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Full Length Article

New energy crop alternatives for Northern Europe: Yield, chemical and physical properties of Giant knotweed (*Fallopia sachalinensis* var. 'Igniscum') and Virginia mallow (*Sida hermaphrodita)*

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ABSTRACT

New energy crops adapted to northern conditions of Europe can broaden the portfolio of agricultural based biofuel options in an area with currently few alternatives. This study evaluates two energy crops, giant knotweed (*Fallopia sachalinensis* var. 'Igniscum') and Virginia mallow (*Sida hermaphrodita*), as possible biomass feedstocks for biofuels in southern Finland. The collected data includes yield productivity, physical and chemical properties, and energy content. The dry matter yield of giant knotweed ranges from 5.41 $odt{\cdot}ha^{-1}$ to 27.67 $odt{\cdot}ha^{-1}$, whereas Virginia mallow ranges from 6.72 $odt{\cdot}ha^{-1}$ to 16.72 $odt{\cdot}ha^{-1}$. Pellets from both crops meet the requirements regarding standards. Giant knotweed presents a bulk density of 677.71 $kg{\cdot}m^{-3}$ and Virginia mallow 725.18 $kg{\cdot}m^{-3}$. The results of mechanical durability of giant knotweed do not exceed the minimum threshold of the standards, with 96.73 w-%, while Virginia mallow is 92.86 w-%. The analysis of the ash content results in 1.5% for giant knotweed and 2.19% for Virginia mallow. The quantities of chlorine (Cl) and sulphur (S) are below the recommended thresholds. Finally, the energy content with moisture content of 5 w-% of giant knotweed and Virginia mallow were 19.97 $MJ{\cdot}kg^{-1}$ and 19.68 $MJ{\cdot}kg^{-1}$, respectively. Both crops prove are valid alternatives in the climatic and soil conditions of Northern Europe.

1. Introduction

Biomass plays a fundamental role in the current energy consumption patterns at European level; the use of biomass helps limit the use of conventional fuels and benefits reducing carbon emissions, among others. However, current trends in wood and biofuels demand translate into an intensification of existing biomass resources. The impacts of the intensive use of fossil fuels have led to the research and development of renewable resources. Renewable biomass resources provide alternative and promising options for localized energy production [1].

In Northern Europe, forest wood already plays an important role in the gross inland consumption of renewable energy; at the same time, there is less margin to increase biomass production from forest sources, as the reported fellings are already close to the estimated maximum potential, making difficult to accommodate increases in wood demand due to increasing marginal costs [2]. As an alternative feedstock, several cultivations have been established at a commercial level in Northern Europe for the production of biomass for energy. In Sweden, willow plantations have been established since the 1980s, followed by a rapid expansion [3], and, to a lesser extent, poplar and hybrid aspen [4] and reed canary grass [5]. In Denmark, willow and miscanthus were established since the 1990s [6], and in Finland, reed canary grass was established in the 2000s [7] in all cases reaching a substantial amount of area planted and becoming commercial alternatives.

Whereas energy crops achieved a degree of acceptance by the farmers, there were limitations that precluded a full scale implementation [8]; for instance, the area of willow plantations in Sweden has been reduced from over 15 000 ha to ca. 8000 ha in a decade [9] and the area of reed canary grass in Finland has been reduced from nearly 20 000 ha to 3000 ha in the same period [10]. In both cases, one single option dominated the energy crop production, and their reduction affected the whole sector, which underlines the need to provide alternatives that could enlarge the portfolio of energy crops. Successful candidates in Northern Europe should be resistant to frost and low temperatures, be

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adapted to mechanization, deliver high yields, and be economically profitable. In addition, since most of the fertile agricultural areas are being considered primarily for food production, these cultivations must be tolerant to low soil qualities.

New energy crops should also demonstrate good properties concerning heat values, and physical and mechanical properties that enable higher added value uses, such as pellets or briquettes, which are particularly relevant in the area. The higher energy content and the higher density of pellets have bilateral benefits for transportation and the end-user, allowing a full scale trade of wood-based biofuels at European level [11]. Pelletizing has become a popular option, and Sweden and Finland have a combined production of nearly 2 M t of pellets [12]. In fact, the uncertainty of feedstock supply was listed as a potential hinther to the future development of pellet production in the area, and new cultivations to supply raw material were proposed as a solution [13]. In fact, advances in torrefaction [14] and more recently, industrial implementation of hydrothermal carbonization [15], are being demonstrated or first applications are under construction, increasing the pressure on new biomass feedstocks.

In this context, the present study assesses the potential of two novel energy crops in Northern Europe: giant knotweed and Virginia mallow. The assessment includes a comprehensive characterization of the cultivation, including yield, pelletization potential and resulting physical and chemical characteristics, as well as heating value and incineration residues of the biofuel. The results of this research can help provide a basis for further considerations for upscaling their cultivation in the area, broadening the portfolio of energy crops alternatives.

2. Material and methods

2.1. Cultivation trials, soil analysis, and harvesting

Giant knotweed (*Fallopia sachalinensis*) originates from the breeding of the Japanese knotweed *Fallopia sp* or Mexican bamboo/round knotweed [16], also referred to as *Polygonum sachalinense* [17]. The variety 'Igniscum' was detected in 1987 in North Rhine-Westphalia, Germany [16], and comprised new morphological characteristics due to natural mutations. This new variety was cultivated to develop and secure beneficial characteristics by excluding molecular interventions and combinations of crossbreeding; one additional benefit is that presents a less invasive spreading than other natural varieties [18]. It is a perennial plant, with significant biomass production the 3 years after establishing the plantation, which can be harvested annually in a period of approximately 15 years [19].

The second tested crop was Virginia mallow (*Sida hermaphrodita* (L.) Rusby), a perennial plant member of the *Malvaceae* family being characterized as an endangered species [20]. The natural distribution of the species covers mainly the eastern provinces of the United States and Canada [21]. Virginia mallow was categorized as a single member of the section *Pseudo-Napea A. Gray* [22], with other investigations suggesting that Viriginia mallow being linked with *Sisasodes*, having affiliation with members of *Abutilon* and *Sida* groups [23,24].

Climatic data were collected by the Finnish Meteorological Institute from the Kaarina Yltöinen observation station (60.39°N, 22.55°E), and 6 m elevation above sea level, in 2012. The data included minimum and maximum values of monthly temperature (°C), the sum of rainfall (mm) and the effective temperature sum over 5 °C. The soil analysis of the cultivated area was analyzed by *Eurofins* laboratories. The tests of the soil type, humus content and analysis of the chemical elements were performed using a method accredited by FINAS ISO/IEC 17025 and the values of the soil conductivity and the acidity were based on the soil--water suspension (1:2.5).

The cultivation of both species in Finland was established at former MTT Agrifood Research Finland in Piikkiö (currently Natural Resources Institute Finland), located in southern Finland. The trials consisted in a planting area of 10 m^2, established in 2010 and 2012, with initial planting densities about 14 520 and 6650 plants/ha^{-1}, for giant knotweed and Virginia mallow, respectively [25]. Yara Kevätviljan Y2 (27–3-3) was used as fertilizer, by adding 370 $kg{\cdot}ha^{-1}$ in both of the species trials before stems start growing.

The first harvest for both species applied two years after establishing their trials, in 2012 for giant knotweed and in 2013 for Virginia mallow. The data of yield productivity were obtained by measuring the number of stems per square meter, the content of dry matter, the weight of fresh mass yield, and the dry matter yield. Moreover, data included the quantities of the applied fertilizers, which were nitrogen (N), phosphorus (P) and potassium (K), as well as the type of the harvested parts of the crops.

2.2. Storing, sampling, pre-treatment, and pellet production

The material of both species was sent to the Mekrijärvi Research Station at the University of Eastern Finland. The harvested material was stored in a dry outdoor shed with no ground contact in order to avoid the potential contamination and absorption of moisture from ground. The harvested dry stalks of giant knotweed were cut in pieces which contained both stem parts of light and dark brown color, as well as attached dry leaves. The color of Virginia mallow dry stalks were light beige, and the stems were much thinner compared with the giant knotweed.

The pretreatment by a MTD 5HP wood chipper/shredder (MTD Products LLC, Cleveland, OH, USA) of stems was required prior to their feeding into a Miller 20 hammer mill (Miller s.r.l., San Giorgio in Bosco, Italy) used with an 8 mm screen. The particle size of the crushed material fluctuated between 4 and 8 mm, being close to the optimal size to produce 4 mm diameter pellets according to [26]. After the process, hammered material of 107.3 kg for giant knotweed and 23.1 kg for Virginia mallow were stored in separate silos.

The pellet production was performed with the use of the Swedish Power Chipper (SPC) Type PP330 with an 8/50 die. The heating elements of the die rose during the processing from 28 °C to fluctuate between 62 °C and 95 °C with the feeding screw setting at value 6 and the hourly production being 89 $kg{\cdot}h^{-1}$. Ready giant knotweed pellets were stored as the pretreated material in prior stages. After the cooling process, the final weight of the giant knotweed pellets produced was 77 kg. The pellets had dark brown color and had notable fluctuation in pellet length. Virginia mallow pellets were produded in a similar way with the temperature of the heating elements fluctuating between 51 °C and 78 °C. The feeding screw was set during the whole process to the value 7 and the production was approximately 82 $kg{\cdot}h^{-1}$. The weight of the produced pellets was 16 kg. In both cases water was added for regulating the moisture content and facilitate the formation of the densified material. Both results of the chemical and mechanical characteristics were compared with the European Standard EN ISO 17225–6:2014 [27], referred to non-woody pellets, and *ENplus* Quality Certification Scheme for wood pellets, quality class B [28].

2.3. Mechanical properties and water content of pellets

The physical characteristics measured were the bulk density, the mechanical durability and the dimensional features of the pellets. The latter characteristic is related to the length and the diameter of the pellets. The measurement of the bulk density as received was conducted for the pretreated material and the pellets. The volume of the measuring cylinder was 5 l, and the particle size of the pretreated materialmatetial was varied from<1 mm to 8 cm with Virginia mallow containing many fibrous particles.The equations for the bulk density and mechanical durability are presented in Eqs (1) and (2) [29]:

$$BD = \frac{(m_2 - m_1)}{V} \quad (1)$$

where BD : Bulk Density

m_1 : mass of the empty container (kg)

m_2 : mass of the full container (kg)
V : net volume of the measuring cylinder (m^3)

$$DU = \frac{m_A}{m_E} \times 100 \quad (2)$$

where DU : mechanical durability (%)
m_E : mass of the pre-sieved wood pellets before (kg)
m_A : mass of the sieved wood pellets after (kg)

The mechanical durability was measured by using a custom made dumpler, which met the requirements for measuring the mechanical durability. The measuring device had been adjusted to 50 rpm and the total duration of the rotating process was 10 min. The preparation stage included the sieving 500 ± 1 g of the pelletized samples by 3.15 mm sieve aperture. The random sample of 300 pellets each type were measured for diameter and length using a digital caliper with technical features of 0.01 mm of resolution and ± 0.02 mm of accuracy.

The moisture content analyses included the oven dry method for pellets for 24 h at 105 °C using Termarks Type TS-5410 oven according to EN 14774–1:2009 [30] and by using a moisture analyzer (Radwag MAC 210/NH). A disc mill (Koneteollisuus KT-30) was used for preparing the pellets for the moisture analyzer.

2.4. Chemical and calorific analysis

The elemental analysis was conducted using the Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) to specify the content of the major and the minor chemical elements of the pellets. The tested material included 5 to 8 randomly selected pellets for each crop ground with Retsch ZM 200 laboratory mill at 10.000 rpm (Retsch GmbH, Haan, Germany) and dried at 105 °C for 24 h. The dry powder was then digested with 65% nitric acid (HNO_3) and 100% hydrogen peroxide (H_2O_2) using the CEM Microwave Accelerated Reaction System, Model MARS 5 (CEM Corporation, Charlotte, NC, USA). The ICP-OES system was IRIS Intrepid II XSP (Thermo Electron Corporation, Waltham, MA, USA).

The analysis of halogenated elements (Cl, F and Br) was obtained separately from an accredited service laboratory following standard methods SFS-EN 15,408 *Solid recovered fuels.* Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content and EN ISO 10304–1:2009 Determination of dissolved anions by liquid chromatography of ions - Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulfate (ISO 10304–1:2007).

The content of ash (575 °C), bulk extractives, soluble and acid insoluble lignin, and sugar monomers were determined according to [31]. For the analysis of the extractives, ethanol and water were used as solvents. For determining the Klason acid, insoluble lignin and acid soluble lignin (ASL) contents, the TAPPI UM 250 method *Acid-soluble lignin in wood and pulp* (1991) was used. The ASL was analyzed on a DIONEX ICS-3000 ion chromatography system (Thermo Fisher Scientific, Waltham, MA, USA) consisting of an electrochemical detector (pulsed amperometric detection), gradient pump, temperature-controlled column, and detector enclosure with an AS50 autosampler that had an injection volume of 10 μL [31]. Briefly, the hydrolysis of the materials to their carbohydrate and lignin components, 3 mL of 72% H_2SO_4 was added to a 300 mg sample, which was followed by incubation for 1 h at 30 °C. The mixture was stirred every 5 min. After incubation, the mixture was diluted to 4% H_2SO_4 by adding water and autoclaved at 120 °C for 60 min. Standard samples with 10 mL of a known sugar solution and 348 μL of 72% H_2SO_4 were prepared and autoclaved to determine the sugar loss during autoclaving. The autoclaved and vacuum filtered samples and standard mixtures were analysed for their sugar composition.

The calorimetric value of pellet samples were analyzed for both acclimatized and dry ground specimen with a calorimeter (EN ISO 1716 Bomb Calorimeter, Fire Testing Technology Ltd, UK) according to ISO

Table 1
Soil features and content of chemical elements ($mg \cdot l^{-1}$) of the plots, with a description of the method performed.

Features and elements	Description and quantities	Description of method
Topsoil[1]	Medium Fine Sand	MMPIMAAL.DOC. Sensory assay
Organic impurity[1]	Soil containing 6–12% organic matter	MMPIMAAL.DOC. Sensory assay
Conductivity value 10xmS/cm	1.0	Conductivity value was measured from the soil–water suspension (1:2.5)
pH	6.3	pH was measured from the soil–water suspension (1:2.5)
Calcium (Ca)[1]	1200	MMVT.DOC. Extraction into acidic ammonium acetate solution, detection with ICP[2]
Phosphorus (P)[1]	13	MMVT.DOC. Extraction into acidic ammonium acetate solution, spectrophotometric measurement of ammonium molybdate complex
Potassium (K)[1]	270	MMVT.DOC. Extraction into acidic ammonium acetate solution, detection with ICP[2]
Magnesium (Mg)[1]	220	MMVT.DOC. Extraction into acidic ammonium acetate solution, detection with ICP[2]
Sulfur (S)[1]	14.3	MMVT.DOC. Extraction into acidic ammonium acetate solution, detection with ICP[2]
Boron (B)	0.7	MMBOORI.DOC. Extraction into hot water, detection with ICP[2]
Copper (Cu)[1]	4.9	MMVT.DOC. Extraction into acidic ammonium acetate EDTA, detection with ICP[2]
Manganese (Mn)[1]	6.7	MMVT.DOC. Extraction into acidic ammonium acetate EDTA, detection with ICP[2]
Zinc (Zn)[1]	1.91	MMVT.DOC. Extraction into acidic ammonium acetate EDTA, detection with ICP[2]

[1] Performed based on the method accredited in accordance with FINAS ISO / IEC 17025.
[2] Inductively Coupled Plasma (ICP)

1716:2010 [32]. Pellets were grinded with a mortar collecting the wood powder passing 2 mm sieve. The sample size in each analysis was 1.0 g and the reported values are always an average of 2 parallel analyses for the collection samples. The analysis were performed in 2015.

3. Results

3.1. Area, cultivation and harvesting

During the studied period, the lowest temperature recorded in the cultivation area was −20 °C (February 2012) and the highest 21.9 °C (July 2012). Concerning monthly precipitation, had a lowest of 20.5 mm (March 2012) and a highest of 107.2 mm (October 2012). During the first year of establishment of giant knotweed there were three months with daily effective temperature below 5 °C. Temperatures in spring during the second year were colder (average temperature −7.6 °C (Standard Error, SE: 0.75), monthly minimum −15.9 °C in March 2013 compared to the respective 0.45 °C (SE: 0.76) and −10.1 °C, in 2012). The top soil type was medium fine sand and humus. The soil contained 6–12% of organic matter. The detected chemical elements ($mg\ l^{-1}$) calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), copper (Cu), boron (B), manganese (Mn), zinc (Zn) and sodium (Na) (Table 1).

The plots were harvested annually, covering the period 2012–2014, for giant knotweed and 2013–2014 for Virginia mallow. Both the fresh and the dry yield productivity were recorded. Giant knotweed's

Table 2
Estimated annual yield productivity including dry matter content (w-%), fresh weight yield (t·ha^{-1}), and dry matter yield (t·ha^{-1}) of giant knotweed and Virginia mallow, as well as the harvested part from each crop. (Fertilization 100–11-11 N-P-K kg ha^{-1}, except on *: not fertilized). e: early harvest (April, May, June), l: late harvest (July, August, September). Standard errors are presented in parenthesis.

Species	Year	Dry matter content	Fresh weight yield	Dry matter yield	Harvested parts of the crop
Giant knotweed	2012	20.8	70.2	14.64 (1.74)	Stems, leaves (l)
		27.2	88.72	24.15 (2.83)	Stems, leaves (l)
		36.6	75.5	27.67 (3.40)	Stems, leaves (l)
		31.6	41.67	15.27	Stems (l)
	2013	87.3	8.83	7.71 (1.31)	Stems (e)
	2014	64.3*	8.42*	5.41* (0.35)	Stems (e)
		15.9	109.7	17.5	Stems, leaves (e)
		37.9	59.44	22.6	Stems, leaves (l)
Virginia mallow	2013	84	7.69	6.46 (0.81)	Stems (e)
	2014	81*	10.1*	8.2* (0.40)	Stems (e)
		37	45.2	16.72	Stems, leaves (l)

Table 3
Measured bulk density (kg·m^{-3}) and moisture content (w-%), both acquired results with the oven dry method and by using the moisture analyzer, of raw, pretreated, and hammered material of giant knotweed and Virginia mallow.

Type of material	Properties	Giant knotweed	Virginia mallow
Raw material	Moisture content Oven dry method	14.75	14.95
	(moisture analyzer)	13.24	15.09
Pretreated material	Bulk density	132.43	115.25
	Moisture content Oven dry method	11.74, 10.45[1]	11.38, 10.32[1]
	(moisture analyzer)	8.58, 8.56[1]	10.26, 9.21[1]
Hammered material	Moisture content Oven dry method	9.88	8.68
	(moisture analyzer)	10.37	8.6

[1] Second measurement performed 14 days after the first measurement.

estimated yield ranged between 5.4 odt ha^{-1} yr^{-1} and 27.67 odt ha^{-1} yr^{-1}, and Virginia mallow between 6.46 odt ha^{-1} yr^{-1} and 16.72 odt ha^{-1} yr^{-1}. The corresponding fresh yield productivity of giant knotweed ranged from 8.41 t ha^{-1} yr^{-1} to 109.7 t ha^{-1} yr^{-1}, whereas Virginia mallow was between 7.69 t ha^{-1} yr^{-1} and 45.24 t ha^{-1}yr^{-1}; the peak took place at the second harvest (in the 2014 growing season).

The highest values of yield productivity amounted 27.67 odt·ha^{-1}, including stems and leaves, in 2012, 7.71 odt·ha^{-1}(only stems), in 2013, and 22.57 odt·ha^{-1}, both stems and leaves, in 2014. The Virginia mallow plot rendered a lower yield with 6.46 odt·ha^{-1} of stems in 2013; being the highest value 16.72 odt·ha^{-1} during the second harvesting in 2014 (Table 2).

3.2. Mechanical and chemical properties

The results of the bulk density of the pretreated material for giant knotweed was 132.4 kg·m^{-3} and for Virginia mallow 115.3 kg·m^{-3} (Table 3). The results of the properties met the requirements of the certification sytems for both of the tested species, excluding the mechanical durability (Table 4). The bulk density as received of giant knotweed and Virginia mallow pellets were 677.7 kg·m^{-3} and 725.2 kg·m^{-3}, having moisture content of 7.1% and 6.6%, respectively. The obtained mechanical durability as received of the pellets were 96.7% for giant knotweed and 92.9% for Virginia mallow, with moisture content of 6.7% and 6%. The length of pellets ranged from 5.62 mm to 82.63 mm for giant knotweed, with mean value 29.14 mm, and from 4.34 mm to 47.92 mm for Virginia mallow, with mean value 21.29 mm.

The statistical analysis of the pellet diameter showed giant knotweed pellets having a consistent and homogeneous normal distribution, whereas the Virginia mallow batch had a negative skew. Concerning length, giant knotweed showed a right skew distribution while the length distribution of Virginia mallow had negative skewness (Fig. 1).

Table 4
Physical and chemical properties of giant knotweed and Virginia mallow pellets in comparison with the ISO and ENplus standards. Standard errors are presented in parenthesis.

Properties	Giant knotweed	Virginia mallow	ISO[1]	ENplus[2]
Diameter (mm)	8.13 (2.48x10^{-3})	8.15 (3.00 x10^{-3})	8 ± 1	8 ± 1
Length (mm)	29.14 (0.043)	21.29 (0.052)	3.15 < L < 40	3.15 < L < 40
Moisture content (w-%) - Oven dry method	6.35	5.92	≤ 12	≤ 10
(moisture analyzer)	6.69	6.01		
Net calorific value (MJ·kg^{-1})	19.97[3] (0.12)	19.68[3] (0.16)	≥ 14.5	≥ 16.5
	17.47[4] (0.024)	17.2[4](0.020)		
Ash (w-% dry)	1.5	2.19	≤ 6	≤ 2
Bulk density (kg·m^{-3} as received)	677.71	725.18	≥ 600	600 ≤ BD ≤ 750
Mechanical durability (w-% as received)	96.73	92.86	≥97.5	≥97.5
Sulfur (S) (w-% dry)	0.033	0.024	≤ 0.2	≤ 0.05
Chlorine (Cl) (w-% dry)	0.008	0.01	≤ 0.1	≤ 0.03
Arsenic (As) (mg·kg^{-1})	<LOD[6]	<LOD[6]	≤ 1	≤ 1
Cadmium (Cd) (mg·kg^{-1})	0.2	0.1	≤ 0.5	≤ 0.5
Chromium (Cr) (mg·kg^{-1})	1.1	1	≤ 50	≤ 10
Copper (Cu) (mg·kg^{-1})	3.5	3.5	≤ 20	≤ 10
Lead (Pd) (mg·kg^{-1})	<LOD[5]	<LOD[5]	≤ 10	≤ 10
Mercury (Hg) (mg·kg^{-1})	<LOD[5]	<LOD[5]	≤ 0.1	≤ 0.1
Nickel (Ni) (mg·kg^{-1})	1	0.6	≤ 10	≤ 10
Zinc (Zn) (mg·kg^{-1})	7.4	6.2	≤ 100	≤ 100

[1] ISO 17225–6:2014, quality class A
[2] ENplus Handbook V3.0 2015, pellet quality class ENplus B
[3] Moisture content 5 w-%
[4] Moisture content 10 w-%
[5] Limit of detection, below this limit the element cannot be detected

Concerning moisture contents, there was a constant reduction of the values with Virginia mallow having lower values in the majority of the tests (Fig. 2).

The chemical elements were also analysed (Table 5), particularly those with a potential negative impact on the boiler performance, such as scaling and corrosion, were on a level below the threshold criteria set for bioenergy carriers. The content of carbohydrates and extractives present in pellets (Table 6) varied between the crops, giant knotweed included lower content of lignin and extractive compounds than Virginia mallow. Giant knotweed had additionaly slightly higher content on most carbohydrates tested.

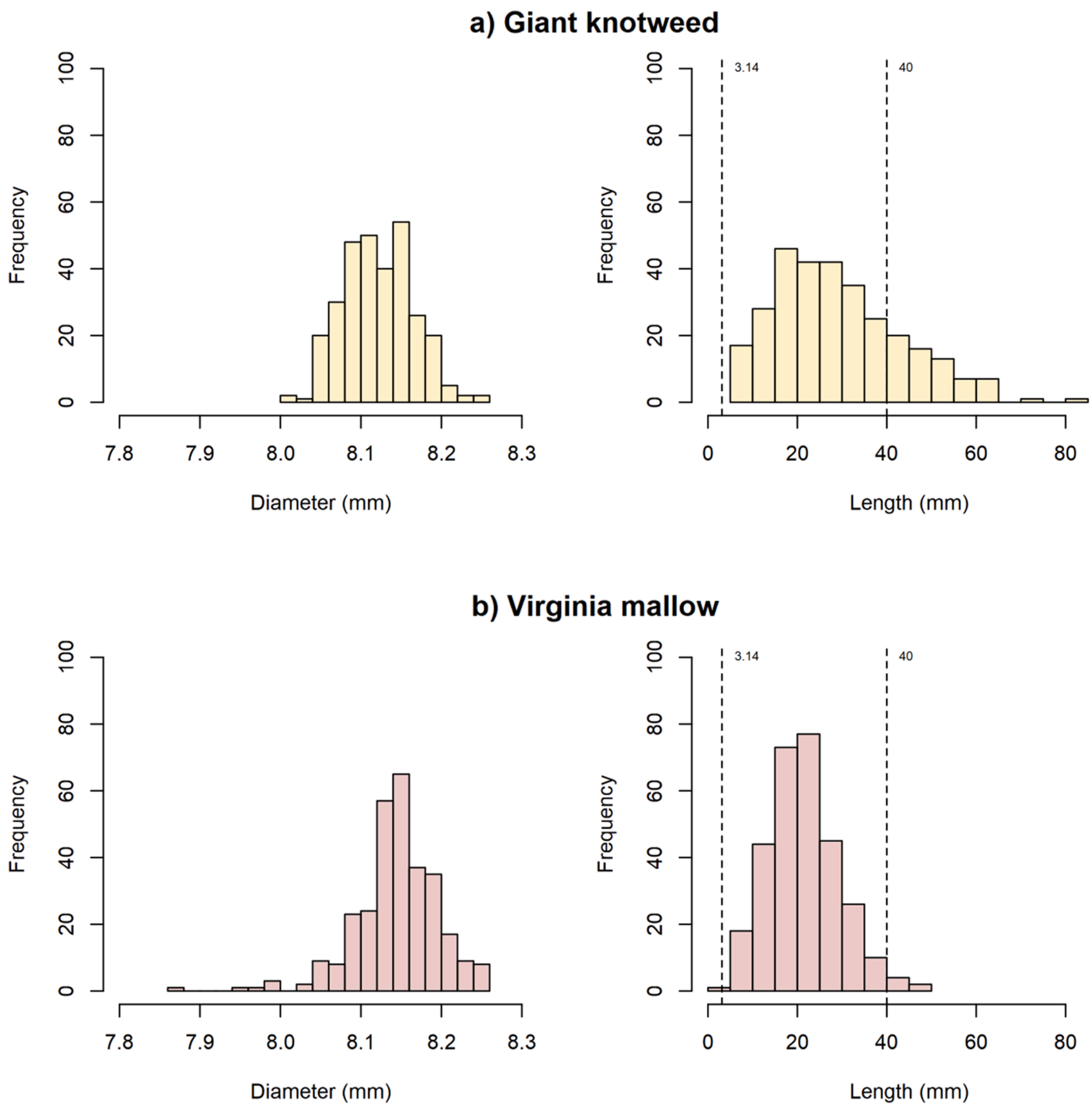

Fig. 1. Histograms of the diameter and length distribution for the pellet samples of giant knotweed and Virginia mallow. Number of samples for each crop N = 300. Discontinuous lines represent the thresholds according to the European Pellet Council standards, for reference.

Finally, concerning the combustion characteristics, the calorimetric values of giant knotweed and Virginia mallow pellets, with moisture content of 5%, were 19.97 MJ·kg^{-1} and 19.68 MJ·kg^{-1}, respectively. The heat value of the pellets after being acclimized and having moisture content of 10% was 17.47 MJ·kg^{-1} for giant knotweed and 17.2 MJ·kg^{-1} for Virginia mallow.

4. Discussion

The current developments of biomass demand suppose a clear need to assess the performance of alternative energy crops adapted to northern conditions. The present study explores the potential of two energy crops, giant knotweed and Virginia mallow, by evaluating their energy performance, as well as their mechanical and chemical characteristics in northern latitudes. However, as in any preliminary assessment of novel energy crops, it must be taken into account that there are some limitations, such as the availability of biomass material, due to being the result of experimental cultivation. In addition, the storage procedure in a shed for almost a year might also affect some properties of the raw material.

Some more extreme results showed values of 27.2 odt ha^{-1} yr^{-1} and 28.8 odt ha^{-1} yr^{-1} for the first and the second year (106.3 t ha^{-1} yr^{-1} and 109.8 t ha^{-1} yr^{-1} of fresh yield), for an experiment of *Fallopia sachalinensis* var. Gigant, fertilized with sewage sludge in Moldova [33]. A trial of hybrid *Reynoutria* × *bohemica*, deriving from giant knotweed and Japanese knotweed, in unfertilized plots showed mean yield of 19.78 odt ha^{-1} yr^{-1} during autumn and 13.07 odt ha^{-1} yr^{-1} in spring, in a period of 8 years [34]. The results showed yield levels that were in line with the experience in other countries, even with better climatic and soil conditions. In Austria, yield productivity of Virginia mallow was estimated between 7.1 odt ha^{-1} yr^{-1} to 14.3 odt ha^{-1} yr^{-1} during the second and the third year of the trial [35].

In closer geographic conditions, the yield levels were, however, lower, as climatic and soil conditions restrict the overall productivity of energy crops. Experience in central Lithuania showed yield levels around 5.13 odt ha^{-1} yr^{-1} (unfertilized) and 9.58 odt ha^{-1} yr^{-1} (fertilized) for giant knotweed and Virginia mallow, respectively, while the dry matter contents were 35.8% and 51% [36]. In Poland, a trial of Virginia mallow cultivated for a 4-year period showed yields around 7.47 to 9.19 odt ha^{-1} yr^{-1} in Poland [37]. The yield productivity of

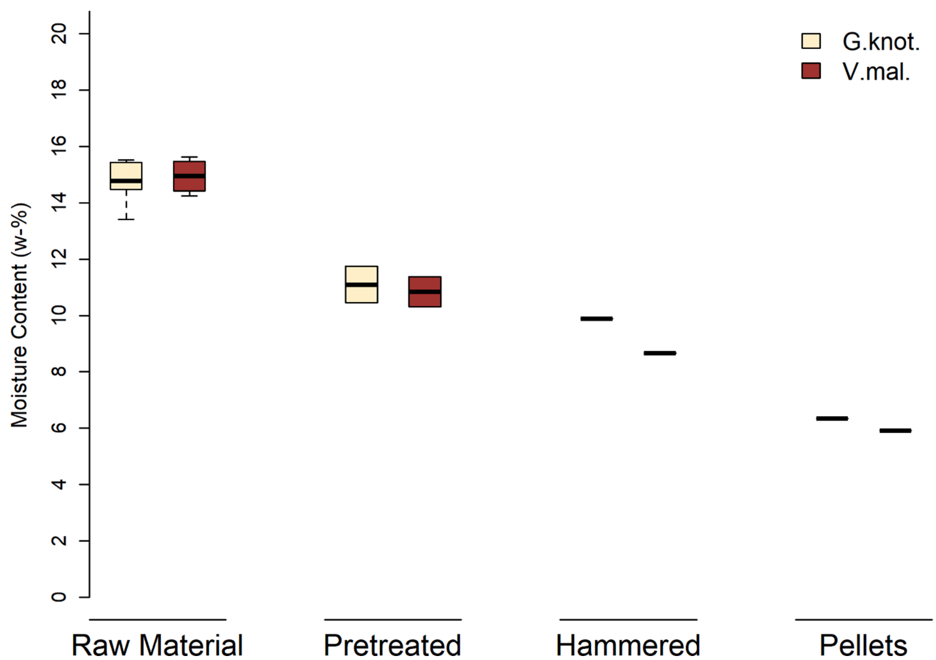

Fig. 2. Constant reduction of the moisture content during the experiments of giant knotweed and Virginia mallow for pellet production. The number of the measures for each stage were: raw material N = 34, pretreated material N = 15 (including measurements with high values, which were not used for the calculation of the mean values), hammered material N = 4, pellets N = 6.

Table 5
Analysis of the chemical elements of the studied energy crops.

Chemical element	Giant knotweed		Virginia mallow	
	$mg \cdot l^{-1}$	$mg \cdot kg^{-1}$	$mg \cdot l^{-1}$	$mg \cdot kg^{-1}$
Aluminium (Al)	0.208	18	0.325	31.6
Antimony (Sb)	<LOD	<LOD	<LOD	<LOD
Boron (B)	0.032	2.8	0.035	3.4
Bromine (Br)		<10		<10
Calcium (Ca)	61.695	5336.9	35.045	3409
Cobalt (Co)	<LOD	<LOD	0.0003	<LOD
Fluorine (F)		<10		<10
Iron (Fe)	0.425	36.7	0.439	42.7
Lithium (Li)	<LOD	<LOD	<LOD	<LOD
Magnesium (Mg)	8.052	696.5	7.611	740.4
Manganese (Mn)	0.345	29.8	0.094	9.1
Molybdenum (Mo)	<LOD	<LOD	<LOD	<LOD
Sodium (Na)	0.818	70.7	0.532	51.7
Phosphorus (P)	3.442	297.8	2.211	215.1
Potassium (K)	39.26	3396.5	23.09	2246.4
Selenium (Se)	<LOD	<LOD	<LOD	<LOD
Silicon (Si)	0.477	41.3	0.675	65.7
Titanium (Ti)	<LOD	<LOD	<LOD	<LOD
Vanadium (V)	0.019	1,6	0.024	2.3

Table 6
Pellet content of monosaccharides, soluble and insoluble lignin content, and extractives, of the studied energy crops.

Analysis	Giant knotweed	Virginia mallow
Glucan (%)	38.06	35.93
Xylan (%)	16.83	13.81
Arabinan (%)	0.33	0.34
Mannan (%)	1.23	1.07
Acid soluble lignin (%)	2.29	1.97
Klason lignin (%)	19.99	23.19
Extractives (%)	4.17	7.00

Virginia mallow depending on nitrogen (N) amount varied from 6.5 odt ha^{-1} yr^{-1} to 9.6 odt ha^{-1} yr^{-1} [38], and the soil types of brown soil, deriving from loess, and black soil, as a result of a medium loam on heavy loam, had values of 15 odt ha^{-1} yr^{-1} and 18 odt ha^{-1} yr^{-1} [39]. The results showed higher yield levels after the first harvest, due to the development of the root system in the earlier stages of the cultivation, which is common in multi-annual energy crops as seen in other plantation systems [40]. This was not observed in the giant knotweed trial, which may be explained by early spring frost at the start of the second year (2013), not affecting Virginia mallow as it was established later. However, additional plots and replications would be needed to analyse with more rigour the specific effect of climate in the growth and yield of these crops.

The results show a promising alternative for Finnish conditions, as other commercial energy crops in the area, such as reed canary grass (*Phalaris arundinacea* L.) had productivity from 3.3 odt ha^{-1} yr^{-1} to 7.72 odt ha^{-1} yr^{-1}. Other experimental crops such as meadow fescue (*Festuca pratensis* Hudson), tall fescue (*Festuca arundinacea* Schreber), and goat's rue (*Galega orientalis* L.) produced from near 2 odt ha^{-1} yr^{-1} to 6.5 odt ha^{-1} yr^{-1} [41]. The results show that although reed canary grass has been considered one of the most suited crops for northern Europe [42–43], the studied cultivations present an interesting potential. In fact, giant knotweed and Virginia mallow could be developed efficiently in soils with inadequate amounts of nutrients, demonstrating a good potential for marginal land [44], and show potential to adapt to different soil qualities with good performance [37].

However, it must be taken into account that yields from small plots may present too optimistic values. Yield studies of energy crops based on small trials in northern Europe tend to overestimate the productivity levels especially when the measured area is smaller than 200 m^2, as it is the case [45]. The bias is attributed to the intensive dedication of small plots versus commercial plantations, possible edge effects and measurement methods, the absence of harvest losses and hazards. In addition, the lack of replicates in different locations precluded a deeper statistical treatment of the data and modelling approaches that could address the differences due to climate or to management alternatives. The generalization of these results can therefore be done with caution, especially if taken as a uncritacally to estimate potential for commercial uses.

The results of the bulk density for both giant knotweed (677.7 $kg \cdot m^{-3}$) and Virginia mallow (725.2 $kg \cdot m^{-3}$) meet the recommended thresholds certification system for non wood and wood pellets. Pellets produced by using biomass of giant Knotweed (*Fallopia sachalinensis*) had a bulk density of 509.9 kg·m^{-3} [46]. Tested pellets of Virginia mallow with moisture content of 6.1% had bulk density of 999.3 kg·m^{-3} [47].The potential use of the varieties gigant (*Polygonum sachalinense*) and Energo (*Sida hermaphrodita*) for pellet production was also investigated and resulting in 570 kg·m^{-3} for *Polygonum sachalinense* and 487 kg·m^{-3} for *Sida hermaphrodita* [48]. As a reference, pellet production from wood, willow, miscanthus, wheat straw, barley straw and rape straw had bulk densities of 680.8 kg·m^{-3}, 654.8 kg·m^{-3}, 615.2 kg·m^{-3}, 637.2 kg·m^{-3}, 644.2 kg·m^{-3}, and 684.6 kg·m^{-3}, respectively [49].

The mechanical durability is related to the rate of fragility of pellets, while the dimensional features of the affect the feeding process [26]. Concerning mechanical durability, the values were below the thresholds of 97.5%, which has been set as the lowest limit value. On the other hand, mechanical durability is directly related to moisture content and be improved by adding pine sawdust [50]. According to the certification system (ISO 17829:2015) related to length only 1% of the measured pellets should exceed 40 mm, and none of the pellets should be longer than 45 mm. giant knotweed had 1.3% and Virginia mallow 6.7% of pellets being longer 40 mm., respectively. Both crops had some pellets exceeding the threshold of 45 mm; 0.8% of the giant knotweed pellets and approximately 15% of Virginia mallow pellets. Lenght can be optimized easily by adding a blade close to the surface of the die [26]. The moisture content of the hammered material was$<$10 w-%, which affected the early stage of the pellet production process. The water supply had to be increased in order to acquire pellets. Increasing the moisture content of biomass has used for producing pellets with better quality [51]. Moisture content of biomass is related to input energy and carbon emissions for pellet production if drying process is required [52]. In addition, omitting drying process of biomass compasates the cost of production and logistics [53].

In case of the resulting energy outputs, the values agree with previous studies in Germany, Lithuania, Poland, and Moldova. In those, the estimated high heating value (HHV) for giant knotweed was 18.96 MJ·kg^{-1} [46], and the corresponding for Virginia mallow was 18.7 MJ·kg^{-1} [54], being 16.13 MJ·kg^{-1} the low heating value (LHV) [55]. The results of the chemical element analysis depicted that calcium (Ca), potassium (K), magnesium (Mg) had the higher values for both crops, with giant knotweed having higher the first two elements and Virginia mallow the last one. The contents of ash, chlorine (Cl), and sulfur (S) were quite below the recommended thresholds from both wood and herbaceous derived crops. Other studied crops had values of ash 2.22 w-% – 6.49 w-%, chlorine (Cl) 0.018 w-% – 0.221 w-%, and sulfur (S) 0.022 w-% – 0.291 w-% [49].

Finally, the contribution of the energy crops is not only in their conversion for energy purposes but also the beneficial role in environmental issues. An example is the contribution of energy crops to carbon sequestration restoration in the soil through their cultivation [56], concerning soil contains metal pollutants [57] and biodiversity, increasing the range of land uses [58], or on soil [59]. Perennial energy crops could provide benefits for marginal landscapes by improving biodiversity and enhancing a variety of environmental services [60]. In addition, stakeholders of marginal areas can have economic benefits by reactivating the use of these areas through the cultivation of energy crops [61].

The success of biomass alternatives will depend on regional factors: whereas in some areas there may be negative factors for the exploitation of a specific energy crop, that can be beneficial in other locations [62]. The prospects of viable cultivation and pellet utilization from the studied energy crops in Northern Europe should be designed by taking into account parameters such as the cost of production and transportation, the energy content, as well as the competition with other resources of biomass.

5. Conclusions

The overall results of this study demonstrate that from the point of view of production and biofuel properties, both giant knotweed and Virginia mallow are valid alternatives for energy crops in the climatic and soil conditions of Northern Europe. The resulting chemical and physical characterization shows the potential as a feedstock for pellet use, which can be used as basis for further economic considerations for their full viability.

CRediT authorship contribution statement

Nikolaos Papamatthaiakis: Data curation, Funding acquisition, Validation, Writing - original draft, Writing - review & editing. **Antti Laine:** Data curation, Funding acquisition, Resources, Validation, Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Antti Haapala:** Methodology, Resources. **Risto Ikonen:** Methodology, Writing - review & editing. **Suvi Kuittinen:** Writing - review & editing. **Ari Pappinen:** Writing - review & editing. **Marja Kolström:** Methodology, Resources, Supervision, Writing - review & editing. **Blas Mola-Yudego:** Supervision, Funding acquisition, Formal analysis, Validation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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