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Low-temperature hydrothermally treated *Eucalyptus globulus* bark: From by-product to horticultural fiber-based growing media viability

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ABSTRACT

Worldwide, the circular economy approach increased the need of waste-streams minimization, promoting by-products re-circulation into the value chain which creates sustainable industrial synergies. *Eucalyptus globulus* bark fiber is a waste from pulp and paper industry that can be re-used in horticultural applications. This work aims to use low-temperature hydrothermally treated *E. globulus* bark as a fiber material for growing media formulation. Three types of bark fiber were used: industrial *E. globulus* fresh bark (IB) ground to output sieve of 6 × 6 mm, and two low-temperature hydrothermally treated barks (TB60: 60 °C, 20 min; TB100: 100 °C, 40 min). The three fiber materials were blended at 25 and 50% (v v^{-1}) (B25; B50) with peat. IB was phytotoxic for Cress (*Lepidum sativum)* seeds, causing low germination (91%) and root growth inhibition. TB60 and TB100 reduced significantly phytotoxicity with germination rates of 98 and 100%, and Munoo Liisa index around 90% compared to commercial substrate. A pot experiment using Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) as a model plant, revealed lower germination (95%) in IB blends than in treated ones and in commercial substrate (CS) (98–100%), reinforcing the IB phytotoxicity. B50 decreased water retention, and reduced plant growth due to nitrogen immobilization inherent to woody biomass. B25 showed shoot weight, and root growth statistically equal or higher than CS, encouraging use of this blending proportion of low-temperature hydrothermally treated bark in future growing media formulation. Circular horticulture approach is applied through the present fiber valorization into substrate component.

1. Introduction

Horticultural plant production is aligned with challenges to feed the world by 2050, where 50% more food is estimated to be needed to feed global population of 9.8 billion (European Comission, 2019; United Nations, 2019). Worldwide, essential steps have been taken towards circular horticulture concept: producing high quality, quantity and safe food with less inputs focused on efficient resource use, and re-introduction of organic side-streams as new raw-materials (European Comission, 2019).

Given the advantages of soilless growing and the increasing world population, growing media demand is predicted to increase by four times in next 30 years (Blok et al., 2021). Currently, peat moss is the most used organic material and is expected to keep the highest demand by 2050, however being less representative, dropping from more than 65% of the growing media needs in 2017 (Vandecasteele et al., 2020) to around 35% in 2050 (Blok et al., 2021). However, due to increased environmental awareness of peatlands conservation, by 2050 peat bog extraction will be restricted by European regulation, thus peat availability will reduce (FAO, 2015). Comparing the estimated needs of growing media by 2050 and the potential volumes available per material, Blok et al. (2021) found a gap of 65 Mm^3 $year^{-1}$ which may or may not be filled by alternative materials.

Intensive research aiming new peat alternative materials in horticultural industry has been done (Carlile et al., 2019; Chemetova et al., 2019; Gruda et al., 2009; Illera-Vives et al., 2015; Jackson et al., 2010; Petropoulos et al., 2019; Ribeiro et al., 2009; Zhong et al., 2018). Wood-based materials from locally sourced biomass (Gruda, 2019), mainly from spruce (*Picea* spp.), pine (*Pinus* spp.) and other softwood trees, including wood chips, wood fiber and sawdust, have been studied

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and commercialized as growing media components (Caron and Michel, 2017; Gruda and Schnitzler, 2004; Jackson et al., 2010, Vandecasteele et al., 2018). Physical properties of organic growing media are one of the main characteristics for successful plant growth due to their influence in container media ability to store and supply adequate air and water (Bonaguro et al., 2017; Wallach, 2019). Using bark and wood-based materials as growing media component improve airiness, porosity, and drainage capacity; when blended with peat-based substrates, fibers reduce shrinkage by improving re-wettability and water distribution (Buamscha et al., 2008; Chemetova et al., 2018; Jackson et al., 2010).

At European level, biomass waste-streams transformation into opportunities as integrate process for value-chain creation, potentiates micro to macro-level synergies (European Comission, 2019; Gruda, 2019) e.g., between horticultural and pulp and paper (PP) industries. In 2017, European PP industry used 149 Mm^3 of wood, where 13 Mm^3 belongs to *Eucalyptus* (CELPA, 2017). In Iberian countries, *Eucalyptus globulus* is the main species for PP production (Domingues et al., 2013; Neiva et al, 2014, 2016). In bleached pulp production bark remains excess fiber, and 7–20% of *E. globulus* stem's dry weight is bark (Neiva et al., 2014), thus total *E. globulus* bark surplus resulted in 0.91–2.6 Mm^3 y^{-1}. As an industrial by-product it is normally burned for energy production in power plants within industrial facilities (Neiva et al., 2016), which remains a low added value product application.

Due to its availability and fibrous nature, *E. globulus* bark might be a candidate for use as raw-material in horticulture growing media formulation. However, chemically, *E. globulus* bark is rich in phenolic, triterpenic and other inhibitory compounds (Domingues et al., 2013; Neiva et al, 2014, 2016), being toxic for plants Chemetova et al. (2018). Phytotoxicity is a common issue of woody biomass caused by natural chemical barriers (Chemetova et al., 2019). In the natural environment, the role of these chemical compounds has a protection effect against diseases or infections of native plants, although they also act as toxins for other cultivations in growing media applications (Gruda et al., 2009; Petropoulos et al., 2019).

Treatment of bark with water at temperatures below 150 °C (low-temperature hydrothermal treatment) was proposed by Chemetova et al. (2018) to reduce toxicity and microbial activity in *E. globulus* bark, making this treated bark a potential component for horticulture growing media. In addition, low-temperature hydrothermal treated bark maintains its physical properties, namely, a very high air content that can be a plus in aeration improvement of growing media. Low-temperature hydrothermal treatment is, also, attractive due to its simplicity, low construction material cost requirement, rapid implementation with null material corrosion and chemical free nature.

In literature, there is no information on viability of using treated *E. globulus* bark as raw-material for growing media formulation. In line with previous study (Chemetova et al., 2018), the objective of this research is to evaluate two low-temperature hydrothermal treated *E. globulus* barks, in comparison with fresh untreated bark, as a growing media component for the horticulture industry, assessing (i) physical, chemical and biological properties of bark-based growing media and, (ii) plant performance in bark-based growing media contrasting to settled commercial substrate.

2. Materials and methods

2.1. Raw-material and treatment selection

Fresh industrial *E. globulus* bark (IB) was collected from The Navigator Company pulp mill (Setúbal, Portugal) in November 2015. Bark samples were dried at 35 °C in an electric oven for 7 days and grinded in a knife mill (Fritsch pulverisette 15 - Fritsch GmbH, Idar-Oberstein, Germany) with an output sieve size of 6 mm, producing a fibrous material: bark-fiber.

Chemetova et al. (2018) optimized a low-temperature hydrothermal treatment to remove phytotoxic compounds a reduce microbial decomposition of *E. globulus* bark, and concluded that temperature was the significant factor, with an optimal window temperature between 40 °C and 80 °C. Thus, two low-temperature hydrothermal treatment were used in this study: an optimal temperature TB60 (60 °C for 20 min) and a highest temperature treatment TB100 (100 °C for 40 min). The TB60 and TB100 treatments were performed according Chemetova et al. (2018) methodology. All experiments were done in randomized order to minimize uncontrolled factors.

2.2. Growing media formulation

IB, and TB60 and TB100 were blended with peat moss slightly decomposed (H2-H5 on Von post scale) amended with 4 g L^{-1} of dolomitic lime to adjust the pH (5.6–5.8), in volumetric proportion of 25 and 50% (bark/peat) (B25; B50). According to European Standard (CEN, 2011a), all bark-based blends were fertilized with a nutrient-based solution: 15 mmol NO_3-N L^{-1}, 8 mmol K L^{-1}, 4 mmol Ca L^{-1}, 1.5 mmol Mg L^{-1}, 1.25 mmol Sulfate (SO_4^{2-}) L^{-1}, 1.5 mmol Dihydrogen phosphate ($H2PO_4^{-}$) L^{-1}, 15 μmol Iron (Fe) L^{-1}, 8 μmol Manganese (Mn) L^{-1}, 4 μmol Zink (Zn) L^{-1}, 25 μmol Boron (B) L^{-1}, 0.75 μmol Copper (Cu) L^{-1}, 0.5 μmol Molybdenum (Mo) L^{-1}).

A peat-based commercial propagation substrate (CS) from Floragard Co. (Germany) with volumetric proportion 3:1 (v v^{-1}) of white/black peat, limed (pH 5.6) and fertilized, was adopted as control reference in plant response experiments.

2.3. Physical, chemical and biological properties

The pH, electrical conductivity (EC), and water-soluble Potassium (K), Phosphorous (P), Calcium (Ca), Magnesium (Mg), Sodium (Na) and mineral N i.e. Ammonium (NH_4^{+}-N) plus Nitrate (NO_3^{-}-N), were measured in water extract 1:5 by volume, according to the European Standards (CEN, 2001, 1999a; 1999b). The dry mass (DM) was assessed by oven-drying bark at 105 °C for 24 h and the ash content was determined by combustion of the oven-dried sample at 550 °C for 5 h in a muffle furnace. The difference between DM and ash was considered the organic matter content. Based on incubation methodology described by Chemetova et al. (2018), the N immobilization (NR) and respiration rates (CR) were measured during 14 days (Buamscha et al., 2008; Fangueiro et al., 2012).

The physical properties as defined by Wallach (2019), were determined according to literature methodology (Caron et al., 2010): total porosity (TP), bulk density (BD), easily available water (EAW) as the difference between the water content at suctions of 1 and 5 kPa, water-buffering capacity (WBC) as the difference between the water content at 5 and 10 kPa, available water (AW) as the difference between the water content at suctions of 1 and 10 kPa, air-filled porosity (AFP) as the amount of air at a suction of 1 kPa, and shrinkage.

2.4. Plant response: Petri dish and pot experiment

According to European Standards (CEN, 2011a), a total of 10 cress (*Lepidium sativum*) seeds were incubated in Petri dishes (square, 100 mm length and width, 18 mm height) filled with samples (180 cm^3), at room temperature (25 °C) in the dark, for 3 days. The experiment was carried out in triplicate (1–3) and using CS as control (C). Phytotoxicity was evaluated by the Munoo Lisa Vitality Index (MLV; Eq. (1)), using germination rate (GR, where GR_{1-3} are the triplicates and GR_C is the control) and root length (RL, where RL_{1-3} are the triplicates and RL_C is the control).

$$Munoo\ Liisa\ Vitality\ Index\ (\%) = \frac{(GR_1 \times RL_1 + GR_2 \times RL_2 + GR_3 \times RL_3)}{3 \times GR_C \times RL_C} \times 100 \quad (1)$$

Adapted from European Standards Soil improvers and growing media - determination of plant response (CEN, 2011b), a pot experiment using containers with a volume of 290 mL (Ø = 8.5 cm; height = 8.2 cm) filled with substrate blends and a total of 10 Chinese cabbage (*Brassica napa* subsp. *pekinensis*) seeds per pot were sown and grown for 5 weeks. During the entire experiment time range, all pots were placed in an unheated glass greenhouse, distributed in a complete randomized design. Pots were daily irrigated with deionized water, to avoid the effect of different compounds usually present in tap water. The experiment was carried out in triplicate (1–3) and using CS as control. At the end of the growing period, sample fresh weight (FW), dry weight (DW, at 65 °C for 48 h), germination rate and root visual rating (1 = the worst; 5 = the best) were measured.

2.5. Statistics

The experimental design was a "completely randomized design", with one primary factor: substrate. Data were subject to analysis of variances (ANOVA), followed by least square difference test (LSD) based on the p-value with 95% of confidence level ($p \leq 0.05$). Data were analyzed using Statistica ® 10.0 (StatSoft, USA).

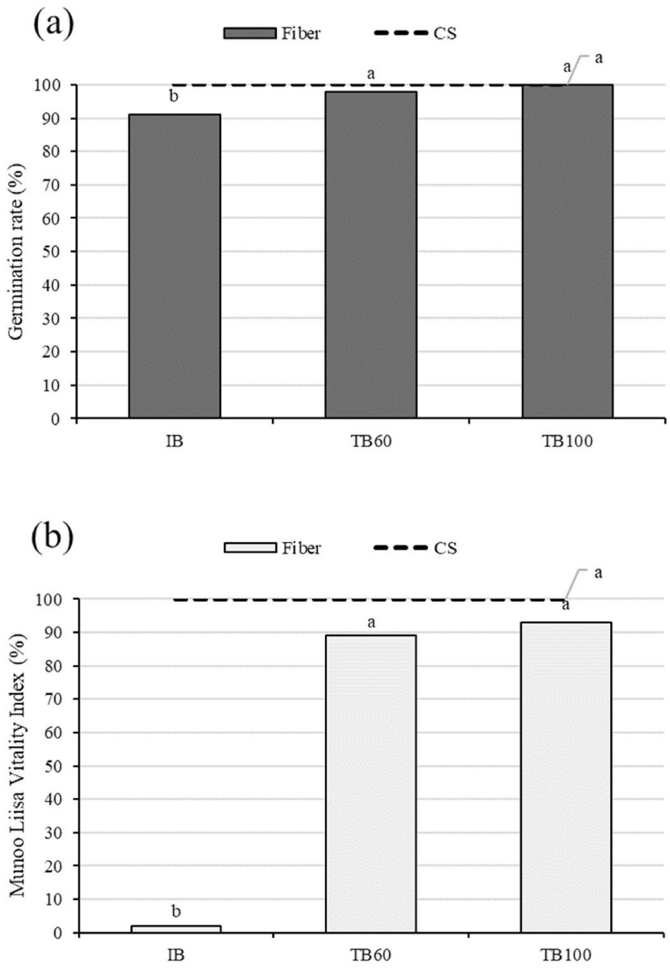

Fig. 1. Phytotoxicity evaluation of fiber material industrial fresh bark (IB), both low-temperature hydrothermal treated barks (TB60, TB100) and commercial substrate (CS): **(a)** germination rate and **(b)** Munoo-Lisa Vitality Index.

3. Results and discussion

3.1. *E. globulus* bark fiber properties

Fresh bark was phytotoxic for cress seeds (Fig. 1), causing low germination rate (GR) and root growth inhibition with MLV of 2%. The hydrothermal treatment of barks reduced bark toxicity, with GR of 98.3 and 100%, and MLV of 89 and 93%, in TB60 and TB100, respectively. The TB60 and TB100 statistically equal results as CS may indicate the efficient removal of toxic elements on both treatments. Research on aqueous washing of pine bark (Gruda et al., 2009) also recorded reduction of toxins levels, associated with decline of resin acids, fatty acids and phenols content. *E. globulus* bark chemical composition had demonstrated high extractable inhibitory compounds (Neiva et al., 2016) and GR and MLV of fresh bark fiber (Fig. 1) are in accordance with previous phytotoxicity findings (Chemetova et al., 2018). Thus, as strongly recommended for other wood-based fibers (Brito et al., 2013; Buamscha et al., 2008; Gruda, 2012a; Jackson et al., 2010), *E. globulus* bark must be treated before use as growing media.

All fiber materials were biologically unstable in contrast with peat which showed a very low microbial activity (Table 1). After 14 days incubation, higher N immobilization (NR) and respiration rates (CR) were measured in IB and TB100, followed by TB60. Although treatments removed part of organic material, maximum NR in TB100 (0.9 mmol N L^{-1} d^{-1}) might be explained by fiber structural fragmentation, associated to higher treatment temperatures, that increased cellulose digestibility (Neiva et al., 2016) and strongly promoted microorganism activity (Depardieu et al., 2016). The high amount of N consumption by microorganisms in wood fiber materials have been broadly reported (Carlile et al., 2019; Chemetova et al., 2018; Gruda, 2019; Van Gerrewey et al., 2020). Biological activity promotes simultaneous release of CO_2 and proportional capacity to immobilize N, and if there is a microbial need for N, it may occur soon after potting and therefore N fertilization should be applied before pot planting (Buamscha et al., 2008).

Acidic pH of 4.0 was verified in peat moss (before liming), followed by IB with 4.9 and treatments significantly increased barks pH (Table 1). No mineral nitrogen was detected in bark fibers neither in peat (levels below the quantification limit of 2 mg L^{-1}) and IB had higher levels of water-soluble P, K, Ca, Mg and Na. The use of demineralized water in the low-temperature hydrothermal treatments may have leached the soluble elements (Chemetova et al., 2018), decreasing their concentration in TB60 and TB100, consequently, reducing the EC. However, all materials had low EC values and low levels of available nutrients, except for K and Mg. It is noticeable that peat, TB60 and TB100 showed statistical equal chemical composition regarding water-soluble nutrients.

Fig. 2 and Table 2 show substrate air-water relationships. The treatments did not affect fiber physical properties, with all barks presenting low bulk density (BD) and water availability, and very high total porosity (TP) plus aeration (AFP), greater than 80% (v v^{-1}). On the contrary, peat had low AFP (8% v v^{-1}) and high-water availability. Wood fibers relative lightweight and very high air capacity have been recognized for good drainability and aeration improvement in peat-based substrate (Caron and Michel, 2017). Similar shrinkage was observed in all bark raw-material.

3.2. *E. globulus* bark fiber-based growing media properties

All bark-based growing media blends were fertilized with a complete nutrient solution (section 2.2), and with an extra amount of 100 mg N L^{-1} (total 200 mg N L^{-1}) compared to CS (100 mg L^{-1}), to compensate potential bark mineral N competition documented in previous work (Chemetova et al., 2018) and confirmed in Table 1. All substrates pH values were within recommended range (5.3–6.5) and EC values lower than the threshold value of 60 mS m^{-1} (Table 3). The fiber-based blends nutrient content was within or slightly higher than the recommended range for a growing media (Barrett et al., 2016); consequently, no

Table 1

Chemical properties of fiber barks and peat moss: nitrogen immobilization rate (NR), respiration rate (CR), pH, electrical conductivity (EC), mineral nitrogen (N_{min}), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). Means followed by the same letter, in column, do not differ at $P \leq 0.05$ by the LSD-test. n.d. = not detected, below quantification limit (<2 mg L^{-1}).

Raw-material	NR	CR	pH	EC	N_{min}	P	K	Ca	Mg	Na
	mmol N L^{-1} d^{-1}	mmol CO_2 L^{-1} d^{-1}		mS m^{-1}	mg L^{-1}					
IB	0.80 a	15.4 a	4.9 c	22 a	n.d.	8	167 a	9 a	22 a	38 a
TB60	0.63 b	14.1 a	5.8 a	6 b	n.d.	n.d.	32 b	3 a	5 b	3 b
TB100	0.90 a	15.7 a	5.5 b	6 b	n.d.	n.d.	27 b	3 a	4 b	3 b
Peat	0.00 c	1.3 b	4.0 d	5 b	n.d.	n.d.	6 b	3 a	1 c	3 b

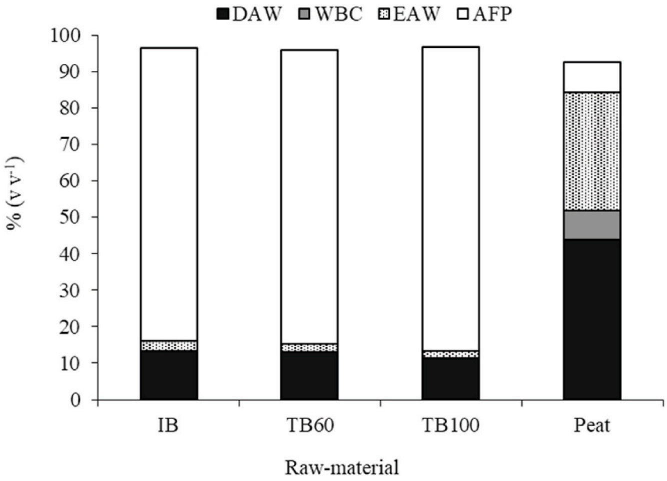

Fig. 2. Raw-materials physical properties, air-filled porosity (AFP), easy available water (EAW), water buffering capacity (WBC), and difficult available water (DAW).

Table 2

E. globulus fibers and peat physical properties: bulk density (BD), total porosity (TP) and shrinkage. Means followed by the same letter, in column, do not differ at $P \leq 0.05$ by the LSD-test.

Raw-material	BD	TP	Shrinkage
	g L^{-1}	% (v v^{-1})	
IB	58.0 c	96.3 a	8.2 b
TB60	64.7 b	95.9 a	11.2 b
TB100	52.3 d	96.7 a	8.1 b
Peat	119.8 a	92.4 b	34.9 a

limitations to plant growth are expected caused by nutrient deficit (Vandecasteele et al., 2020).

Bark addition to peat had a significant effect on substrates physical properties (Table 4). Bark increased total porosity and improved peat aeration. AFP rose from 8.3% v v^{-1} in peat (Table 4) to an average of 26.9% in B25, and 46.1% in B50 blends. Following an inverse trend, gradual bark addition decreased water availability. Shrinkage was also reduced by bark increment and tended to meet previous results from Table 2. Shrinkage is often related to hydrophobic effects caused by drying and it is a problem mainly for outside plant production (Gruda and Schnitzler, 2004). In these cases, due to channeling, irrigation water drains very fast through the cracks or the void between container wall and the substrate (Caron and Michel, 2017; Jackson et al., 2010). Concerning standard range for substrate physical properties, B25 blends fitted in recommended values. Generally, it is assumed that high AFP promote air supply to the roots but can compromise water availability (Jackson et al., 2010), but with addition of 25% of bark, aeration may improve while water availability remains adequate (Table 4). Gruda (2012b) pointed out the relevance of higher irrigation frequency when wood fibers are used as a component of growing media to maintain container water content.

3.3. *Plant response*

3.3.1. *Petri dish test using cress*

Fig. 3 (a) and (b) shows the results of the cress seed germination rate and Munoo-Liisa vitality index (MLV), using the commercial substrate as control. Equal GR (100%) was recorded for all substrates, but there were significant differences concerning MLV. Bark increment in the blends led to MLV reduction, with lower values in B50 substrates. In B50 substrates, IB presented the lowest MLV (73.8%), against 80.3% in TB60 and 88.5% in TB100, underlining the positive effect of treatments on phytotoxicity reduction.

B25 substrates showed high MLV values (>90%), suggesting that mixing 25% of bark with peat-based growing media may present favorable results for further consideration in substrates formulation, which is in accordance with previous determination (Chemetova et al., 2018). The percentage of bark in a mixture could influence the extent of phytotoxicity and generally recommended peat substitution by wood fiber materials is up to 30% (v v^{-1}) (Barrett et al., 2016; Brito et al., 2013; Gruda, 2019; Petropoulos et al., 2019).

3.3.2. *Pot growth test with Chinese cabbage*

Potting test, using Chinese cabbage (Table 5), revealed lower

Table 3

Bark fiber-based blends and commercial substrate pH, electrical conductivity (EC), and nutrients: mineral nitrogen (N_{min}), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). Means followed by the same letter, in column, do not differ at $P \leq 0.05$ by the LSD-test. Acceptable range adapted from Barret et al. (2016).

Substrate	Bark type	pH	EC	N_{min}	P	K	Ca	Mg	Na
			mS m^{-1}	mg L^{-1}					
B25	IB	5.7 a	59 a	193 a	50 a	313 ab	154 c	61 a	22 c
	TB60	5.6 a	56 ab	203 a	45 a	257 c	164 bc	58 a	12 d
	TB100	5.7 a	58 ab	197 a	39 a	268 c	155 c	65 a	12 d
B50	IB	5.7 a	58 a	196 a	34 a	336 a	167 bc	69 a	32 b
	TB60	5.7 a	53 b	209 a	35 a	279 bc	172 bc	62 a	12 d
	TB100	5.7 a	53 b	203 a	36 a	282 bc	192 b	64a	11 d
CS	–	5.9 a	37 c	94 b	26 a	181 d	264 a	22 b	40 a
Acceptable range	–	5.5–6.5	<50	50–250	19–75	51–400	16–80	16–80	<100

Table 4
Bark fiber-based blends physical properties: bulk density (BD), total porosity (TP), air-filled porosity (AFP), easy available water (EAW), water buffering capacity (WBC), available water (AW) and shrinkage. Means followed by the same letter, in column, do not differ at $P \leq 0.05$ by the LSD-test. Acceptable range adapted from Caron and Michel (2017).

Substrate	Bark type	BD	TP	AFP	EAW	WBC	AW	Shrinkage
		g L^{-1}	% (v v^{-1})					
B25	IB	109.3 b	93.3 b	28.0 bc	23.1 b	5.1 bc	28.2 b	24.1 bc
	TB60	110.2 b	93.2 b	29.1 b	23.4 b	5.1 bc	28.5 b	26.5 b
	TB100	113.6 b	93.0 b	23.7 c	26.0 b	5.2 b	31.2 b	25.6 b
B50	IB	96.8 c	94.0 a	45.1 a	16.4 c	4.3 bc	20.7 c	19.4 cd
	TB60	94.8 c	94.1 a	46.1 a	16.3 c	3.6 c	20.0 c	15.5 d
	TB100	92.9 c	94.3 a	47.1 a	15.8 c	4.2 bc	20.0 c	17.9 d
CS	–	139.1 a	91.5 c	10.5 d	30.9 a	8.3 a	39.2 a	39.7 a
Acceptable Range		<400	>85	10–30	20–30	4–10	24–40	<30

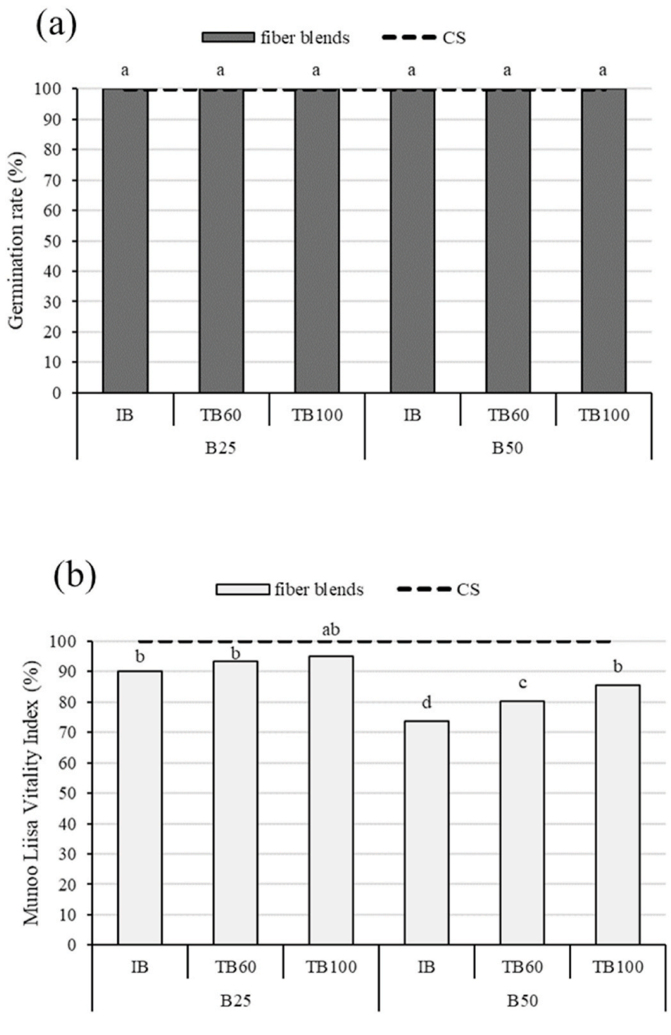

Fig. 3. Phytotoxicity evaluation of fiber growing media blends and commercial substrate (CS): **(a)** germination rate and **(b)** Munoo-Lisa Vitality Index.

germination rate (95%) in IB blends than in TB60, TB100 and CS (98–100%), reinforcing the fresh bark phytotoxicity. Phytotoxicity is a problem to solve when wood and bark-based materials are used as growing media component, due to the presence of inhibitory compounds like phenolic, terpenes and tannins (Caron et al., 2010; Gruda, 2012a) and *E. globulus* bark is known to be rich in inhibitory compounds (Domingues et al., 2013; Neiva et al., 2016). These chemical compounds are a natural protection against diseases or infections of native plants, although they also act as toxins for other plants when used as growing media (Gruda et al., 2009; Petropoulos et al., 2019).

Table 5
Potted plant response: Chinese cabbage germination rate (GR) fresh weight per pot (FW), dry weight per pot (DW), roots rating. Means followed by the same letter, in column, do not differ at $P \leq 0.05$ by the LSD-test.

Substrate	Bark type	GR	FW	DW	Root rating
		%	g pot^{-1}		[1–5]
B25	IB	95 b	17.4 ab	2.9 ab	4.7 a
	TB60	100 a	15.7 ab	2.8 ab	4.0 a
	TB100	100 a	18.5 a	3.3 a	3.7 ab
B50	IB	95 b	9.0 c	1.5 c	2.7 cd
	TB60	100 a	8.3 c	1.5 c	2.7 cd
	TB100	98 ab	6.9 c	1.2 c	2.4 d
CS	–	100 a	14.3 b	2.6 b	3.2 bc

Due to its negative effect on plant growth, different approaches have been suggested to reduce fresh bark phytotoxicity. Aging douglas fir bark (*Pseudotsuga menziesii*) (Buamscha et al., 2008) and acacia bark (*Acacia melanoxylon*) (Chemetova et al., 2019), washing/leaching pine bark (Gruda et al., 2009) and composting pine bark (Jackson et al., 2010) have been proposed to remove bark phytotoxicity. Our results show that low-temperature hydrothermal treatment is, also, effective in removing *E. globulus* bark toxicity, and are in accordance with previous results reported by Chemetova et al. (2018). Low-temperature hydrothermal treatment is as an attractive process due to its simplicity and rapid implementation (Chemetova et al. (2018), while using only water as the main reagent (Barrett et al., 2016).

B25 blends showed shoot weight and roots rating statistically equal or higher than CS. B25 increased Chinese cabbage growth may be due to favorable conditions for plant and root development as bark incorporation improved substrate aeration while maintained adequate water availability (Table 4). Indeed, bark and wood-based materials improve airiness, porosity, and drainage capacity of growing media component and when blended with peat-based substrates, fibers reduce shrinkage by improving re-wettability and water distribution (Buamscha et al., 2008; Chemetova et al., 2018; Jackson et al., 2010). In addition, it seems that the N surplus applied (100 mg N L^{-1}) was enough to counteract bark N immobilization in B25 blends. As the CS treatment did not receive the N surplus (no N immobilization was expected), it is possible that the CS yield is slightly lower because of that underfertilization. Our results are in accordance with Wright et al. (2008) and Gruda (2012b), that recommend an additional supply of 100 mg L^{-1} of nitrogen to plants grown in substrates containing wood-based materials.

However, plant growth was lower in substrates with 50% bark (B50). Reduction of plant growth, when high percentages of wood and bark-based materials are used in growing media, have been found by several authors (Buamscha et al., 2008; Depardieu et al., 2016; Petropoulos et al., 2019; Zawadzinska et al., 2021) and it is probably related with unsuitable water retention properties as well as N immobilization.

The water availability in substrates with 50% bark (B50) has a lower than the other tested substrates (Table 4). Substrates based on wood and bark fibers have a much lower water holding capacity than peat substrates and using the same irrigation strategy, as in peat-based substrates, a reduction of plant growth is often found (Gruda, 2012b), like was observed in B50 substrates.

High nitrogen immobilization (NR) and respiration rates (CR) were found in both treated barks (Table 1). Nitrogen immobilization has been widely reported in wood and bark-based materials (Chemetova et al., 2018; Gruda, 2019; Van Gerrewey et al., 2020), and is associated with activity of microorganisms that degrade polysaccharides components, like cellulose and hemicellulose, and assimilate the resulting monosaccharides. Microorganisms activity/growth involves acquisition of nitrogen (Carlile et al., 2019), reducing its availability for plants. The high percentage of bark in B50 substrates, and the high nitrogen immobilization in *E. globulus* barks (Table 1), justifies the lower plant growth. In addition, it seems that the N surplus applied (100 mg N L^{-1}) was not enough to counteract bark N immobilization in B50 blends.

4. Conclusions

The study confirms that hydrothermal treatments were effective regarding phytotoxicity removal from *E. globulus* fresh bark. Due to less temperature, energy and time consumption, and less N immobilization, the TB60 treatment (60 °C and 20 min) seems to be the most adequate. Blending 25% (in volume) of treated bark with peat shows simultaneously improvements in growing media aeration properties, while adequate water content is maintained. An additional N amendment (100 mg N L^{-1}) in 25% bark fiber-based blends (to counteract N-immobilization), allowed a Chinese cabbage growth (shoot weight and roots rate) statistically equal or higher than in commercial substrate. Results encourage the use of this proportion of hydrothermally treated *E. globulus* bark, as growing media component, in horticulture industry.

CRediT authorship contribution statement

C. Chemetova: Conceptualization, Formal analysis, Writing – original draft. **D. Mota:** Investigation, Validation. **A. Fabião:** Writing – review & editing. **J. Gominho:** Resources, Writing – review & editing. **H. Ribeiro:** Conceptualization, Visualization, Supervision.

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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References

Barrett, G.E., Alexander, P.D., Robinson, J.S., Bragg, N.C., 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems - a review. Sci. Hortic. (Amst.) 212, 220–234. https://doi.org/10.1016/j.scienta.2016.09.030.

Blok, C., Eveleens, B., van Winkel, A., 2021. Growing media for food and quality of life in the period 2020-2050. Acta Hortic. 1305, 341–354. https://doi.org/10.17660/ActaHortic.2021.1305.46.

Bonaguro, J.E., Coletto, L., Zanin, G., 2017. Environmental and agronomic performance of fresh rice hulls used as growing medium component for Cyclamen persicum L. pot plants. J. Clean. Prod. 142, 2125–2132. https://doi.org/10.1016/j.jclepro.2016.11.071.

Brito, L.M., Saldanha, J., Mourão, I., Nestler, H., 2013. Composting of acacia longifolia and acacia melanoxylon invasive species. Acta Hortic. 1013, 211–216. https://doi.org/10.17660/ActaHortic.2013.1013.24.

Buamscha, M.G., Altland, J.E., Sullivan, D.M., Horneck, D.A., McQueen, J.P.G., 2008. Nitrogen availability in fresh and aged douglas fir bark. HortTechnology 18, 619–623. https://doi.org/10.21273/HORTTECH.18.4.619.

Carlile, W.R., Raviv, M., Prasad, M., 2019. Organic soilless media components. In: Soilless Culture. Elsevier, pp. 303–378. https://doi.org/10.1016/B978-0-444-63696-6.00008-6.

Caron, J., Michel, J.C., 2017. Overcoming physical limitations in alternative growing media with and without peat. Acta Hortic. 1168, 413–422. https://doi.org/10.17660/ActaHortic.2017.1168.53.

Caron, J., Morel, P., Rivière, L.-M., Guillemain, G., 2010. Identifying appropriate methodology to diagnose aeration limitations with large peat and bark particles in growing media. Can. J. Soil Sci. 90, 481–494. https://doi.org/10.4141/CJSS09015.

CELPA, 2017. Indústria papeleira portuguesa, boletim Estatístico. https://doi.org/10.1017/CBO9781107415324.004.

CEN, 2011a. EN 16086-2 - Soil Improvers and Growing Media, Determination of Plant Response – Part 2: Petri Dish Test Using Cress. European Committee for Standardization, Brussels.

CEN, 2011b. EN 16086- 1 Soil Improvers and Growing Media, Determination of Plant Response - Part 1: Pot Growth Test with Chinese Cabbage (Brussel).

CEN, 2001. EN 13652 - Soil Improvers and Growing Media, Extraction of Water Soluble Nutrients and Elements. European Committee for Standardization, Brussels.

CEN, 1999a. EN 13038 - Soil Improvers and Growing Media, Determination of Electrical Conductivity. European Committee for Standardization, Brussels.

CEN, 1999b. EN 13037 - Soil Improvers and Growing Media. determination of pH, European Committee for Standardization, Brussels.

Chemetova, C., Fabião, A., Gominho, J., Ribeiro, H., 2018. Range analysis of Eucalyptus globulus bark low-temperature hydrothermal treatment to produce a new component for growing media industry. Waste Manag. 79, 1–7. https://doi.org/10.1016/j.wasman.2018.07.019.

Chemetova, C., Quilhó, T., Braga, S., Fabião, A., Gominho, J., Ribeiro, H., 2019. Aged Acacia melanoxylon bark as an organic peat replacement in container media. J. Clean. Prod. 232, 1103–1111. https://doi.org/10.1016/j.jclepro.2019.06.064.

Depardieu, C., Premont, V., Boily, C., Caron, J., 2016. Sawdust and bark-based substrates for soilless strawberry production: irrigation and electrical conductivity management. PloS One 11, 1–20. https://doi.org/10.1371/journal.pone.0154104.

Domingues, R.M.A., De Melo, M.M.R., Oliveira, E.L.G., Neto, C.P., Silvestre, A.J.D., Silva, C.M., 2013. Optimization of the supercritical fluid extraction of triterpenic acids from Eucalyptus globulus bark using experimental design. J. Supercrit. Fluids 74, 105–114. https://doi.org/10.1016/j.supflu.2012.12.005.

European Comission, 2019. EIP-AGRI Focus Group Circular Horticulture (Final Report).

Fangueiro, D., Ribeiro, H.M., Vasconcelos, E., Coutinho, J., Cabral, F., 2012. Influence of animal slurries composition and relative particle size fractions on the C and N mineralization following soil incorporation. Biomass Bioenergy 47, 50–61. https://doi.org/10.1016/j.biombioe.2012.10.003.

FAO, 2015. Adoption of the Paris Agreement.

Gruda, N., 2012a. Current and future perspective of growing media in Europe. Acta Hortic. 960, 37–43. https://doi.org/10.17660/ActaHortic.2012.960.3.

Gruda, N., 2012b. Sustainable peat alternative growing media. Acta Hortic. 927, 973–979. https://doi.org/10.17660/ActaHortic.2012.927.120.

Gruda, N., Rau, B.J., Wright, R.D., 2009. Laboratory bioassay and greenhouse evaluation of a pine tree substrate used as a container substrate. Eur. J. Hortic. Sci. 74, 73–78.

Gruda, N., Schnitzler, W.H., 2004. Suitability of wood fiber substrate for production of vegetable transplants: I. Physical properties of wood fiber substrates. Sci. Hortic. (Amst.) 100, 309–322. https://doi.org/10.1016/j.scienta.2003.10.001.

Gruda, N.S., 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy 9, 1–24. https://doi.org/10.3390/agronomy9060298.

Illera-Vives, M., López-Fabal, A., López-Mosquera, M.E., Ribeiro, H.M., 2015. Mineralization dynamics in soil fertilized with seaweed-fish waste compost. J. Sci. Food Agric. 95, 3047–3054. https://doi.org/10.1002/jsfa.7207.

Jackson, B.E., Wright, R.D., Barnes, M.C., 2010. Methods of constructing a pine tree substrate from various wood particle sizes, organic amendments, and sand for desired physical properties and plant growth. Hortscience 45, 103–112.

Neiva, D.M., Gominho, J., Fernandes, L., Lourenço, A., Chemetova, C., Simões, R.M.S., Pereira, H., 2016. The potential of hydrothermally pretreated industrial barks from E. Globulus as a feedstock for pulp production. J. Wood Chem. Technol. 36, 383–392. https://doi.org/10.1080/02773813.2016.1184280.

Neiva, D.M., Gominho, J., Pereira, H., 2014. Modeling and optimization of Eucalyptus globulus bark and wood delignification using response surface methodology. BioResources 9, 2907–2921. https://doi.org/10.15376/biores.9.2.2907-2921.

Petropoulos, S., Fernandes, Â., Stojković, D., Pereira, C., Taofiq, O., Di Gioia, F., Tzortzakis, N., Soković, M., Barros, L., Ferreira, I.C.F.R., 2019. Cotton and cardoon byproducts as potential growing media components for Cichorium spinosum L. commercial cultivation. J. Clean. Prod. 240 https://doi.org/10.1016/j.jclepro.2019.118254.

Ribeiro, H.M., Vasconcelos, E., Cabral, F., Ribeiro, D., 2009. Fertilization of Pinus pinea L. seedlings with a sewage sludge-based compost. Waste Manag. Res. 27, 112–118. https://doi.org/10.1177/0734242X08089463.

United Nations, 2019. Growing at a Slower Pace, World Population Is Expected to Reach 9.7 Billion in 2050 and could peak at nearly 11 billion around 2100 [WWW

Document]. URL. https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html, 1.20.20.

Van Gerrewey, T., Ameloot, N., Navarrete, O., Vandecruys, M., Perneel, M., Boon, N., Geelen, D., 2020. Microbial activity in peat-reduced plant growing media: identifying influential growing medium constituents and physicochemical properties using fractional factorial design of experiments. J. Clean. Prod. 256, 120323 https://doi.org/10.1016/j.jclepro.2020.120323.

Vandecasteele, B., Blindeman, L., Amery, F., Pieters, C., Ommeslag, S., Van Loo, K., De Tender, C., Debode, J., 2020. Grow - store - Steam - Re-peat: reuse of spent growing media for circular cultivation of Chrysanthemum. J. Clean. Prod. 276, 124128 https://doi.org/10.1016/j.jclepro.2020.124128.

Vandecasteele, B., Muylle, H., De Windt, I., Van Acker, J., Ameloot, N., Moreaux, K., Coucke, P., Debode, J., 2018. Plant fibers for renewable growing media: potential of defibration, acidification or inoculation with biocontrol fungi to reduce the N drawdown and plant pathogens. J. Clean. Prod. 203, 1143–1154. https://doi.org/10.1016/j.jclepro.2018.08.167.

Wallach, R., 2019. Physical characteristics of soilless media. In: Soilless Culture. Elsevier, pp. 33–112. https://doi.org/10.1016/B978-0-444-63696-6.00003-7.

Wright, R., Jackson, B., Browder, J., Latimer, J., 2008. Growth of chrysanthemum in a pine tree substrate requires additional fertilizer. HortTechnology 18, 111–115. https://doi.org/10.21273/HORTTECH.18.1.111.

Zhong, Z., Bian, F., Zhang, X., 2018. Testing composted bamboo residues with and without added effective microorganisms as a renewable alternative to peat in horticultural production. Ind. Crop. Prod. 112, 602–607. https://doi.org/10.1016/j.indcrop.2017.12.043.

Zawadzińska, A., Salachna, P., Nowak, J.S., Kowalczyk, W., 2021. Response of interspecific geraniums to waste wood fiber substrates and additional fertilization. Agriculture 11, 119. https://doi.org/10.3390/agriculture11020119.