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On the Way to Sustainable Peat-Free Soil Amendments

Zane Vincevica-Gaile[1], Karina Stankevica[1], Maris Klavins[1], Roy Hendroko Setyobudi[2], Damat Damat[3*], Praptiningsih Gawawati Adinurani[4], Lili Zalizar[5], Muhammad Zul Mazwan[6], Juris Burlakovs[7], Didiek Hadjar Goenadi[8,9], Rista Anggriani[3] and Aamir Sohail[10]

[1]Department of Environmental Science, Faculty of Geography and Earth Sciences, University of Latvia, Jelgavas Street 1, Riga LV-1004, Latvia, Indonesia; [2]Department of Agriculture Science, Postgraduate Program, University of Muhammadiyah Malang, Jl. Raya Tlogomas No 246, Malang 65144, East Java, Indonesia; [3]Department of Food Technology, Faculty of Agriculture and Animal Science, University of Muhammadiyah Malang, Malang 65144, Indonesia; [4]Department Agrotechnology, Faculty of Agriculture, Merdeka University of Madiun, Jl. Serayu No.79, Madiun 63133, East Java, Indonesia; [5]Department of Animal Science, Faculty of Agriculture and Animal Science, University of Muhammadiyah Malang, Malang 65144, Indonesia; [6]Department of Agribusiness, Faculty of Agriculture and Animal Science, University of Muhammadiyah Malang, Malang, 65145, Indonesia; [7]Chair of Rural Building and Water Management, Estonian University of Life Sciences, 51014 Tartu, Estonia; [8]Indonesian Research Institute for Biotechnology and Bioindustry, Jl Taman Kencana No. 1 Bogor 16128, West Java, Indonesia; [9]Indonesian Inventor Association, Jl. Rawa Bambu Raya No. 17 A Pasar Minggu, Special Capital Region of Jakarta 12520, Indonesia; [10]University of Bolton, A676 Deane Rd, Bolton BL3 5AB, UK.

Abstract | Increasing global population and urbanization demands enhanced food and feed crop production, but due to several reasons, the areas of fertile agricultural lands are reducing worldwide. The market of growing substrates, soil amendments, and improvers still is based on peat extraction and processing. Due to peat's fossil origin, it can be considered environmentally unfriendly and unsustainable. Seeking peat-substituting materials is of crucial importance on a global scale and may become a vitally significant assignment for future generations. The necessity for peat-free soil amendments is also directed by the targets of circular economy and environmental sustainability goals, leading to reducing or abandoning the use of fossil resources and paying attention to waste utilization as secondary raw material. This paper aims to discuss general features of peat-free soil amendments as well as provide efforts into the use of secondary raw materials such as biomass ashes for the elaboration of peat-free soil-improving products. As a case example, may serve a description of the peat-free product made by rotary drum granulation from biomass fly ashes (energy production waste) and local freshwater sediments in a mass ratio mixture of 67:100, optimally applicable for soil improvement at a rate of 50 g L^{-1}. Besides, regional opportunities in Indonesia and Latvia are referred. It was concluded that peat-free soil amendment elaboration can be better implemented on a regional scale after assessing agricultural needs, soil specifics, and available raw material variety applicable as ingredients in soil-improving products.

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***Correspondence** | Damat Damat, University of Muhammadiyah Malang, Malang 65144, Indonesia; **Email:** damatumm@gmail.com
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Introduction

The need for peat replacement

The growth of the global population and urbanization leads to increased demand for water, food, and feed, which, in turn, requires larger and larger areas of fertile agricultural lands (Mohamed *et al*., 2016; Shah; *et al*., 2021). At the same time, large agricultural areas covered by monocultures such as oil palms (*Elaeis guineensis* Jacq.), rubber (*Hevea brasiliensis* Müll.Arg.), maize (*Zea mays* L.), sugarcane (*Saccharum officinarum* L.), and fuel crops such as rapeseed (*Brassica napus* L.) take up space instead of multicultural food crops resulting in adverse impact leading to loss of soil fertility, increased soil salinity, erosion, depletion, and decreased environmental quality and biodiversity soil depletion (Ghadeer and Al Khalil, 2019; Guillaume *et al*., 2016; Mohamed *et al*., 2016; Putra *et al*., 2020; Schiefer *et al*., 2016; Vanham *et al*., 2021). In particular, several experts have discussed the problem of soil fertility in oil palms in Indonesia (Herry *et al*., 2020; Hsiao-Hang *et al*., 2016; Petrenko *et al*., 2016; Shahputra and Zen, 2018), while other scientists (Hartemink, 1964; Kusumawati *et al*., 2020; Putra *et al*., 2020) have discussed and reported about soil degradation in sugarcane plantations in Indonesia.

Furthermore, climate change predictions point at more frequent environmental instabilities such as extensive heat resulting in dryness and natural fires, excessive precipitation leading to floods, sudden and intense cold bringing crop yield loss. It can be said convincingly that warmer climate zones will be affected much more severely than the lands located in temperate climatic conditions (Ghadeer and AlKhalil, 2019; Gruda, 2019; Nizami *et al*., 2020; Schiefer *et al*., 2016). Food crop cultivation in controlled environment conditions and soil-less systems is increasing and can solve only a part of the problems. Instead of natural soil, various growing mediums are used, or soilless plant growth is provided (Bar-Tal *et al*., 2019; Gruda, 2019). For sustainable management of agricultural/ arable lands systemic approach must be implemented that becomes an everyday practice and is established at the governmental level directing the economic systems altering from the linear economy to circular approach where waste becomes a value (Abdullah *et al*., 2020; Setyobudi *et al*., 2019; 2021; Sadik *et al*., 2021; Zakaria *et al*., 2020). Limitations of global resources and dependence on fossil resources lead to broader utilization of secondary resources, meaning reuse and recovery of materials and reducing disposed waste, more or less in every economic sector (Chojnacaka *et al*., 2020; Millar *et al*., 2019; Setyobudi *et al*., 2018; Yandri *et al*., 2021). In this aspect, the need to develop bio-based soil-improving products is driven by the global trends of environmental sustainability and circular economy (Abdullah *et al*., 2020; Adinurani *et al*., 2017; Chojnacaka *et al*., 2020; Klavins and Obuka, 2018; Millar *et al*., 2019; Urbinati *et al*., 2017; Vincevica-Gaile *et al*., 2019 and 2021b): i) to expand and increase reuse of biodegradable industrial waste; ii) to exploit renewable natural resources instead of non-renewable (fossil) resources; iii) to pay greater attention to the use of locally available resources.

The market of growing media (growth substrates), soil improvers, and amendments still are greatly based on peat extraction and processing and, due to that, can be considered as environmentally unfriendly as a fossil resource is utilized in significant amounts (Carlile *et al*., 2015; Jürgen *et al*., 2017; Schmilewski, 2009). Peat is an economically significant yield of peatlands, generally recognized as swamps, bogs, marshes, wetlands, and mires, globally covering more than 4×10^6 km^2. Furthermore, the Baltic states (Latvia, Lithuania, Estonia) are among the worldwide leaders in peat extraction (Index Mundi, 2013; Tanneberger *et al*., 2017), but Indonesia holds almost 25 % of the world's total tropical peatland areas (Osaki, *et al*., 2016; Rieley and Page, 2016; Vincevica-Gaile *et al*., 2021b; Xu *et al*., 2018). Also, studies on CO_2 emissions from peat extraction have revealed that Europe highly depends on this resource (Taparia *et al*., 2021; Quintero *et al*., 2015), nevertheless, the target of the European Green Deal is climate-neutral Europe by 2050 (EC, 2019) and it should serve as a step towards global climate change mitigation. It is the reason why at the national level, several countries are starting to reduce peat utilization and are looking for new, more sustainable substituting materials. The problem can be solved by implementing new strategies in the development of growing media, soil conditioners, or amendments based on material cycling and utilization of secondary resources instead of primary ones (Carlile *et al*., 2015; Chojnacka *et al*., 2020; Nurzakiah *et al*., 2013; Stankevica *et al*., 2013).

The necessity for peat-free soil amendments and substrates is directed by the targets of circular economy and goals of environmental sustainability such as increasing recycling and reuse of renewable natural

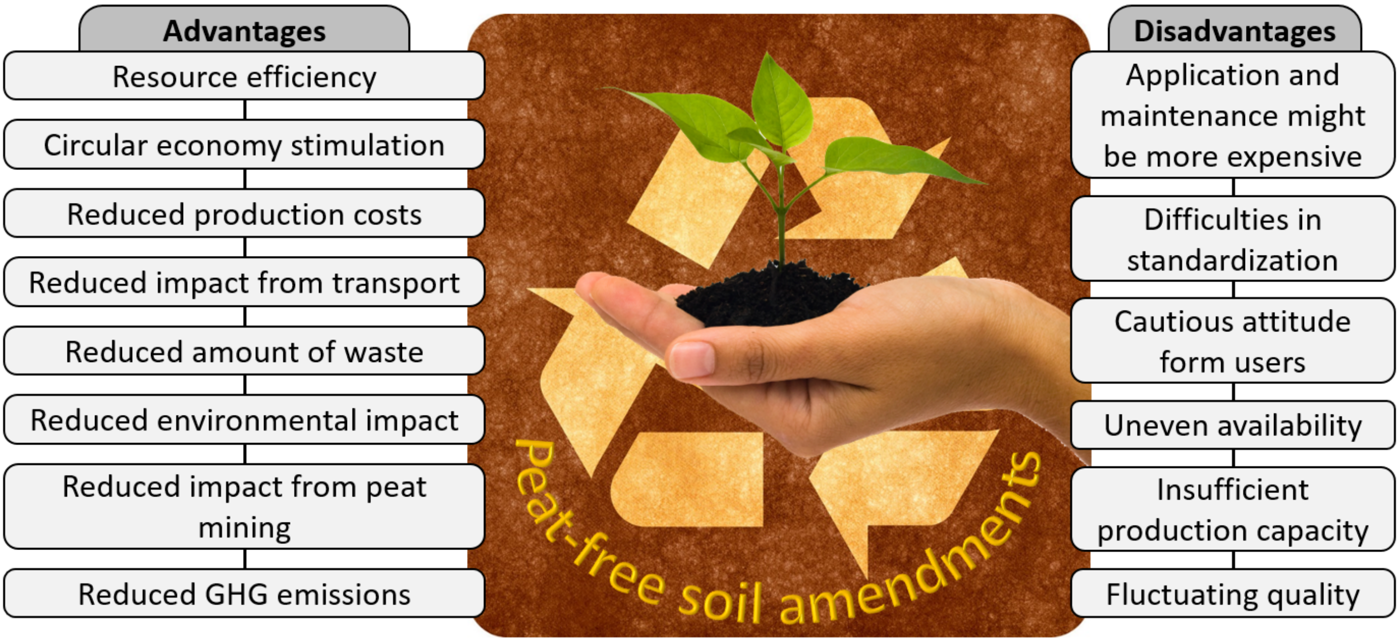

Figure 1: *Advantages and disadvantages of peat-free soil-improving amendments (EC, 2018; EUBIA, 2021).*

resources instead of fossil ones (such as peat is), decreasing global greenhouse gas emissions by using local resources avoiding long transportation routes (Chojnacka *et al.*, 2020; Klavins and Obuka, 2018; Pursula *et al.*, 2018).

This paper aims to discuss the features of peat-free soil amendments and provide insight into the efforts in the elaboration of granulated peat-free soil amendment using organic-rich freshwater sediments – sapropel, in a mixture with industrial waste from energy production – biomass ashes as a case example.

Features of peat-free soil amendments

Several goals need to be achieved by implementing sustainable soil management in agriculture, *e.g.*, positive nutrient budget, reduction of erosion and pollution, increased carbon content, presence of beneficial microorganisms, optimal water supply, and infiltration (Chojnacka *et al.*, 2020; Schiefer *et al.*, 2016; Shahen, 2016). Soil improvers are applied to reach one or more of these goals if the natural environmental state of soil is damaged. The general term of a soil improver or amendment is referred to a '*substance/material applied periodically to the soil in situ to maintain or improve its physical, and/or chemical and/or biological properties or activity*, but excluding typical liming agents (EC, 2017; EC, 2018). Conventional soil improvers include peat and its products and various mineral-based and synthetic fertilizers. An organic soil improver is a mixture containing carbonaceous materials with the primary function to increase soil organic matter content; furthermore, in this case, peat is not assessed as an organic constituent (EC, 2017).

As an alternative to conventional soil-improving amendments, the term 'bio-based' or 'peat-free' soil improver is attributed to the materials such as compost, mulch, and particular sludge. Furthermore, bio-based/peat-free soil improvers can contain secondary raw material derived from various waste streams (Chojnacka *et al.*, 2020; EC, 2017; Taparia *et al.*, 2021). Motivation to develop peat-free soil-improving amendments is based on a sustainable bioeconomy approach, also grounded in the ideas of the European Green Deal, such as moving to 'zero waste' production, resource efficiency, ensuring the quality of the environment (Awasthi *et al.*, 2021; EC, 2019). Advantages prevail over disadvantages, especially in the long-term (Figure 1).

Deeper comprehension and environmental awareness step in step with stricter regulations on energy efficiency and environmental pollution are acting as driving forces. The struggle to attain the compromise between the goals of the environment and economics is going on without ceasing (Nizami *et al.*, 2020; Sadiq *et al.*, 2019). Globally growing waste streams must be reduced and turned to create beneficial outcomes. Extraction and utilization of primary resources should be reduced; instead, generated waste can be utilized as secondary raw materials, depending on the origin and character, can be applied to improve soil state, gravimetric properties, physical-chemical properties,

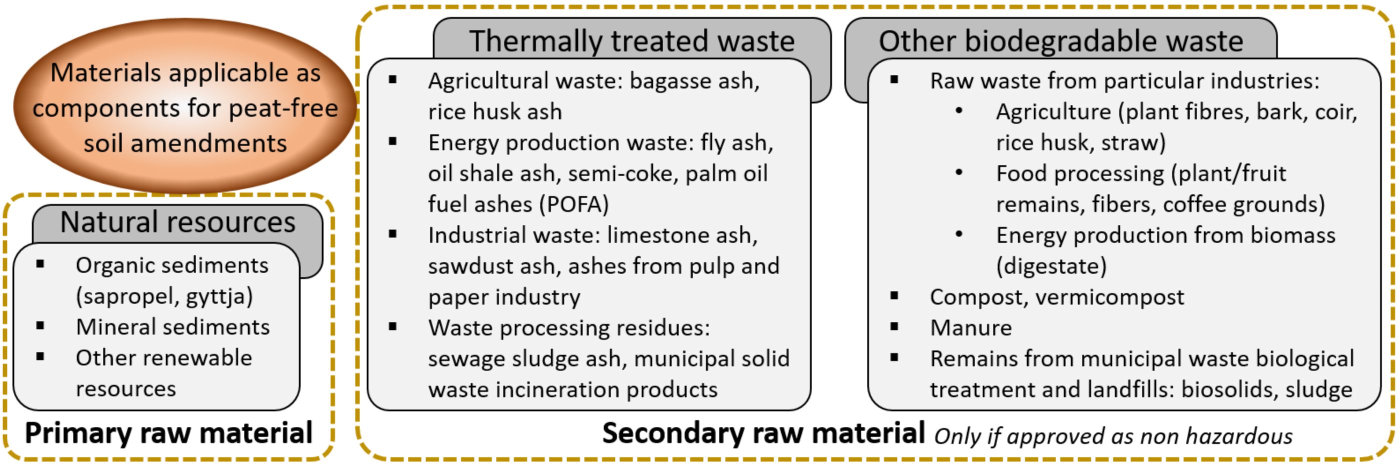

Figure 2: *Examples of materials applicable as constituents of peat-free soil amendments.*

as well as fertility, leading to circular economy implementation in agricultural practices and urban gardening (Coenen *et al*., 2015; Urbinati *et al*., 2017). The choice of sustainable materials (Figure 2) is vast, but the problem remains in the elaboration of 'the perfect composition' in terms of applicability, efficiency, cost-effectiveness.

Environmental concern must be considered when selecting components from the list of secondary raw materials to be used for the elaboration of peat-free soil-improving amendments.

Case Example in Elaboration of Peat-Free Soil Amendment

Choice of biomass ashes as appropriate raw material: Biomass ashes are the primary waste material generated during the energy (heat and power) production at cogeneration plants (Masto *et al*., 2015). Biomass ashes (fly and bottom ashes), if securely and adequately applied into the soil, may play a significant role in plant nutrition and soil improvement as well as nutrient cycling favorable for agriculture, gardening, and greenery landscaping purposes (Anggarani *et al*., 2021; Bhattacharya and Chattopadhyay, 2002; Jain *et al*., 20212; Romdhane *et al*., 2021). The composition of wood ashes incorporates a mixture of chemical elements mainly in the form of oxides, hydroxides, carbonates, and silicates (Demeyer *et al*., 2001). Biomass ashes are useful to increase the soil pH and supply the soil with nutrients such as Ca, K, Mg, and P (Chirenje and Ma, 2002; Prisca *et al*., 2021; Ram and Masto, 2014; Samadhi *et al*., 2019; Sparrevik *et al*., 2014), but they are depleted in nitrogen and, therefore, cannot be used as a general soil improver or fertilizer (Röser *et al*., 2008). However, specific security measures have to be applied in the use of biomass ashes as some toxic and possibly toxic elements (As, Co, Cu, Ni, Pb, and Zn) may be present and can be toxic to plants as well as are of environmental concern (Masto *et al*., 2015; Perkiömäki, 2004; Utami *et al*., 2019).

Biomass ashes have been used in this project because it was relatively easy to obtain in large quantities due to the waste from the boiler power plant. However, several experts stated that biochar is more effective as a soil enhancer (Deenik *et al*., 2011; Martinsen *et al*., 2015; Nur *et al*., 2021; Omil *et al*., 2013; Puvan *et al*., 2021; Santalla *et al*., 2011; Titiek *et al*., 2011; Zaffar *et al*., 2017) and also in suppressing greenhouse gases (Atanu and Lal, 2013; Kamman *et al*., 2017).

Meanwhile, in Indonesia, potential sources of ashes that are commonly used for soil improvement are derived from palm oil processing and sugar factories. The power plant boilers in the two factories use solid waste, namely palm fiber, and shells, as well as bagasse in the sugar factory. Another source of ashes in oil palm plantations is empty fruit bunches. This organic material or its ashes is used internally as a substitute for potassium fertilizer based on the recycling principle (Arfiana *et al*., 2021; Herry *et al*., 2020; Kusumaningtyas *et al*., 2015).

Another source of biomass ashes in Indonesia is a waste of bioethanol factories (based on molasses). For example, a bioethanol factory in East Java, Indonesia, produces 80 000 kL yr^{-1} with liquid waste amounts of 1.2×10^6 L of vinasse d^{-1}. This vinasse is utilized in three products, namely, (i) boiler vinasse fuel capable of producing 56 t of steam which can be converted into 4.9 MW of electricity that is used for 90 % of the electricity needs of the bioethanol plant; (ii) vinasse is burned into ashes which are granulated with binder molasses into solid organo-mineral fertilizer (OMF), especially as potassium fertilizer; (iii) liquid vinasse is mixed in a mixture of organic materials (including filter cake, sugar factory waste). The mixture of materials is dried in the greenhouse (3 ha), granulated, and then sold as organic fertilizer (Agusta *et al*., 2021; Brotodjojo and Dyah, 2016; Gurgel *et al*., 2015; Utami *et al*., 2021). The unit production of potassium fertilizers and organic fertilizers is estimated at 10 500 t yr^{-1} and 10 000 t yr^{-1}, respectively (Molindo, 2021).

Several scientific groups (Dirbeba *et al*., 2019a; 2019b; Gurgel *et al*., 2015; Kamalia *et al*., 2021; Kusumaningtyas *et al*., 2015; 2020) have studied the process of solid OMF vinasse base. While others (Anas *et al*., 2007; Kusumaningtyas *et al*., 2017) have reported the positive impact of OMF vinasse based on the productivity of tomatoes (*Solanum lycopersicum* L.) and sugarcane.

Case study in Latvia

A prototype of peat-free soil amendment formulation was developed at the Department of Environmental Science, University of Latvia, located in North-East Europe. Local materials and industrially produced secondary resources were selected to elaborate peat-free products applicable for soil improvement.

Biomass ashes for the elaboration of peat-free soil amendment were collected at commercial power plants in Lithuania and Latvia, assessing fly ashes among the ash types as the most appropriate. Biomass fuel used in these cogeneration plants consisted of coniferous softwood chips with a negligible admixture of deciduous (< 5 %) and herbaceous (< 1 %) biomass, or a variety of forest wood waste chips. Full-scale characterization was performed to estimate descriptive parameters of ashes such as dry matter, volatile matter, fixed carbon, gravimetric water and dry matter, bulk density, solid density, as well as elemental content and element bioavailability. Complete details on the investigation, including methodology and results, of biomass ashes, can be found in an open-access dataset (Vincevica-Gaile *et al*., 2021a).

Specific organic-rich sediments were used as a natural adhesive, providing organic matter into peat-free soil amendment formulation. Organic-rich freshwater sediments – sapropel – are formed mainly in eutrophic freshwater lakes. Sapropel primarily consists of the remains of water plants, plankton, and benthic organisms transformed by microorganisms in a mixture with mineral components supplied from the water body basin. Various types of sapropel usually contain a high amount of organic matter (15 % to 90 %). Fresh sapropel is characterized as a mud-like, colloidal substance, occurring at the bottom of continental water bodies, with characteristic finely dispersed and plastic structure. Sapropel is assessed as a strategical resource in such countries as Latvia, Lithuania, Estonia, Belarus, Russia, where it can be found in industrially significant amounts in eutrophic lakes and bogs. For example, in Latvia, after geological surveys in 1 600 freshwater lakes, sapropel deposits were estimated at 930 × 10^{6} m^{3}. Already historically, sapropel has been exploited as a soil amendment, but due to the variability of physical-chemical properties among its types and classes seeking new sustainable and cost-effective utilization ways is ongoing. Application possibilities of sapropel are not limited only to agriculture and soil improvement. However, it can be used as a raw material also in the construction industry, chemical industry, and medical and pharmaceutical industry (*e.g*., applied as healing mud in balneology) (Stankeviča, 2020).

Sapropel samples for the elaboration of soil amendment were extracted from freshwater lakes in Latvia and Lithuania by coring using a 10 cm diameter peat sampler with a 1.0 m long camera according to the procedure (Stankevica *et al*., 2020). Sapropel type and the class were identified according to the classification (Stankeviča, 2020). Sapropel of biogenic class, organogenic order, and peaty, green algae or cyanobacteria type was selected to elaborate a peat-free soil amendment.

Among the methods that were applied to investigate sapropel samples, the most important were loss-on-ignition (LOI) for estimating the content of moisture, organic matter, ash, and carbonates (Stankevica *et al*., 2020), as well as chemical composition analysis for trace and major element detection (Vincevica-Gaile and Stankevica, 2018) implemented by atomic absorption spectrometry (AAS) (AANAYLST 200, Perkin Elmer) and inductively coupled plasma mass spectrometry (ICP-OES) (iCAP 7000, Thermo Scientific).

Methodology: Ash-sapropel granulation

Peat-free soil amendment from biomass ashes in a mixture with sapropel as a natural binder was elaborated by applying extrusion and rotary drum granulation resulting in two types of granules – extruded and spherical (Rodrigues *et al*., 2017; Vincevica-Gaile *et al*., 2019). Wet granulation was chosen as an appropriate method due to several advantages as it is a size-enlargement process applied in many industrial fields, such as pharmaceuticals, nutraceuticals, zootechnicals, to improve the flowability and compressibility properties of powders (De Simone *et al*., 2018). Screened by sieving (1 500 µm), biomass fly ashes were used for granulation together with homogenized sapropel, which was gradually admixed to gain the best consistency applicable for granulation. Mixing was performed using an anchor type mixer (KM3350, Clatronic) at 50 rev min^{-1}. Granulation was implemented using an elaborated laboratory-scale granulator, being successfully used for the granulation of clay-containing mixtures (Shishkin *et al*., 2017).

Broad physical-chemical characterization of granules was performed, including bioavailability detection of trace and major elements, as well as testing the plant and soil response to the addition of granules into the substrate.

Remarks on results: Characterization of ash-sapropel granules

Experimental tests revealed that the most promising for granulation with biomass ashes was peaty sapropel and its characteristic parameters were as follows: pH 7.6, moisture 92 %, organic matter 81 %, ash content 19 %, bulk density 1 066 kg m^{-3}. In turn, biomass ashes were represented by the following parameters: pH 12.6, moisture 1 %, volatile matter 8.8 %, fixed carbon 28 %, ash content 62 %, bulk and solid density – 370 and 2 430 kg m^{-3}, respectively, porosity 0.84 m m^{-3}. After granulation trials and application of the bisection method to detect the best ratio of the composition (Green and Southard, 2019), the mass ratio 67:100, respectively biomass ashes to sapropel, was assessed as the most suitable. Application of rotary drum granulation allowed deriving granules characterized with increased mechanical strength and bulk and apparent density higher in comparison with granules derived by the process of extrusion (Table 1).

Rotary drum-derived granules inhered greater mechanical strength (by 10 % to 25 %) and density (by 25 % to 50 %) if compared to extruded granules. Water absorption of granules was variable and mainly influenced by the properties of used sapropel type reaching up to 200 % for extruded granules. Besides, extrusion granules are characterized by lower moisture content.

Table 1: *Average values characterizing ash-sapropel granules.*

Parameter	Unit	Type of granules	
		Extruded (cylindrical)	From drums (spherical)
Diameter	cm	0.8	0.8
Height	cm	2.1	0.8
Volume	cm^3	1.1	0.4
Material column*	m	82 / 27 / 7	32 / 11 / 3
Density**	kg m^{-3}	137 / 280	393 / 560
Compressive strength	MPa	0.110	0.112
Specific surface area	m^2 g^{-1}	178	70
Water absorption	%	198	67

* Calculated with safety coefficient 1/3/10, respectively
**Bulk density / Apparent density

It was assessed that there might occur differences in physical parameters among the types of granules due to the technical peculiarities of the granulation process, *e.g*., spherical granules are harder, but with lower porosity and lower content of moisture, thus they can be more convenient for transporting and storage at industrial scale. The size of granules can be adjusted regarding the potential application target. The composition of granules can be adjusted regarding necessary outcome properties. Properties and moisture content of ingredients used for granulation are the main limiting factors for the quality of the derived product. pH measurements revealed that the use of biomass ashes for the production of granules in a mixture with sapropel could favorably lead to a decrease of alkaline character.

The total content of elements revealed the abundance of Ca, K, Mg, Mn, P, Al, Fe, and Na in granules, while other elements were detected in smaller amounts (Figure 3). Bioavailability of elements was assessed, considering their concentration in water or weak acid solution versus residual fraction.

Quantitative analysis revealed that the majority of elements (except K, Ca, Mg, Na, Li, and Sr) were bound in a residual fraction, which indicates their low solubility and slow release at ambient environmental conditions. However, a change of pH could affect the release of elements, whereas non-essential and

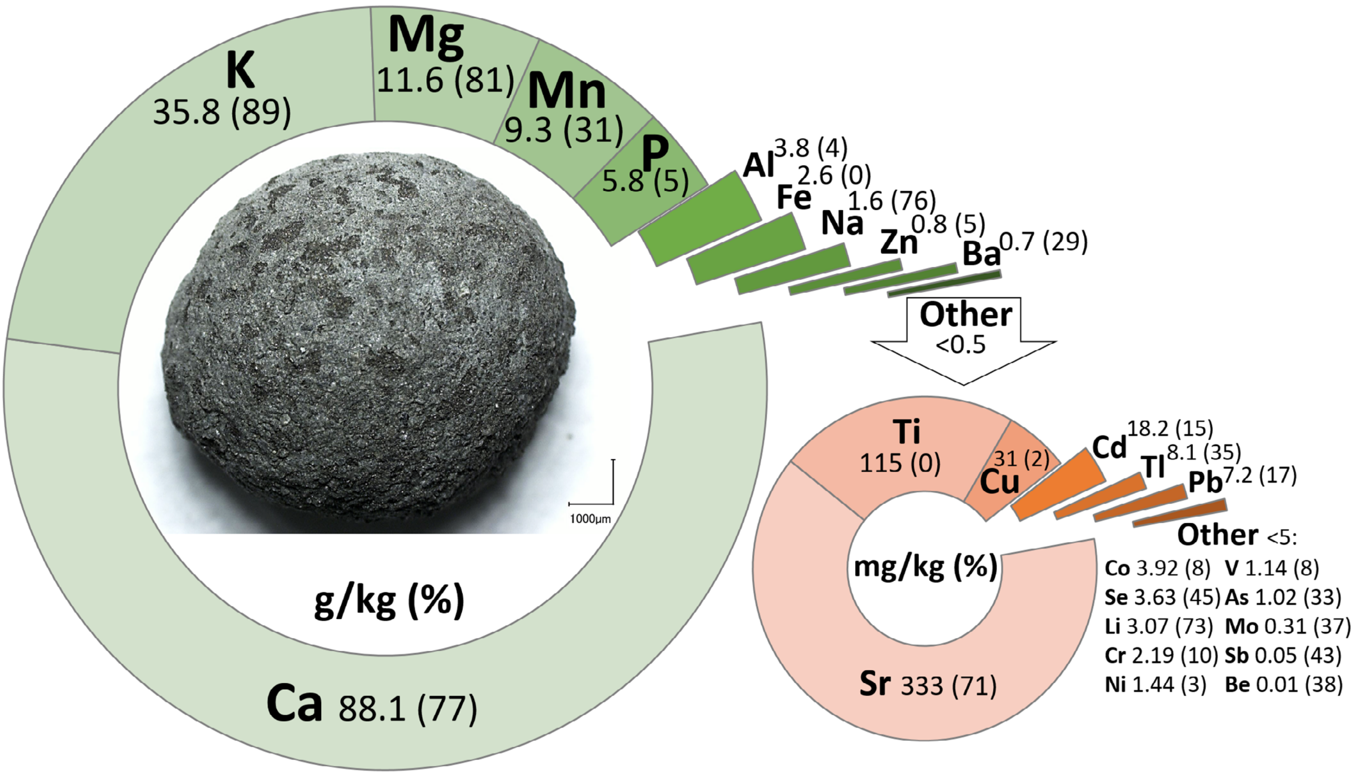

Figure 3: *Total content and bioavailability (in brackets) of elements (indicating maximum detected values as a worst-case), and visualization of a spherical ash-sapropel granule.*

potentially toxic elements preferably should be bound into insoluble compounds.

Regarding potentially toxic contaminants, quality provision requirements in Europe have been set specifically for bio-based soil improvers (EC, 2018). In the final product, the content of the following chemical elements must not be exceeded (expressed as mg kg^{-1} dry weight): Cd and Hg each 1 mg kg^{-1}, Mo 2 mg kg^{-1}, Ni 50 mg kg^{-1}, Cr, Cu, and Pb each 100 mg kg^{-1}, Zn 300 mg kg–1, and for products containing raw material from industrial processes Se 1.5 mg kg^{-1}, As 10 mg kg^{-1} and F 200 mg kg^{-1}. Furthermore, the content of glass, metal, and plastic must be lower than 0.5 % each and a product must not exceed the maximum levels of primary pathogens (*Salmonella* absent in 25 g of product, helminth ova absent in 1.5 g of product, *E. coli* < 1 000 MPN g^{-1}, where MPN – most probable number (EC, 2018). Nevertheless, these requirements may vary due to country-specific governmental regulations. Potentially toxic elements in elaborated ash-sapropel granules were detected at low concentrations, and their bioavailability was assessed as insignificant corresponding to the findings of other studies (Pesonen *et al.*, 2017). However, the obtained maximum values (Figure 3) indicated that some elements might be of concern, *i.e.*, the concentration of Zn, Se, and Cd in batch analyses can exceed those values set for bio-based soil improvers. However, it should be taken into account that the optimal application rate is relatively low and, therefore, adverse effects of potentially toxic elements in the environment would be unlikely. Plant response tests using fast-growing species such as *Lactuca sativa* L. revealed that the most optimal was the addition of 50 g L^{-1} of ash-sapropel granules; however, additional nutrient (N and P) source is needed for better plant development. Therefore, this peat-free formulation for soil improvement is still in need of beneficial modifications.

The purity and safety of raw material and final product is an important question of concern in elaborating such products as peat-free soil amendments. The problem related to biomass used for energy production is its variable chemical composition that depends on various factors (*e.g.*, plant species used, plant parts used, seasonality) and also affects generated waste – ashes – utilized as a raw material (EC, 2018; Masto *et al.*, 2015; Pesonen *et al.*, 2017; Vincevica-Gaile *et al.*, 2019). It results in problematic product validation and standardized quality assurance. The measures to monitor the concentration of elements of awareness involve batch analyses of raw material and the final product (EC, 2017; 2018).

It was assessed that the elaborated peat-free soil amendment is applicable as a soil amendment at particular conditions, i.e., specifics of soil conditions should be taken into account. The formula can be used to improve the state of soils exposed to salinization at certain conditions, as well sapropel content in it may serve as a metal immobilizer. The formula itself is not a universal but specific soil amendment, and it can be upgraded to a more widely applicable product (*e.g.*, peat-free substrate) when the development of the product is continued. However, the results indicated that adjusting other nutrients and pH is needed for a more optimal plant response, and it should be tested on various plant species. Therefore, the formula of peat-free soil conditioner preferably should be complemented sustainably by adding a natural source or secondary raw material rich in these essential nutrients, for example, by incorporating liquid manure, manure, slurry, compost, vermicompost, sapropel, or digestate.

Conclusions and Recommendations

Notwithstanding the broad availability of various materials, the way to sustainable peat-free soil amendments is obstacles covered. Several aspects have to be considered, such as the safety of materials (absence of chemical and biological hazardous components), chemical specification and composition, physical properties, material consistency, degradation potential, amount and seasonality of availability, etc. The complexity of peat-free soil amendment development involves its conformity to target functionality as it has to reconcile with soil-like texture and peat-like properties, as well as positive (or at least not adverse) effects on plant response.

The economically and environmentally justified choice of raw materials is one of the cornerstones in elaborating sustainable peat-free soil amendments. Locally available raw material should be considered as the most important source of possible ingredients. The case studies revealed the broad availability and appropriate utility of biomass ashes in soil improvement; however, their characteristic physical-chemical properties do not favor environmental awareness. Therefore, as a solution can be considered ash granulation with a natural binder. Peat-free soil amendment derived by granulation of energy production waste in a mixture with fresh organic-rich lake sediments presented as a case example is a step forward in sustainable material cycling; furthermore, extraction of freshwater sediments leads to expanded exploitation of local resources and prevention of lakes from overgrowth and extensive eutrophication. Derived granules are abundant in several elements (*e.g.*, Ca, K, Mg, Mn) with variable bioavailability; however, essential nutrient (N and P) enrichment and pH adjustment might be needed for a more optimal plant response essentially significant for the application in agriculture.

It can be concluded that peat-free soil amendment elaboration can be better implemented on a regional scale after assessing agricultural needs, soil specifics, and improvement needs, as well as available raw material variety applicable as ingredients in soil-improving products.

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Novelty Statement

The novelty of this study is driven by the global trends to find new sustainable and renewable materials that can replace peat which is a fossil resource but used in vast amounts for gardening, agriculture, planting, horticulture worldwide. General features for peat-free soil-improving products are stated in the article as well as an example of product development from biomass ashes and sapropel is shortly described.

Author's Contribution

ZVG: Designed and implemented the study, elaborated the data analysis, performed literature search, and analysis, manuscript preparation and revision.
KS: Performed literature search and analysis, data tabulation and manuscript revision.
MK and DD: Elaborated the intellectual content and study supervision.
RHS: Performed literature search and analysis, data tabulation, manuscript format, manuscript review and manuscript revision.
PGA, MZM, LZ, AS and RA: Performed literature

search and manuscript review.

JB and DHG: Performed literature search, manuscript review and guarantor.

All authors have read and approved the final manuscript.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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