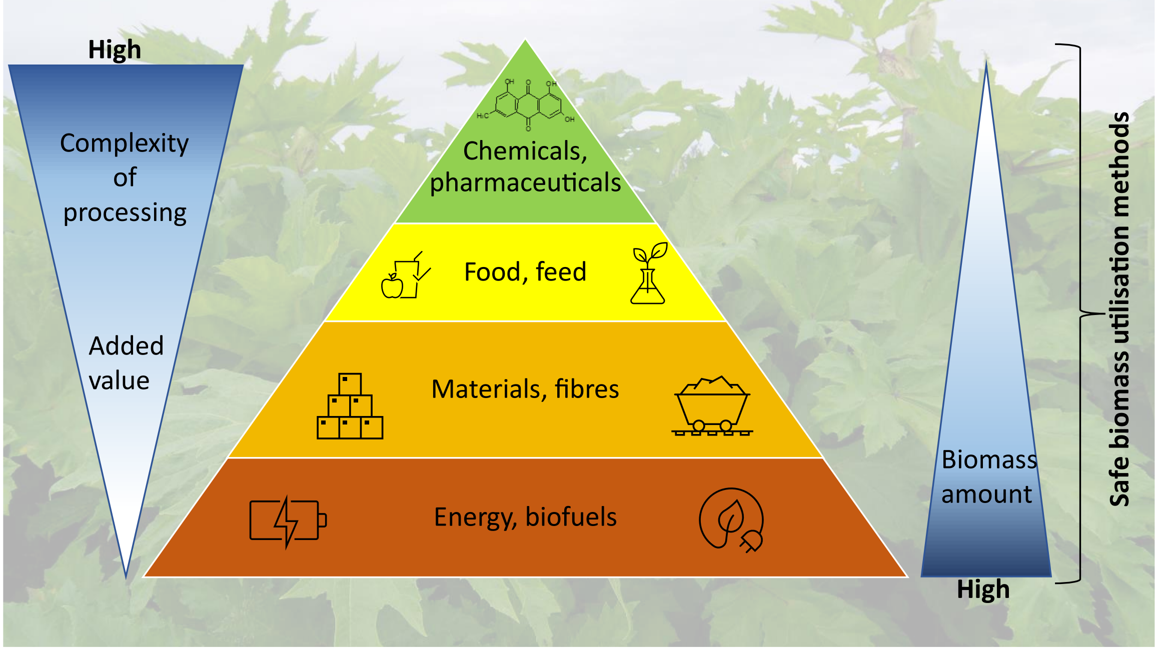


Fig. 9. Invasive plant biomass processing solutions according to bio-based value pyramid (after Davis *et al*. 2017, Stegmann *et al*. 2020)

A high number of studies on invasive plant phytochemistry reveal the high application potential of their biomass obtained after plant removal. The exploitation of invasive plant biomass for the production of energy, high-value-added products, and materials for diverse applications should consequently promote their management and eradication. In the development of invasive plant biomass utilization strategies, the bio-based value pyramid (Fig. 9) and the waste hierarchy should be considered. Many plants are producing high biomass and no valuable substances in their composition have been found thus biomass of such plants preferably can be processed to produce energy, fibers or materials for construction. On the other hand, plants with high concentrations of biologically active substances can be processed into value-added chemicals with application potential in food, cosmetics, pharmaceuticals and other high-added-value products. Of significance are also volumes of biomass produced, seasonal production character as well as possibilities to integrate invasive plant biomass processing into existing production lines. In general, invasive plant biomass has value and it cannot be wasted if we consider them as raw materials for use in the bioeconomy as these plants can be used to produce all kinds of biomass-derived products.

Already, pilot-scale production of active added-value extracts from invasive plants is elaborated and tested (Hren *et al*. 2023), and obtained results demonstrate possibilities of pilot-scale production of invasive plant extracts.

The decision of which control method to use depends heavily on the growth forms of invasive plant species, the local economic situation at restoration sites, and the resources available for control (Lindenmayer *et al.* 2015). Scientific sound strategies of invasive plant management will not only contribute to their spread limitation but also eradication by providing economic benefits. The success of invasive plant combatting efficiency will depend on invaded plant biomass, species, already existing biomass processing capacities, plants, technologies, and knowledge, but also on the identification of new application areas in the biomedicine, food industries, energy production, and other areas.

ACKNOWLEDGMENTS

This research was funded by the Latvia Science Council project “Chemical ecology of invasive plants as a tool to understand their competitiveness in NATURE, elaborate their control and develop new generation of herbicides”, “InnoHerb” (lzp-2022/1-0103).

REFERENCES CITED

Ahmed, M. B., Zhou, J. L., Ngo, H. H., and Guo, W. (2016). “Insight into biochar properties and its cost analysis,” *Biomass and Bioenergy* 84, 76-86. DOI: 10.1016/j.biombioe.2015.11.002

Akinyede, K. A., Ekpo, O. E., and Oguntibeju, O. O. (2020). “Ethnopharmacology, therapeutic properties and nutritional potentials of *Carpobrotus edulis*: A comprehensive review,” *Scientia Pharmaceutica* 88(3), article 39. DOI: 10.3390/scipharm88030039

Alam, S. N., Singh, B., and Guldhe, A. (2021). “Aquatic weed as a biorefinery resource for biofuels and value-added products: Challenges and recent advancements,” *Cleaner Engineering and Technology* 4, article 100235. DOI: 10.1016/j.clet.2021.100235

Aller, M. F. (2016). “Biochar properties: Transport, fate, and impact,” *Critical Reviews in Environmental Science and Technology* 46(14-15), 1183-1296. DOI: 10.1080/10643389.2016.1212368

Alperth, F., Melinz, L., Fladerer, J.-P., Bucar, F. (2021). “UHPLC Analysis of *Reynoutria japonica* Houtt. Rhizome preparations regarding stilbene and anthranoid composition and their antimycobacterial activity evaluation,” *Plants* 10, article 1809. DOI: 10.3390/plants10091809

Amini, S., Ghadiri, H., Chen, C., and Marschner, P. (2016). “Salt-affected soils, reclamation, carbon dynamics, and biochar: A review,” *Journal of Soils and Sediments* 16, 939-953. DOI: 10.1007/s11368-015-1293-1

Andreeva, L. V. (2020). "Sosnowsky hogweed: new ways to use," in: *IOP Conference Series: Earth and Environmental Science* 613(1), article 012006. IOP Publishing. DOI 10.1088/1755-1315/613/1/012006

Ashokkumar, V., Venkatkarthick, R., Jayashree, S., Chuetor, S., Dharmaraj, S., Kumar, G., Chen W.-H., and Ngamcharussrivichai, C. (2022). "Recent advances in lignocellulosic biomass for biofuels and value-added bioproducts – A critical review," *Bioresource Technology* 344, article 126195. DOI: 10.1016/j.biortech.2021.126195

Baležentienė, L. (2015). "Secondary metabolite accumulation and phytotoxicity of invasive species *Solidago canadensis* L. during the growth period," *Allelopathy Journal* 35, 217-226.

Baranová, B., Gruľová, D., Szymczak, K., Oboňa, J., and Moščáková, K. (2023). "Composition and repellency of *Solidago canadensis* L. (Canadian goldenrod) essential oil against aphids (Hemiptera: Aphididae)," *Allelopathy Journal* 58(1). 10.26651/allelo.j/2023-58-1-1418

Baranová, B., Troščáková-Kerpčárová, E., and Gruľová, D. (2022). "Survey of the *Solidago canadensis* L. morphological traits and essential oil production: Aboveground biomass growth and abundance of the invasive goldenrod appears to be reciprocally enhanced within the invaded stands," *Plants* 11(4), article 535. DOI: 10.3390/plants11040535

Beňová, B., Adam, M., Pavlíková, P., and Fischer, J. (2010). "Supercritical fluid extraction of piceid, resveratrol and emodin from Japanese knotweed," *The Journal of Supercritical Fluids* 51(3), 325-330. DOI: 10.1016/j.supflu.2009.10.009

Bensa, M., Glavnik, V., and Vovk, I. (2020). "Leaves of invasive plants—Japanese, Bohemian and giant knotweed—the promising new source of flavan-3-ols and proanthocyanidins," *Plants* 9(1), article 118. DOI: 10.3390/plants9010118

Bhattacharya, A., Sood, P., Citovsky, V. (2010). "The roles of plant phenolics in defence and communication during *Agrobacterium* and *Rhizobium* infection," *Molecular Plant Pathology* 11, 705-719. DOI: 10.3390/molecules16021486

Boppré, M., and Colegate, S. M. (2015). "Recognition of pyrrolizidine alkaloid esters in the invasive aquatic plant *Gymnocoronis spilanthoides* (Asteraceae)," *Phytochemical Analysis* 26(3), 215-225. DOI: 10.1002/pca.2555

Budzianowski, J., Thiem, B., and Kikowska, M. (2021). "*Solidago virgaurea* L.—Chemical composition, traditional and medicinal use, pharmaceutical properties, potential applications, and biotechnological studies—A review," in: *Medicinal Plants: Domestication, Biotechnology and Regional Importance,* H. M. Ekiert, K. G. Ramawat, J. Arora (eds.), Springer, pp. 661-692.

Cai, M. T., Zhou, Y., Ding, W. L., Huang, Y. H., Ren, Y. S., Yang, Z. Y., Zhang, L., Sun, F., Guo, H.B., Zhou, L.-Y. Ge, Y. W. *et al*. (2023). "Identification and localization of morphological feature-specific metabolites in *Reynoutria multiflora* roots," *Phytochemistry* 206, article 113527. DOI: 10.1016/j.phytochem.2022.113527

Canabarro, N., Soares, J. F., Anchieta, C. G., Kelling, C. S., and Mazutti, M. A. (2013). "Thermochemical processes for biofuels production from biomass," *Sustainable Chemical Processes* 1, 1-10. DOI: 10.1186/2043-7129-1-22

Carson, B. D., Lishawa, S. C., Tuchman, N. C., Monks, A. M., Lawrence, B. A., and Albert, D. A. (2018). "Harvesting invasive plants to reduce nutrient loads and produce bioenergy: an assessment of Great Lakes coastal wetlands," *Ecosphere* 9(6), article e02320. DOI: 10.1002/ecs2.2320

Castaneda-Loaiza, V., Placines, C., Rodrigues, M. J., Pereira, C., Zengin, G., Uysal, A., Jeko, J., Cziaky, Z., Reis, C. P., Gaspar, M. M., and Custódio, L. (2020). "If you cannot beat them, join them: Exploring the fruits of the invasive species *Carpobrotus edulis* (L.) NE Br as a source of bioactive products," *Industrial Crops and Products* 144, article 112005. DOI: 10.1016/j.indcrop.2019.112005

Castells, E., Mulder, P. P., and Pérez-Trujillo, M. (2014). "Diversity of pyrrolizidine alkaloids in native and invasive *Senecio pterophorus* (Asteraceae): Implications for toxicity," *Phytochemistry* 108, 137-146. DOI: 10.1016/j.phytochem.2014.09.006

Cha, J. S., Park, S. H., Jung, S. C., Ryu, C., Jeon, J. K., Shin, M. C., and Park, Y. K. (2016). "Production and utilization of biochar: A review", *Journal of Industrial and Engineering Chemistry* 40, 1-15. DOI: 10.1016/j.jiec.2016.06.002

Cucu, A.-A., Baci, G.-M., Dezsi, Ş., Nap, M.-E., Beteg, F.I., Bonta, V., Bobiş, O., Caprio, E., Dezmirean, D.S. (2021). "New approaches on Japanese knotweed (*Fallopia japonica*) bioactive compounds and their potential of pharmacological and beekeeping activities: Challenges and future directions," *Plants* 10(12), 2621. DOI: 10.3390/plants10122621

Davis, C. B., Aid, G., and Zhu, B. (2017). "Secondary resources in the bio-based economy: A computer assisted survey of value pathways in academic literature," *Waste and Biomass Valorization* 8(7), 2229-2246. DOI: 10.1007/s12649-017-9975-0

de Cortes Sánchez, M., Altares, P., Pedrosa, M. M., Burbano, C., Cuadrado, C., Goyoaga, C., Muzquiz, M., Jimenez-Martinez, C., and Dávila-Ortiz, G. (2005). "Alkaloid variation during germination in different lupin species," *Food Chemistry* 90(3), 347-355. DOI: 10.1016/j.foodchem.2004.04.008

De La Lastra, C. A., and Villegas, I. (2005). "Resveratrol as an anti-inflammatory and anti-aging agent: Mechanisms and clinical implications," *Molecular Nutrition & Food Research* 49(5), 405-430. DOI: 10.1002/mnfr.200500022

Demirbas, A. (2011). "Competitive liquid biofuels from biomass," *Applied Energy* 88(1), 17-28. DOI: 10.1016/j.apenergy.2010.07.016

Elshafie, H. S., Gruľová, D., Baranová, B., Caputo, L., De Martino, L., Sedlák, V., Camele, I., and De Feo, V. (2019). "Antimicrobial activity and chemical composition of essential oil extracted from *Solidago canadensis* L. growing wild in Slovakia," *Molecules* 24(7), article 1206. DOI: 10.3390/molecules24071206

Epanchin-Niell, R. S. (2017). "Economics of invasive species policy and management," *Biological Invasions* 19, 3333-3354. DOI: 10.1007/s10530-017-1406-4

European Commission (EC) Circular economy action plan. (2020). A new Circular Economy Action Plan For a cleaner and more competitive Europe.

European Commission, Directorate-General for Research and Innovation, Publications Office (2018) A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment: Updated bioeconomy strategy https://data.europa.eu/doi/10.2777/792130

European Commission. (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan. For a cleaner and more competitive Europe. Brussels, Belgium. COM/2020/98 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0098

European Commission. (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the

Committee of the Regions. EU Biodiversity Strategy for 2030. Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380

Fakudze, N. T., Sarbadhikary, P., George, B. P., and Abrahamse, H. (2023). "Ethnomedicinal uses, phytochemistry, and anticancer potentials of African medicinal fruits: A Comprehensive review," *Pharmaceuticals* 16(8), article 1117. DOI: 10.3390/ph16081117

Fałtynowicz, H., Kaczmarczyk, J., and Kułażyński, M. (2015). "Preparation and characterization of activated carbons from biomass material–giant knotweed (*Reynoutria sachalinensis*)," *Open Chemistry* 13(1), 000010151520150128. DOI: 10.1515/chem-2015-0128

Flax, B., Bower, A. H., Wagner-Graham, M. A., Bright, M., Cooper, I., Nguyen, W., Nunez, H., Purdy, B., Wahba, N., Savage T. *et al*. (2022). "Natural dyes from three invasive plant species in the United States," *Journal of Natural Fibers* 19(15), 10964-10978. DOI: 10.1080/15440478.2021.2002784

Fletcher, C. S., Westcott, D. A., Murphy, H. T., Grice, A. C., and Clarkson, J. R. (2015). "Managing breaches of containment and eradication of invasive plant populations," *Journal of Applied Ecology* 52(1), 59-68. DOI: 10.1111/1365-2664.12361

Fursenco, C., Calalb, T., Uncu, L., Dinu, M., and Ancuceanu, R. (2020). "*Solidago virgaurea* L.: A review of its ethnomedicinal uses, phytochemistry, and pharmacological activities," *Biomolecules* 10(12), article 1619. DOI:10.3390/biom10121619

Georgin, J., Franco, D. S., Netto, M. S., Gama, B. M., Fernandes, D. P., Sepúlveda, P., Silva, L. F. O., and Meili, L. (2022). "Effective adsorption of harmful herbicide diuron onto novel activated carbon from *Hovenia dulcis*," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 654, article 129900. DOI: 10.1016/j.colsurfa.2022.129900

Gioria, M., Hulme, P. E., Richardson, D. M., and Pyšek, P. (2023). "Why are invasive plants successful?" *Annual Review of Plant Biology* 74, 635-670. DOI: 10.1146/annurev-arplant-070522-071021

Grice, A. C., Murphy, H. T., Clarkson, J. R., Friedel, M. H., Fletcher, C. S., and Westcott, D. A. (2020). "A review and refinement of the concept of containment for the management of invasive plants," *Australian Journal of Botany* 68(8), 602-616. DOI: 10.1071/BT20092

Haubrock, P. J., Turbelin, A. J., Cuthbert, R. N, Novoa, A., Taylor, N.G., Angulo, E., Ballesteros-Mejia, L., Bodey, T. W., Capinha, C., Diagne, C., Essl, F., Golivets, M., Kirichenko, N., Kourantidou, M., Leroy, B., Renault, D., Verbrugge, L., and Courchamp, F. (2021). "Economic costs of invasive alien species across Europe," *NeoBiota* 67, 153-190. ff10.3897/neobiota.67.58196ff. ffhal-03329736

Hellmann, J. J., Byers, J. E., Bierwagen, B. G., and Dukes, J. S. (2008). "Five potential consequences of climate change for invasive species," *Conservation Biology* 22(3), 534-543. DOI: 10.1111/j.1523-1739.2008.00951-x

Hess, M. C., Mesléard, F., and Buisson, E. (2019). "Priority effects: Emerging principles for invasive plant species management," *Ecological Engineering* 127, 48-57. DOI: 10.1016/j.ecoleng.2018.11.011

Hinz, H. L., Winston, R. L., and Schwarzländer, M. (2019). "How safe is weed biological control? A global review of direct nontarget attack," *The Quarterly Review of Biology* 94(1), 1-27.

Hoddle, M. S. (2023). “A new paradigm: Proactive biological control of invasive insect pests,” *BioControl* 1-14. DOI: 10.1007/s10526-023-10206-5

Hren, R., Naumoska, K., Jug, U., Čuček, L., Likozar, B., Novak, U., and Vujanović, A. (2023). “Life cycle assessment of pilot-scale bio-refining of Invasive Japanese knotweed alien plant towards bio-based bioactive compounds,” *Processes* 11(5), article 1393. DOI: 10.3390/pr11051393

Jo, H., Lee, H. J., Kim, C. Y., Son, J. K., and Jung, S. H. (2013). “8-Hydroxycalamenene isolated from the rhizomes of *Reynoutria elliptica* exerts neuroprotective effects both in vitro and in vivo,” *Food and Chemical Toxicology* 51, 231-241. DOI: 10.1016/j.fct.2012.09.025

Joseph, B., Hensgen, F., and Wachendorf, M. (2020). “Life cycle assessment of bioenergy production from mountainous grasslands invaded by lupine (*Lupinus polyphyllus* Lindl.),” *Journal of Environmental Management* 275, article 111182. DOI: 10.1016/j.jenvman.2020.111182

Kalisz, S., Kivlin, S. N., and Bialic-Murphy, L. (2021). “Allelopathy is pervasive in invasive plants,” *Biological Invasions* 23, 367-371. DOI:10.1007/s10530-020-02383-6

Kanda, H., Oishi, K., Machmudah, S., Wahyudiono, and Goto, M. (2021). “Ethanol-free extraction of resveratrol and its glycoside from Japanese knotweed rhizome by liquefied dimethyl ether without pretreatments,” *Asia-Pacific Journal of Chemical Engineering* 16(2), article e2600. DOI: 10.1002/apj.2600

Kato-Noguchi, H., Kato, M. (2023). “Evolution of the secondary metabolites in invasive plant species *Chromolaena odorata* for the defense and allelopathic functions,” *Plants* 12, 521. DOI: 10.3390/plants12030521

Kaur, M., Kumar, M., Singh, D., Sachdeva, S., and Puri, S. K. (2019). “A sustainable biorefinery approach for efficient conversion of aquatic weeds into bioethanol and biomethane,” *Energy Conversion and Management* 187, 133-147. DOI: 10.1016/j.enconman.2019.03.018

Khan, M. K., Karnpanit, W., Nasar-Abbas, S. M., Huma, Z. E., and Jayasena, V. (2015). “Phytochemical composition and bioactivities of lupin: A review,” *International Journal of Food Science and Technology* 50(9), 2004-2012. DOI: 10.1111/ijfs.12796

Klančnik, M. (2021a). “Screen printing with natural dye extract from Japanese knotweed rhizome,” *Fibers and Polymers* 22(9), 2498-2506. DOI: 10.1007/s12221-021-0955-4

Klančnik, M. (2021b). “Printing with natural dye extracted from *Impatiens glandulifera* royle,” *Coatings* 11(4), 445. DOI: 10.3390/coatings11040445

Koley, A., Mukhopadhyay, P., Gupta, N., Singh, A., Ghosh, A., Show, B. K., Thakur, R. G., Chaudhury, S., Hazra, A. K., and Balachandran, S. (2023). “Biogas production potential of aquatic weeds as the next-generation feedstock for bioenergy production: A review,” *Environmental Science and Pollution Research* 1-31. DOI: 10.1007/s11356-023-30191-7

Kraujalienė, V., Pukalskas, A., and Venskutonis, P. R. (2017). “Biorefining of goldenrod (*Solidago virgaurea* L.) leaves by supercritical fluid and pressurized liquid extraction and evaluation of antioxidant properties and main phytochemicals in the fractions and plant material,” *Journal of Functional Foods* 37, 200-208. DOI: 10.1016/j.jff.2017.07.049

Lachowicz, S., and Oszmiański, J. (2019). “Profile of bioactive compounds in the morphological parts of wild *Fallopia japonica* (Houtt) and *Fallopia sachalinensis* (F. Schmidt) and their antioxidative activity,” *Molecules 24*(7), article 1436. DOI: 10.3390/molecules24071436

Lakienko, G. P., Bobyleva, Z. V., Apostolova, M. O., Sultanova, Y. V., Dyakonov, A. K., Zakharkin, M. V., Sobolev, N. A.; Alekseeva, A. M., Drozhzhin, O. A., Abakumov, A. M., and Antipov E. V. (2022). “Sosnowskyi hogweed based hard carbons for sodium-ion batteries,” *Batteries* 8, article 131. DOI: 10.3390/ batteries8100131

Łapczyńska-Kordon, B., Ślipek, Z., Słomka-Polonis, K., Styks, J., Hebda, T., and Francik, S. (2022). “Physicochemical properties of biochar produced from goldenrod plants,” *Materials* 15(7), article 2615. doi.org/10.3390/ma15072615

Lapuerta, M., Hernández, J. J., Pazo, A., and López, J. (2008). “Gasification and co-gasification of biomass wastes: Effect of the biomass origin and the gasifier operating conditions,” *Fuel processing technology* 89(9), 828-837. DOI: 10.1016/j.fuproc.2008.02.001

Lazarotto, J. S., Schnorr, C., Georgin, J., Franco, D. S., Netto, M. S., Piccilli, D. G., Silva, L. F. O., Rhoden, C. R. B., and Dotto, G. L. (2022). “Microporous activated carbon from the fruits of the invasive species *Hovenia dulcis* to remove the herbicide atrazine from waters,” *Journal of Molecular Liquids* 364, article 120014. DOI: 10.1016/j.molliq.2022.120014

Lee, D., Nam, H., Seo, M. W., Lee, S. H., Tokmurzin, D., Wang, S., and Park, Y. K. (2022). “Recent progress in the catalytic thermochemical conversion process of biomass for biofuels,” *Chemical Engineering Journal* 447, article 137501. DOI: 10.1016/j.cej.2022.137501

Leitner, P., Fitz-Binder, C., Mahmud-Ali, A., and Bechtold, T. (2012). “Production of a concentrated natural dye from Canadian Goldenrod (*Solidago canadensis*) extracts,” *Dyes and Pigments* 93(1-3), 1416-1421. DOI: 10.1016/j.dyepig.2011.10.008

Li, G., and Ishikawa, Y. (2006). “Leaf epicuticular wax chemicals of the Japanese knotweed *Fallopia japonica* as oviposition stimulants for *Ostrinia latipennis*,” *Journal of Chemical Ecology* 32, 595-604. DOI: 10.1007/s10886-005-9022-7

Li, Y., Zhao, Q., Hu, J., Zou, Z., He, X., Yuan, H., and Shi, X. (2009). “Two new quinoline alkaloid mannopyranosides from *Solidago canadensis*,” *Helvetica Chimica Acta* 92(5), 928-931.

Lian, W., Yang, L., Joseph, S., Shi, W., Bian, R., Zheng, J., Li, L., Shan, S., and Pan, G. (2020). “Utilization of biochar produced from invasive plant species to efficiently adsorb Cd (II) and Pb (II),” *Bioresource Technology* 317, article 124011. DOI: 10.1016/j.biortech.2020.124011

Liang, J., Wang, L., Shi, Y., Lin, S., Evrendilek, F., Huang, W., Chen, Z., Zhong, S., Yang, Z., Yang, C., and Liu, J. (2023). “Air and oxy-fuel incineration disposal of invasive biomass water lettuce (*Pistia stratiotes* L.): Performance, kinetics, flue gas emissions, mechanisms, and ash characteristics,” *Biomass Conversion and Biorefinery* 1-20. DOI: 10.1007/s13399-023-04853-y

Liao, R., Gao, B., and Fang, J. (2013). “Invasive plants as feedstock for biochar and bioenergy production,” *Bioresource Technology* 140, 439-442. DOI: 10.1016/j.biortech.2013.04.117

Lindenmayer, D. B., Wood, J., MacGregor, C., Buckley, Y. M., Dexter, N., Fortescue, M., Hobbs R.J. and Catford, J. A. (2015). “A long-term experimental case study of the ecological effectiveness and cost effectiveness of invasive plant management in achieving conservation goals: Bitou Bush control in Booderee National Park in Eastern Australia,” *PLoS One* 10(6), article e0128482. DOI: 10.1371/journal.pone.0128482

López-Rodríguez, A., Hernández, M., Carrillo-Galvez, A., Becerra, J., and Hernández, V. (2023). "Phytotoxic activity of *Ulex europaeus*, an invasive plant on Chilean ecosystems: Separation and identification of potential allelochemicals," *Natural Product Research* 37(5), 769-775. DOI: 10.1080/14786419.2022.2081851

Lu, J., and Gao, X. (2021). "Biogas: Potential, challenges, and perspectives in a changing China," *Biomass and Bioenergy* 150, article 106127. DOI: 10.1016/j.biombioe.2021.106127

Lu, J., and Zhang, Y. (2013). "Spatial distribution of an invasive plant Spartina alterniflora and its potential as biofuels in China," *Ecological Engineering* 52, 175-181. DOI: 10.1016/j.ecoleng.2012.12.107

Magalhães, S. C., Fernandes, F., Cabrita, A. R., Fonseca, A. J., Valentão, P., and Andrade, P. B. (2017). "Alkaloids in the valorization of European *Lupinus* spp. seeds crop," *Industrial Crops and Products* 95, 286-295. DOI: 10.1016/j.indcrop.2016.10.033

Marksa, M., Zymone, K., Ivanauskas, L., Radušienė, J., Pukalskas, A., and Raudone, L. (2020). "Antioxidant profiles of leaves and inflorescences of native, invasive and hybrid *Solidago* species," *Industrial Crops and Products* 145, article 112123. DOI: 10.1016/j.indcrop.2020.112123

Matarrese, E., and Renna, M. (2023). "Prospects of hogweed (*Heracleum sphondylium* L.) as a new horticultural crop for food and non-food uses: A review," *Horticulturae* 9(2), article 246. DOI: 10.3390/horticulturae9020246

Metličar, V., and Albreht, A. (2022). "Esterification of lutein from Japanese knotweed waste gives a range of lutein diester products with unique chemical stability," *ACS Sustainable Chemistry and Engineering* 10(18), 6072-6081. DOI: 10.1021/acssuschemeng.2c01241

Metličar, V., Vovk, I., and Albreht, A. (2019). "Japanese and bohemian knotweeds as sustainable sources of carotenoids," *Plants* 8(10), article 384. DOI: 10.3390/plants8100384

Mezentsev, S. D. (2023, March). "Hogweed Sosnowski as a useful plant for the production of bioethanol," in: *IOP Conference Series: Earth and Environmental Science* 1154(1), article 012047). IOP Publishing. DOI:10.1088/1755-1315/1154/1/012047

Míguez, C., Cancela, Á., Álvarez, X., and Sánchez, Á. (2022). "The reuse of bio-waste from the invasive species *Tradescantia fluminensis* as a source of phenolic compounds," *Journal of Cleaner Production* 336, article 130293. DOI: 10.1016/j.jclepro.2021.130293

Mikulic-Petkovsek, M., Veberic, R., Hudina, M., and Misic, E. (2022). "HPLC-DAD-MS Identification and quantification of phenolic components in Japanese knotweed and American pokeweed extracts and their phytotoxic effect on seed germination," *Plants* 11(22), article 3053. DOI: 10.3390/plants11223053

Mudimba, T. N., and Nguta, J. M. (2019). "Traditional uses, phytochemistry and pharmacological activity of *Carpobrotus edulis*: A global perspective," *The Journal of Phytopharmacology* 8, 111-116. DOI: 10.31254/phyto.2019.8305

Nawrot-Hadzik, I., Granica, S., Domaradzki, K., Pecio, Ł., and Matkowski, A. (2018). "Isolation and determination of phenolic glycosides and anthraquinones from rhizomes of various *Reynoutria* species," *Planta Medica* 84(15), 1118-1126. DOI: 10.1055/a-0605-3857

Nguyen, D. T. C., Van Tran, T., Nguyen, T. T. T., Nguyen, D. H., Alhassan, M., and Lee, T. (2023). "New frontiers of invasive plants for biosynthesis of nanoparticles towards biomedical applications: A review," *Science of the Total Environment* 857, article 159278. DOI: 10.1016/j.scitotenv.2022.159278

Nguyen, X. C., Nguyen, T. T. H., Nguyen, T. H. C., Van Le, Q., Vo, T. Y. B., Tran, T. C. P., La, D. D., Kumar, H., Nguyen, V. K., Nguyen, D. D., *et al*. (2021). "Sustainable carbonaceous biochar adsorbents derived from agro-wastes and invasive plants for cation dye adsorption from water," *Chemosphere* 282, and 131009. DOI: 10.1016/j.chemosphere.2021.131009

Parshetti, G. K., Hoekman, S. K., and Balasubramanian, R. (2013). "Chemical, structural and combustion characteristics of carbonaceous products obtained by hydrothermal carbonization of palm empty fruit bunches," *Bioresource Technology* 135, 683-689. DOI: 10.1016/j.biortech.2012.09.042

Pereira, A., Ramos, F., and Sanches Silva, A. (2022). "Lupin (*Lupinus albus* L.) seeds: Balancing the good and the bad and addressing future challenges," *Molecules* 27(23), and 8557. DOI: 10.3390/molecules27238557

Pereira, C. G., Neng, N. R., and Custódio, L. (2023). "From threat to opportunity: harnessing the invasive *Carpobrotus edulis* (L.) NE Br for nutritional and phytotherapeutic valorization amid seasonal and spatial variability," *Marine Drugs* 21(8), article 436. DOI: 10.3390/md21080436

Pérez, A., Ruiz, B., Fuente, E., Calvo, L. F., and Paniagua, S. (2021). "Pyrolysis technology for *Cortaderia selloana* invasive species. Prospects in the biomass energy sector," *Renewable Energy* 169, 178-190. DOI: 10.1016/j.renene.2021.01.015

Pérez, E. A., Téllez, T. J., Maqueda, S. R., Linares, P. J. C., Pardo, F. M. V., Medina, P. L. R., Moreno, J. L., Gallegoo, F. L., Cortes, J. G., and Guzmán, J. M. S. (2015). "Seed germination and risks of using the invasive plant *Eichhornia crassipes* (Mart.) Solms-Laub. (water hyacinth) for composting, ovine feeding and biogas production," *Acta Botanica Gallica* 162(3), 203-214. DOI: 10.1080/12538078.2015.1056227

Peter, A., Žlabur, J. Š., Šurić, J., Voća, S., Purgar, D. D., Pezo, L., and Voća, N. (2021). "Invasive plant species biomass—Evaluation of functional value," *Molecules* 26(13), article 3814. DOI: 10.3390/molecules26133814

Pisupati, S. V., and Tchapda, A. H. (2015). "Thermochemical processing of biomass," *Advances in Bioprocess Technology* 277-314. DOI: 10.1007/978-3-319-17915-5_15

Quideau, S., Deffieux, D., Douat-Casassus, C., and Pouységu, L. (2011). "Plant polyphenols: Chemical properties, biological activities, and synthesis," *Angewandte Chemie International Edition* 50(3), 586-621. DOI: 10.1002/anie.201000044

Quinty, V., Nasreddine, R., Colas, C., Launay, A., Nehmé, R., El-Khiraoui, A., Piot, C., Draye, M., Destandau, E., da Silva, D., and Chatel, G. (2023). "Antioxidant and anti-lipase capacities from the extracts obtained from two invasive plants: *Ambrosia artemisiifolia* and *Solidago canadensis*," *Food Bioscience* 55, article 103069. DOI: 10.1016/j.fbio.2023.103069

Radušienė, J., Karpavičienė, B., Marksa, M., Ivanauskas, L., and Raudonė, L. (2022). "Distribution patterns of essential oil terpenes in native and invasive *Solidago* species and their comparative assessment," *Plants* 11(9), article 1159. DOI: 10.3390/plants11091159

Radusiene, J., Marska, M., Ivanauskas, L., Jakstas, V., and Karpaviciene, B. (2015). "Assessment of phenolic compound accumulation in two widespread goldenrods," *Industrial Crops and Products* 63, 158-166. DOI: 10.1016/j.indcrop.2014.10.015

Rai, P. K., and Singh, J. S. (2020). "Invasive alien plant species: Their impact on environment, ecosystem services and human health," *Ecological indicators* 111, article 106020. DOI: 10.1016/j.ecolind.2019.106020

Ramli, N. N., and Epplin, F. M. (2017). "Cost to produce liquid biofuel from invasive eastern redcedar biomass," *Biomass and Bioenergy* 104, 45-52. DOI: 10.1016/j.biombioe.2017.06.008

Ramos, A., Monteiro, E., and Rouboa, A. (2022). "Biomass pre-treatment techniques for the production of biofuels using thermal conversion methods – A review," *Energy Conversion and Management* 270, article 116271. DOI: 10.1016/j.enconman.2022.116271

Reinhard, H., Rupp, H., Sager, F., Streule, M., and Zoller, O. (2006). "Quinolizidine alkaloids and phomopsins in lupin seeds and lupin containing food," *Journal of Chromatography A* 1112(1-2), 353-360. DOI: 10.1016/j.chroma.2005.11.079

Resta, D., Boschin, G., D'Agostina, A., and Arnoldi, A. (2008). "Evaluation of total quinolizidine alkaloids content in lupin flours, lupin-based ingredients, and foods," *Molecular Nutrition and Food Research* 52(4), 490-495. DOI: 10.1002/mnfr.200700206

Reza, M. S., Afroze, S., Kuterbekov, K., Kabyshev, A., Zh. Bekmyrza, K., Taweekun, J., Ja'afar, F., Saifullah Abu Bakar, M., Azad, A.K., Roy, H., *et al*. (2023). "Ex situ catalytic pyrolysis of invasive *Pennisetum purpureum* grass with activated carbon for upgrading Bio-Oi," *Sustainability* 15(9), article 7628. DOI: 10.3390/su15097628

Reza, M. S., Ahmed, A., Caesarendra, W., Abu Bakar, M. S., Shams, S., Saidur, R., Aslfattahi N, and Azad, A. K. (2019). "*Acacia holosericea*: An invasive species for bio-char, bio-oil, and biogas production," *Bioengineering* 6(2), 33. DOI: 10.3390/bioengineering6020033

Rezania, S., Ponraj, M., Din, M. F. M., Songip, A. R., Sairan, F. M., and Chelliapan, S. (2015). "The diverse applications of water hyacinth with main focus on sustainable energy and production for new era: An overview," *Renewable and Sustainable Energy Reviews* 41, 943-954. DOI: 10.1016/j.rser.2014.09.006

Richardson, D. M., and Blanchard, R. (2011). "Learning from our mistakes: Minimizing problems with invasive biofuel plants," *Current Opinion in Environmental Sustainability* 3(1-2), 36-42. DOI: 10.1016/j.cosust.2010.11.006

Sakhiya, A. K., Anand, A., and Kaushal, P. (2020). "Production, activation, and applications of biochar in recent times," *Biochar* 2, 253-285. DOI: 10.1007/s42773-020-00047-1

Shahrtash, M., and Brown, S. P. (2021). "A path forward: promoting microbial-based methods in the control of invasive plant species," *Plants* 10(5), article 943. DOI: 10.3390/plants10050943

Shelepova, O., Vinogradova, Y., Vergun, O., Grygorieva, O., and Brindza, J. (2019). "Invasive *Solidago canadensis* L. as a resource of valuable biological compounds," *Slovak Journal of Food Sciences* 13(1), 280-286. DOI: 10.5219/1125

Singla, R. K., Dubey, A. K., Garg, A., Sharma, R. K., Fiorino, M., Ameen, S. M., Haddad, M. A., and Al-Hiary, M. (2019). "Natural polyphenols: Chemical classification, definition of classes, subcategories, and structures," *Journal of AOAC International* 102(5), 1397-1400. DOI: 10.1093/jaoac/102.5.1397

Šoln, K., Horvat, M., Iskra, J., and Dolenc Koce, J. (2022). "Inhibitory effects of methanol extracts from *Fallopia japonica* and *F.*× *bohemica* rhizomes and selected phenolic compounds on radish germination and root growth," *Chemoecology* 32(4-5), 159-170. DOI: 10.1007/s00049-022-00375-

Song, J. H., Kim, S., Yu, J. S., Park, D. H., Kim, S. Y., Kang, K. S., Lee, S., and Kim, K. H. (2019). "Procyanidin B2 3 ″-O-gallate isolated from *Reynoutria elliptica* prevents glutamate-induced HT22 cell death by blocking the accumulation of intracellular reactive oxygen species," *Biomolecules* 9(9), article 412. DOI: 10.3390/biom9090412

Srivastava, R. K., Shetti, N. P., Reddy, K. R., Kwon, E. E., Nadagouda, M. N., and Aminabhavi, T. M. (2021). "Biomass utilization and production of biofuels from carbon neutral materials," *Environmental Pollution* 276, article 116731. DOI: 10.1016/j.envpol.2021.116731

Stefanowicz, A. M., Frąc, M., Oszust, K., and Stanek, M. (2022). "Contrasting effects of extracts from invasive *Reynoutria japonica* on soil microbial biomass, activity, and community structure," *Biological Invasions* 24(10), 3233-3247. DOI: 10.1007/s10530-022-02842-2

Stefanowicz, A. M., Kapusta, P., Stanek, M., Frąc, M., Oszust, K., Woch, M. W., and Zubek, S. (2021). "Invasive plant *Reynoutria japonica* produces large amounts of phenolic compounds and reduces the biomass but not activity of soil microbial communities," *Science of the Total Environment* 767, article 145439. DOI: 10.1016/j.scitotenv.2021.145439

Stegmann, P., Londo, M., and Junginger, M. (2020). "The circular bioeconomy: Its elements and role in European bioeconomy clusters," *Resources, Conservation and Recycling: X*, 6, article 100029. DOI: 10.1016/j.rcrx.2019.100029

Suleymanova, F., Nesterova, O., and Matyushin, A. (2019). "HPLC quantification of hydroxycinnamic and organic acids of Canadian Goldenrod (*Solidago canadensis* L.)," *Pharmacognosy Journal* 11(2). DOI: 10.5530/pj.2019.11.62

Teem, J. L., Alphey, L., Descamps, S., Edgington, M. P., Edwards, O., Gemmell, N., Harvey-Samuel, T., Melnick, R.L., Oh, K.P., Roberts, A. *et al*. (2020). "Genetic biocontrol for invasive species," *Frontiers in Bioengineering and Biotechnology* 8, article 452. DOI: 10.3389/fbioe.2020.00452

The European Green Deal (2020) Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions. COM/2019/640 finalhttps://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640

The Invasive Alien Species Regulation (2014) Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1483614313362anduri=CELEX:32014R1143

Thiébaut, G., Tarayre, M., and Rodríguez-Pérez, H. (2019). "Allelopathic effects of native versus invasive plants on one major invader," *Frontiers in Plant Science* 10, article 854. DOI: 10.3389/fpls.2019.00854

Trigui, E., Ben Hassen, H., Zaghden, H., Trigui, M., and Achour, S. (2023). "A bioinformatic study on the potential anti-vitiligo activity of a *Carpobrotus edulis* compound," *Molecules* 28(22), article 7545. DOI: 10.3390/molecules28227545

Uzelac, M., Sladonja, B., Šola, I., Dudaš, S., Bilić, J., Famuyide, I. M., McGaw, L. J., Eloff, J. N., Mikulic-Petkovsek, M., and Poljuha, D. (2023). "Invasive alien species as a potential source of phytopharmaceuticals: Phenolic composition and antimicrobial and cytotoxic activity of *Robinia pseudoacacia* L. leaf and flower extracts," *Plants* 12(14), article 2715. DOI: 10.3390/plants12142715

Van Meerbeek, K., Appels, L., Dewil, R., Calmeyn, A., Lemmens, P., Muys, B., and Hermy, M. (2015). "Biomass of invasive plant species as a potential feedstock for bioenergy production," *Biofuels, Bioproducts and Biorefining* 9(3), 273-282. DOI: 10.1002/bbb.1539

Vera, I., Goosen, N., Batidzirai, B., Hoefnagels, R. and van der Hilst, F. (2022). "Bioenergy potential from invasive alien plants: Environmental and socio-economic impacts in Eastern Cape, South Africa," *Biomass and Bioenergy* 158, article 106340. DOI: 10.1016/j.biombioe.2022.106340

Voloshin, R. A., Rodionova, M. V., Zharmukhamedov, S. K., Veziroglu, T. N., and Allakhverdiev, S. I. (2016). "Biofuel production from plant and algal biomass," *International Journal of Hydrogen Energy* 41(39), 17257-17273. DOI: 10.1016/j.ijhydene.2016.07.084

Vrabič-Brodnjak, U., and Možina, K. (2022). "Invasive alien plant species for use in paper and packaging materials," *Fibers* 10(11), article 94. DOI: 10.3390/fib10110094

Wang, J., Zhao, M., Zhang, J., Zhao, B., Lu, X., and Wei, H. (2021). "Characterization and utilization of biochars derived from five invasive plant species *Bidens pilosa* L., *Praxelis clematidea*, *Ipomoea cairica*, *Mikania micrantha* and *Lantana camara* L. for Cd^{2+} and Cu^{2+} removal," *Journal of Environmental Management* 280, article 111746. DOI: 10.1016/j.jenvman.2020.111746

Weber, K., and Quicker, P. (2018). "Properties of biochar," *Fuel* 217, 240- 261. DOI: 10.1016/j.fuel.2017.12.054

Weidlich, E. W., Flórido, F. G., Sorrini, T. B., and Brancalion, P. H. (2020). "Controlling invasive plant species in ecological restoration: A global review," *Journal of Applied Ecology* 57(9), 1806-1817. DOI: 10.1111/1365-2664.13656

Wiatrowska, B. M., Wawro, A., Gieparda, W., and Waliszewska, B. (2022). "Bioethanol production potential and other biomass energy properties of invasive *Reynoutria, Solidago,* and *Spiraea* plants," *Forests* 13(10), article 1582. DOI: 10.3390/f13101582

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., and Joseph, S. (2010). "Sustainable biochar to mitigate global climate change," *Nature Communications* 1(1), 56. DOI: 10.1038/ncomms1053

Woźniak, D., Ślusarczyk, S., Domaradzki, K., Dryś, A., and Matkowski, A. (2018). "Comparison of polyphenol profile and antimutagenic and antioxidant activities in two species used as source of *Solidaginis herba*–goldenrod," *Chemistry and Biodiversity* 15(4), article e1800023. DOI: 10.1002/cbdv.201800023 C

Wrona, O., Rafińska, K., Możeński, C., and Buszewski, B. (2019). "Optimization and upscaling of the supercritical carbon dioxide extraction of *Solidago gigantea* Ait. of an industrial relevance," *Industrial Crops and Products* 142, article 111787. DOI: 10.1016/j.indcrop.2018.12.050

Wunsch, T., Kelch, M., Röhl, V., Wieland, H., Labisch, S., van den Oever, M., Huber, T., and Müssig, J. (2022). "Structure-property relationships in Japanese knotweed–The potential of using the stem for composite applications," *Industrial Crops and Products* 186, article 115191. DOI: 10.1016/j.indcrop.2022.115191

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Gao, B. (2020). "Biochar technology in wastewater treatment: A critical review," *Chemosphere* 252, 126539. DOI: 10.1016/j.chemosphere.2020.126539

Yang, L., Deng, Y., Shu, Z., Chen, Q., Yang, H., and Tan, X. (2022). "Application of invasive plants as biochar precursors in the field of environment and energy storage," *Frontiers in Environmental Science* 10, 902915. DOI: 10.3389/fenvs.2022.902915

Yang, S. Y., and Kang, M. K. (2020). "Biocompatibility and antimicrobial activity of *Reynoutria elliptica* extract for dental application," *Plants* 9(6), 670. DOI: 10.3390/plants9060670

Zekič, J., Vovk, I., and Glavnik, V. (2020). "Extraction and analyses of flavonoids and phenolic acids from Canadian goldenrod and giant goldenrod," *Forests* 12(1), article 40. DOI: 10.3390/f12010040

Zhu, P., Abdelaziz, O. Y., Hulteberg, C. P., and Riisager, A. (2020). "New synthetic approaches to biofuels from lignocellulosic biomass," *Current Opinion in Green and Sustainable Chemistry* 21, 16-21. DOI: 10.1016/j.cogsc.2019.08.005

Zhu, X., Yi, Y., Huang, L., Zhang, C., and Shao, H. (2021). "Metabolomics reveals the allelopathic potential of the invasive plant *Eupatorium adenophorum*," *Plants* 10(7), article 1473. DOI: 10.3390/plants10071473

Zihare, L., Soloha, R., and Blumberga, D. (2018). "The potential use of invasive plant species as solid biofuel by using binders," *Agronomy Research* 16(3), 923-935, DOI: 10.15159/AR.18.102

Zubek, S., Kapusta, P., Stanek, M., Woch, M. W., Błaszkowski, J., and Stefanowicz, A. M. (2022). "*Reynoutria japonica* invasion negatively affects arbuscular mycorrhizal fungi communities regardless of the season and soil conditions," *Applied Soil Ecology* 169, article 104152. DOI: 10.1016/j.apsoil.2021.104152

Article submitted: January 17, 2024; Peer review completed: April 30, 2024; Revised version received: May 3, 2024; Accepted: August 3, 2024; Published: August 16, 2024.
DOI: 10.15376.biores.19.4.Klavins