Current Forestry Reports (2023) 9:413–428
https://doi.org/10.1007/s40725-023-00204-2

FOREST MANAGEMENT (M WATT, SECTION EDITOR)

# A Global Review on Innovative, Sustainable, and Effective Materials Composing Growing Media for Forest Seedling Production

**Barbara Mariotti[1,2] · Juan A. Oliet[3] · Enrique Andivia[4] · Marianthi Tsakaldimi[5] · Pedro Villar-Salvador[6] · Vladan Ivetić[7] · Antonio Montagnoli[8] · Ivona Kerkez Janković[7] · Nebi Bilir[9] · Henrik Bohlenius[10] · Branislav Cvjetković[11] · Kārlis Dūmiņš[12] · Juha Heiskanen[13] · Georgi Hinkov[14] · Inger Sundheim Fløistad[15] · Claudia Cocozza[1]**

Accepted: 18 September 2023 / Published online: 26 October 2023


## Abstract

**Purpose of Review** The demand for forest tree seedlings is increasing globally, and *Sphagnum* peat moss is widely used as a component of growing media for container plant production. However, peat extraction is environmentally unsustainable. The forest nursery sector needs to switch to more sustainable alternatives to peat. This review aims to identify potential substitutes for peat by reviewing the worldwide literature on alternative materials for growing media in forest nurseries.

**Recent Findings** Most studies on alternative growing media focused on single plant species growing under local conditions, thereby limiting generalizations about the effectiveness of alternative materials for plant production. To our knowledge, no systematic reviews of scientific literature on the effectiveness of new, alternative-to-peat materials for enhancing plant growth and the associated growing media characteristics for the forest nursery sector are currently available.

**Summary** Most of the analyzed case studies focused on angiosperms (73.1%), with the majority of studies coming from tropical seasonal forests/savannas (36.5%), followed by woodlands/shrublands (31.6%), and temperate forests (15.0%) biomes. Compost was the most studied material (19.5%), followed by bark, other organic materials, and manure (9.8, 9.7, and 8.0%, respectively). Green and municipal wastes were the principal sources of compost (> 60%), while agriculture and green wastes were the first sources of other materials (> 90%). Tested materials were dependent on the geographic region. Thus, manure was the most tested material in Africa and South America, tree bark in North America, and compost in Europe, Asia, and Oceania. Alternative materials effectively provided optimal physicochemical characteristics of growing media and enhanced seedling nursery growth when compared with peat-based growing media in more than 60% of the case studies. This review helps to identify research gaps and, most importantly, provides the basis for the future application of alternative growing media materials in forest nursery management worldwide.

**Keywords** Environmental sustainability · Forest nursery · Peat substitution · Organic waste recycling · Restoration · Seedling production · Substrate

## Introduction

Global climate change is altering ecosystems' composition and function worldwide, compromising the provision of multiple services [1]. During the last two decades, growing environmental awareness has increased efforts to reverse biodiversity loss and land degradation. Therefore, ecosystem restoration has become a global priority and numerous initiatives have been promoted to implement large-scale programs. For instance, the Bonn Challenge aims to restore 350 million hectares of degraded land by 2030 [2], and the United Nations (UN) has designated 2021–2030 the UN Decade of Ecosystem Restoration [3]. Within this framework, plant science and forestry sectors will play a fundamental role through afforestation, reforestation, and landscape restoration of degraded lands. These efforts will also contribute to climate change mitigation. In this context, the demand for forest reproductive material (i.e., seeds, seedlings, and rooted cuttings) is massive. The nursery sector has to address this ambitious target while switching toward more sustainable production systems without undermining seedling quality [4–6].

Bare-root and container seedlings are the main stock types used in forest restoration plantations [7]. Bare-root

Extended author information available on the last page of the article

seedlings are cultivated directly in the field in mineral soil. In contrast, container seedlings are grown in a confined rooting volume containing a porous medium, either pure or composed of a mixture of components. These media are known as substrate, soilless medium, growth medium, or growing medium (hereafter, GM [8]). Compared with bare-root plant production, container cultivation using GM can be more cost-effective [9] and efficient depending on location and available resources. Container production shortens the production cycle, enhances plant quality, extends the outplanting period, and improves seedling field performance, especially under harsh site conditions [7, 10]. An effective GM should promote simultaneously healthy seedlings free from pests and pathogens and have appropriate physical and chemical characteristics to support optimal root and shoot development [11]. Specifically, an ideal GM should have a balanced air porosity, suitable aeration, optimal bulk density, and adequate water-holding capacity. Such characteristics ensure an efficient exchange of oxygen and carbon dioxide, enhance a proper development of fine roots and of mycorrhizae, and reduce the risk of pathogens. Achieving the right balance of these physical characteristics is important for stimulating root growth throughout the entire container, which ensures that a cohesive root plug is maintained during handling, shipping, and planting [12]. The chemical characteristics of the GM should support adequate nutrition by maintaining high cation exchange capacity, low inherent fertility to control mineral nutrient concentration through fertilization, and a slightly acidic pH to maximize the availability of mineral nutrients in solution [12] and promote the growth of specific microorganisms in the GM. All these physical and chemical properties are usually achieved with GM composed of organic materials at least by 50% in volume, frequently up to 100% [12, 13]. In addition, a good GM should be economically feasible, lightweight, and useful to promote uniform plant growth across growing seasons. Therefore, the choice of an adequate GM is a trade-off among factors such as quality requirements, plant species, costs, and the availability of raw materials [14, 15].

*Sphagnum* peat moss (*Sphagnum* spp.), generally known as peat, is commonly used worldwide in plant production as the primary component of GM due to its balanced physicochemical characteristics, mid-term stability, uniformity, availability, and competitive prices [16, 17••]. However, peat extraction is environmentally unsustainable due to slow natural peatland formation and ecological drawbacks, such as the destruction of the fragile peat bog ecosystems and the consequent loss of carbon sequestration capacity [17••, 18–20, 21••, 22]. On a global scale, the peatlands used as sources of GM cover approximately 2000 $km^2$, accounting for 0.5% of the global uses of peatlands [23]. In Europe alone, over 37 million $m^3$ of GM is produced annually [24], and the global production was calculated at 67 million $m^3$ in 2017 with an estimated increase of 422% in 2050 [25]. In the EU, peat extraction and its use in horticulture resulted in 12 Mt of $CO_2$ emissions in 2019, making this industry sector a significant contributor to greenhouse gases [26]. Consequently, the extraction of peat will be included in mitigation targets (LULUCF regulation EU 2018/841) under the category "wetlands" starting from 2026. In the USA, peat use in horticulture was estimated at 479,000 t in 2018, accounting for approximately 25% of the total [27]. New commercial and technological solutions for implementing sustainable processes in nurseries (i.e., water-saving techniques, plastic recycling, and the use of eco-friendly materials) have been widely investigated in recent years [28–30, 31••]. In this regard, using alternative GM materials is both a challenge and an opportunity for recycling organic wastes [32, 33] and reducing the use of other traditional inorganic, non-renewable materials such as sand, vermiculite, and perlite [34, 35].

In the last two decades, a vast body of scientific literature assessing the performance of peat alternatives for producing forest nursery seedlings has been published [31••, 32–37, 38••, 39, 40•]. Treated and untreated waste and renewable raw materials show great potential as GM constituents and standalone substrates [17••]. However, the dispersal of studies in different plant species under different local conditions and with different measured GM and plant characteristics limits generalizations. Additionally, studied alternative materials are frequently related to local recycling chains [41, 42]. Therefore, a global overview of available information about alternative GM materials is needed.

To the best of our knowledge, no systematic review of scientific literature on the effectiveness of alternative-to-peat materials for enhancing plant growth and GM characteristics has been conducted in the forest nursery sector. In this study, we aimed to identify the most promising alternative GM materials based on their effectiveness, sustainability, and innovation. This information can provide the knowledge background for promoting new policies and practices to achieve higher sustainability in the forest nursery sector. We performed a broad-scale review of peer-reviewed and grey literature about a variety of GM materials used to grow forest plants. We collected information about (i) the most studied alternative materials to peat; (ii) the proportion of these materials in GM composition and whether there was eventual use of traditional materials such as peat, soil, or other inorganic traditional materials; and (iii) the effective alternative materials on GM physicochemical characteristics and seedling growth compared with peat both in the nursery and in the field. Collected information was then evaluated across different biomes and climates, including whether plant responses vary between angiosperms and gymnosperms due to their functional differences that modulate plant response to nursery cultivation [43]. Moreover, we also summarized the origin of prevalent alternative GM materials and the world distribution of case studies.

## Materials and Methods

### Literature Collection

We performed a systematic review of the literature on non-peat materials used in GM for growing forest seedlings in container nurseries following the guidelines of the Collaboration for Environmental Evidence (2010) (e.g., [44]).

Selected papers met the following criteria:

- Studied forest plant species;
- Tested alternative (i.e., sustainable, innovative, and non-peat) GM materials;
- Included peat or other traditional non-renewable or non-sustainable materials in the GM to compare with the alternative materials.

Additionally, we selected articles that contained information about one or more of the following groups of variables:

- Physical and chemical characteristics of the GM such as porosity, pH, or cation exchange capacity;
- Morpho-physiological attributes of nursery seedlings such as height, root collar diameter, biomass, and organ and/or plant nutrient concentration;
- Seedling field survival and /or growth.

The primary search included peer-reviewed papers and was conducted in the following databases:

– Web of Science (WoS — https://www.webofknowledge.com) owned by Clarivate is a paid-access platform providing access to multiple databases that provide reference and citation data from academic journals, conference proceedings, and other documents in various academic disciplines;
– Scopus (https://www.scopus.com), Elsevier's abstract and citation database, covers three types of sources: book series, journals, and trade journals in top-level subject fields of life sciences, social sciences, physical sciences, and health sciences;
– Directory of Open Access Journals (DOAJ — https://doaj.org/) is a website that hosts a community-curated list of open access journals, maintained by Infrastructure Services for Open Access (IS4OA);
– Reforestation, Nurseries, & Genetic Resources (RNGR — https://rngr.net/), sponsored by the United States Department of Agriculture (USDA), a collaborative effort between Forest Service and Southern Regional Extension Forestry agencies, supply people who grow forest and conservation seedlings with the very latest technical information providing a searchable database of over 11,000 technical articles;
– Canadian Forest Service Publications (https://cfs.nrcan.gc.ca/publications) hosted by the Government of Canada—Canadian Forest Service (CFS) and including articles, books, reports, and CFS-prepared series and leaflets;
– Scientific Electronic Library Online (SciELO — https://www.scielo.org/), managed by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil, in collaboration with the Latin American and Caribbean Center for Health Science Information (BIREME), is a digital library that provides a software platform for the publication of scientific journals in electronic format and in the context of unabridged editions;
– Google Scholar (https://scholar.google.com/), owned by Google, is a freely accessible web search engine that indexes the full text or metadata of scholarly literature across an array of publishing formats and disciplines.

We also collected grey literature defined as works that have not been peer-reviewed (e.g., scientific reports, non-ISI papers, national reports, theses, conference proceedings, conference abstracts, posters, conference presentations, unpublished work, books, literature reviews) [45]. The database search was initially made on 5 March 2021 and updated on 2 July 2021. We did not explicitly impose geographic, year of publication, or language restrictions but we were interested in published studies related to forest nurseries, reforestation, and/or restoration, growing medium and seedling quality, and field performance. Thus, the terms were searched in titles, abstracts, and keywords and were based on the following string: (nursery OR reforest* OR restor* OR reveget* OR afforest*) AND (medi* OR growing medi* OR soilless medi* OR substrat*) AND (seedling quality OR morphology OR field performance OR survival). Translated terms to other languages were employed to conduct searches in the native languages of the authors.

### Article Screening

To identify studies relevant to the objectives of our review, collected articles were screened by following steps:

1. Papers were discarded if the title indicated that the study was out of scope.
2. For papers with acceptable titles, the abstracts were reviewed, and the papers were discarded if they did not satisfy the inclusion criteria.
3. Articles that passed the two steps above were fully read, and only those including the required information

related to GM characteristics, nursery seedlings, or field performance were included in the study.

The above screening resulted in 866 articles: 542 in WoS, Scopus, and Google Scholar; 198 in SciELO; 97 in the Directory of Open Access Journals; 27 in the USDA database; two in the Canadian Forest Service databases; and 28 in grey literature (four from Finland and 24 from Spain).

## Data Extraction and Analysis

From each article, we extracted the following information:

1) Study location (country and coordinates);
2) Biome where the experiment was carried out using the classification in Whittaker [46];
3) Plant growth form (herb, shrub, tree);
4) Plant species.

Some of the selected articles described several case studies, i.e., testing different GM mixtures. Thus, we identified case studies based on materials used as the unique alternative component of the GM or the material that was present in the highest proportion (hereafter referred to as "prevalent") for mixtures of alternative materials in a given GM. As a result, we identified 11 widely used alternative materials: tree bark, biochar, chips, coir, compost, manure, rice, sawdust, sludge, wood fiber, and other organic wastes (Tables 1, S1).

For each case study, we extracted the following information:

- The proportion in the volume of the alternative material in relation to other components of the GM according to five classes: 1 = 1–20%, 2 = 21–40%, 3 = 41–60%, 4 = 61–80%, 5 = 81–100%; when the GM included more than one alternative material, the proportion of each material was recorded;
- The origin of each alternative material in the GM mixture according to the related productive sector: agriculture (A), animal husbandry (An), green wastes (Gr, plant waste coming from non-agricultural sectors such as forests, gardens, and parks), industry (I), and solid municipal wastes (Mu). Manure (An) was further classified according to the originating livestock (bovine, goat, horse, pig, poultry, and quail).

For each case study, peat, soil, or inorganic materials (i.e., perlite and vermiculite) were considered traditional GM components. GM with alternative materials were classified in three ways: innovative (I) when commercially uncommon and/or scarcely used in the forestry nursery sector; environmentally sustainable (S) when its production and use involve the conservation of peatlands and other ecosystems, environment preservation, and renewal of natural resources and/or waste material; or both innovative and sustainable (IS). According to these criteria bark, manure, sawdust, and wood fiber were classified as sustainable (S) and the rest of the materials as innovative and sustainable (IS); none of the

**Table 1** A brief description of the 11 main alternative materials composing the growing media (GM), and their classification as sustainable (S), innovative (I), and innovative and sustainable (IS)

| Alternative material | Description | Category |
|---|---|---|
| Bark | The outermost cover (rhytidome) of tree trunks, branches and roots | S |
| Biochar | The solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment | IS |
| Chips | Mechanized finely frittered biomass coming from plants (branches, logging residues, stumps, roots and wood residuals) | IS |
| Coir | Waste product of the coconut industry (coir pith, coir meal, coir dust and coco peat). It consists of the dust and short fibers extracted from the outer husk (the mesocarp) of the fruit | IS |
| Compost | Composted organic matter, it includes all composted materials regardless the origin, from municipality waste to pruning or other wood residues. Composted materials derived from the biological transformation of dead organic matter by microorganisms under aerobic conditions | IS |
| Manure | Animal waste in liquid (urine and wastewater, mainly used as fertilizer) or in solid (fresh, partly composted and fully composted) state | S |
| Other Organic Material | Any organic material not included in the other categories that is locally available | IS |
| Rice | Waste of rice processing (raw material, rice hulls and canes composted, hydrolysed, parboiled, or carbonized) | IS |
| Sawdust | Small wood chips; waste of woodworking such as sawing, sanding, milling, planning, and routing | S |
| Sludge | Semi-solid slurry produced by industrial or municipal wastewater processes; water treatment, wastewater treatment or on-site sanitation systems | IS |
| Wood Fiber | Material produced by mechanical defibrillation or more commonly steam-assisted thermal extrusion of virgin wood chips | S |

defined alternative materials was classified as innovative and not sustainable (Table 1).

For each case study, the effectiveness of alternative materials was established in comparison with peat for selected physicochemical characteristics of the GM, specific morphological traits of nursery seedlings, and field performance. We discarded case studies that did not statistically compare alternative materials with peat. The effectiveness of an alternative material was defined at three levels as follows:

(a) *Promising*, when the GM's pH ranged from 4.0 to 7.0 and total porosity ranged from 60 to 90% according to Landis et al. [12]; otherwise, material was considered to have a negative effect on physicochemical characteristics of the growing media;
(b) *Effective*, when the nursery growth of forest seedlings cultivated with the alternative material was significantly higher or not different than the growth of those cultivated with peat; otherwise, the material was considered to have a negative effect on nursery growth. As several parameters were used to assess growth, we selected parameters in order of importance following Andivia et al. [43, 47]: total biomass, shoot biomass, root collar diameter, or shoot height;
(c) *Most effective*, when the field performance of seedlings cultivated with the alternative material was significantly higher or not different from the performance of seedlings cultivated with peat in the nursery; otherwise, material was considered to have a negative effect on-field performance. Field performance parameters were also selected in order of importance: survival, root collar diameter, and shoot height [43].

We performed a chi-square test to assess differences in the number of positive (*promising*, *effective*, and *most effective*) and negative results between angiosperms and gymnosperms for each alternative material. For every alternative material, we also explored its global effectiveness by tallying the proportion of positive cases for each of the effectiveness categories.

# Results

## Characteristics of Case Studies

After abstract screening and paper carefully reading, we retained 191 references that resulted in 1671 case studies (i.e., different GM mixtures). Studies spanned from 1974 to 2021 and were globally distributed (Tables S1, S2). Brazil accounted for the highest number of publications (44), which included 449 case studies, followed by the USA (25 publications and 256 study cases), Spain, Greece, and Mexico (Table S3).

We compiled information on 181 forest plant species (79.7% trees, 15.7% shrubs, and 4.7% herbs). Most species were angiosperms (73.1%), which were the dominant taxa in most biomes except in the temperate grassland/desert and boreal forest biomes where gymnosperms were dominant (Fig. 1). Most case studies (> 65%) were of species from the tropical seasonal forest/savanna and woodland/shrubland while the less represented biomes were the temperate grassland/desert, tropical rainforest and boreal forest (Fig. 1).

## Origin of Alternative Materials

All alternative GM materials originated from recycled materials or by-products (Table 1). Bark, coir, chips, sawdust, and wood fiber resulted from activities or processes related to vegetation management or vegetal production, even when coir required additional chemical treatment. Biochar originated mainly from green and agricultural wastes (Fig. 2). Green and municipality wastes together provided > 60% of the compost, while > 90% of other organic wastes derived from agriculture and green wastes (Fig. 2). Finally, the municipality waste was the source of half of the sludge produced (Fig. 2). Moreover, bovine and poultry farming was the source of ca. 90% of the manure (data not shown).

The prevalence of tested alternative materials differed among continents (Fig. 3). Manure was the most frequent material in Africa and South America; compost was the material most used in Europe, Asia, and Oceania; bark was the most tested alternative material in North America; and sawdust was mainly used in Africa (Fig. 3).

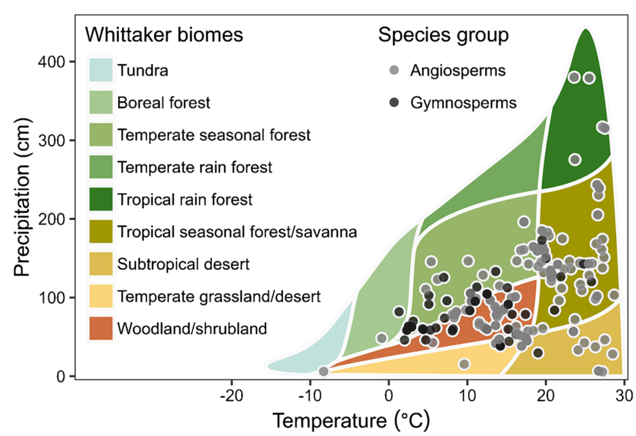


**Fig. 1** Distribution of case studies (i.e., GM) across terrestrial biomes (Whittaker., 1975) and species group (angiosperm and gymnosperm). Case studies were distributed across biomes as follows: tropical seasonal forest/savanna 36.5%, woodland/shrubland 31.6%, temperate forest 15.0%, subtropical desert 8.5%, temperate grassland/desert 4.1%, tropical rainforest 3.8%, and boreal forest 0.4%

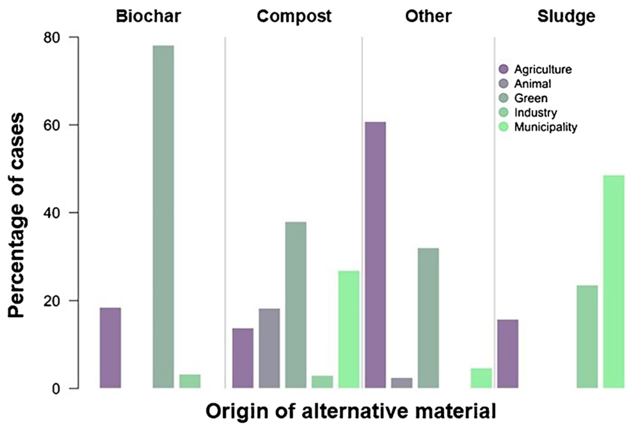


**Fig. 2** Origin of the five prevalent alternative materials composing the GM. Values are expressed as the percentage of case studies that reported the origin of the alternative material

## Use of Alternative Materials

Biochar, compost, manure, and wood fiber were mainly used as single alternative materials in GM and they made up 41–60% of the GM mixture in more than 30% of the case studies (Table 2). The remaining materials were equally used alone or mixed with other alternative materials. Chips constituted 81–100% of the GM mixture in 48% of the case studies, whereas coir and manure made up 21–40% of the GM mixture in 31.6% and 50.7% of the case studies, respectively (Table 2).

In most case studies, bark, chips, coir, compost, other organic material, sawdust, and sludge were tested without mixing with other materials (Table 3). The remaining alternative materials (biochar, manure, rice, sawdust, and wood fiber) were mainly mixed in various proportions with soil and peat (Table 3). Manure and bark were the most and the least mixed material with soil, respectively. The soil was also mixed with other materials such as other organic materials, rice, and wood fiber. Peat was mixed with all alternative GM, although its proportion varied largely. Inorganic traditional materials such as perlite and vermiculite were mixed with bark and chips in 31.7 and 26.7% of the case studies, respectively. Biochar and compost were mixed in the same proportion as peat and other traditional inorganic materials in 7.4% and 14.5% of case studies, respectively (Table 3).

GMs were also mixed with more than one alternative material. Bark, compost, other organic materials, rice, and sludge were the most frequently mixed materials in those cases (> 7%), while biochar, chips, manure, and wood fiber were the least frequently mixed (Table S4). The wood fiber was only combined with bark (Table S4). Finally, the most frequently tested combinations were bark (as the main alternative material) mixed with compost or sludge (secondary alternative materials), rice with other organic waste, and sawdust with bark (Table S4).

## Effectiveness of Alternative Materials

Alternative materials were "promising" according to their effect on GM physicochemical characteristics in 61.7% of all case studies, half of which included bark, compost, other organic material, and rice. Except for sludge in the temperate biomes and coir, compost, and manure in the tropical biomes, the majority of alternative materials were promising in more than 50% of the case studies (Table 4). Coir, compost, and manure performed better in temperate than in tropical biomes, while bark, chips, other organic material, rice, sawdust, and sludge performed better in tropical than in temperate biomes. Wood fiber showed remarkable "promising" results in both temperate and tropical biomes although the number of case studies was low (Table 4).

**Fig. 3** Geographical distribution (%) of the prevalent alternative materials

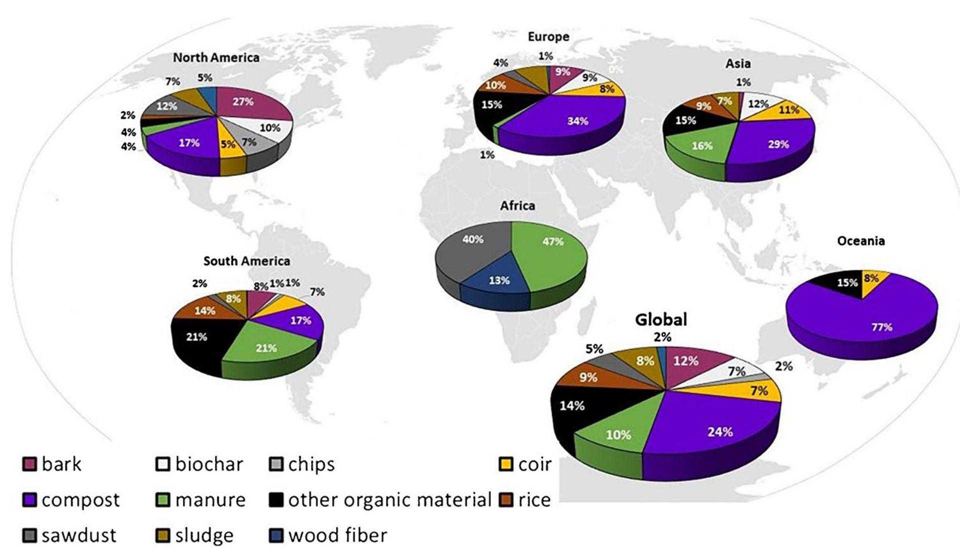

**Table 2** Classes of proportion (%) for each alternative material used for composing the GM

| Alternative material | Proportion (%) | | | | | | Case study (no.) |
|---|---|---|---|---|---|---|---|
| | *0–20* | *21–40* | *41–60* | *61–80* | *81–100* | *Data not given* | |
| Bark | **0.6** | **6.7** | **34.1** | **28.0** | **19.5** | **11.0** | ***164*** |
| *mixed with other alternative materials* | 0 | 3.0 | 23.2 | 17.7 | 4.3 | 9.8 | |
| *single alternative material* | 0.6 | 3.7 | 11.0 | 10.4 | 15.2 | 1.2 | |
| Biochar | **18.5** | **28.3** | **21.7** | **5.4** | **14.1** | **12.0** | ***92*** |
| *mixed with other alternative materials* | 1.1 | 1.1 | 1.1 | 0.0 | 1.1 | 2.2 | |
| *single alternative material* | 17.4 | 27.2 | 20.7 | 5.4 | 13.0 | 9.8 | |
| Chips | **0** | **3.7** | **11.1** | **3.7** | **48.1** | **33.3** | ***27*** |
| *mixed with other alternative materials* | 0 | 0 | 7.4 | 0 | 0 | 33.3 | |
| *single alternative material* | 0 | 3.7 | 3.7 | 3.7 | 48.1 | 0 | |
| Coir | **1.1** | **31.6** | **38.9** | **11.6** | **14.7** | **2.1** | ***95*** |
| *mixed with other alternative materials* | 0 | 11.6 | 15.8 | 11.6 | 4.2 | 0 | |
| *single alternative material* | 1.1 | 20.0 | 23.2 | 0 | 10.5 | 2.1 | |
| Compost | **2.8** | **20.2** | **30.7** | **19.0** | **23.3** | **4.0** | ***326*** |
| *mixed with other alternative materials* | 0 | 3.7 | 7.7 | 7.1 | 0.6 | 1.2 | |
| *single alternative material* | 2.8 | 16.6 | 23.0 | 12.0 | 22.7 | 0.9 | |
| Manure | **9.7** | **50.7** | **23.1** | **9.7** | **2.2** | **4.5** | ***134*** |
| *mixed with other alternative materials* | 0 | 4.5 | 7.5 | 6.7 | 0 | 3.0 | |
| *single alternative material* | 9,7 | 46.3 | 15.7 | 3.0 | 2.2 | 1.5 | |
| Other Organic Material | **3.1** | **22.8** | **31.5** | **14.8** | **23.5** | **4.3** | ***162*** |
| *mixed with other alternative materials* | 1.2 | 12.3 | 18.5 | 11.1 | 5.6 | 0.6 | |
| *single alternative material* | 1.9 | 10.5 | 13.0 | 3.7 | 16.0 | 3.7 | |
| Rice | **9.3** | **28.8** | **47.5** | **5.9** | **8.5** | **0** | **118** |
| *mixed with other alternative materials* | 4.2 | 8.5 | 31.4 | 2.5 | 4.2 | 0 | |
| *single alternative material* | 5.1 | 20.3 | 16.1 | 3.4 | 4.2 | 0 | |
| Sawdust | **1.4** | **11.4** | **42.9** | **27.1** | **15.7** | **1.4** | **70** |
| *mixed with other alternative materials* | 0 | 1.4 | 25.7 | 17.1 | 10.0 | 0 | |
| *single alternative material* | 1.4 | 10.0 | 17.1 | 10 | 5.7 | 1.4 | |
| Sludge | **4.9** | **24.5** | **28.4** | **16.7** | **20.6** | **4.9** | **102** |
| *mixed with other alternative materials* | 0 | 2.0 | 18.6 | 10.8 | 3.9 | 4.9 | |
| *single alternative material* | 4.9 | 22.5 | 9.8 | 5.9 | 16.7 | 0 | |
| Wood Fiber | **0** | **12.0** | **18.0** | **40.0** | **30.0** | **0** | **50** |
| *mixed with other alternative materials* | 0 | 4.0 | 0 | 0 | 0 | 0 | |
| *single alternative material* | 0 | 8.0 | 18.0 | 40.0 | 30.0 | 0 | |

In particular, for each alternative material is reported the total percentages (in bold), the percentage of case studies when alternative material is mixed with other alternative materials, and the percentage of the case studies when alternative material is used as single material. *Case study (no.)* is the total number of the case studies including the alternative material. *Data not given* corresponds to the percentage of studies not reporting the proportion of materials composing the GM

Alternative materials were found to be "effective" in promoting seedling growth at the nursery stage in 62.1% of the case studies. When each material was considered individually, more than 50% of the cases showed positive results, except for coir in angiosperms, which success rate was 43.5%. Additionally, organic materials and wood fiber in gymnosperms had effective rates of 35.3% and 8.3% respectively. Compost, manure, other organic material, and sludge showed the highest effectiveness, between 21.9 and 11.2% of the total "effective" case studies. We only found significant differences in effectiveness between angiosperms and gymnosperms for other organic materials (Table 5). The effectiveness of alternative materials in angiosperms was observed in > 50% of cases except for coir (43.5%), whereas there were not enough case studies to define chips and wood fiber as effective materials (Table 5). The effectiveness of alternative materials was higher in tropical than in temperate biomes, except for bark and biochar (Table 5). Manure and sludge were generally "effective" despite the limited number of available case studies. However, their effectiveness was comparatively lower in temperate and boreal biomes than in other biomes. Rice, biochar, and bark were only tested in temperate biomes and resulted in "effective" in > 50% of the case studies.

**Table 3** The percentage (%) of case studies using traditional base-material mixed with alternative material in the GM (total case studies 1366)

| Alternative material | Traditional base-materials | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *No additional base* | *Soil* | *Soil and other inorganic base* | *Peat* | *Equal proportion of peat and other inorganic base (1:1)* | *Other inorganic base (perlite, vermiculite)* | *Other organic base* | *Data not given* | *Case study (no.)* |
| Bark | 38.9 | 0.6 | 0 | 24.6 | 3.6 | 31.7 | 0 | 0.6 | 167 |
| Biochar | 9.5 | 44.2 | 0 | 38.9 | 7.4 | 0 | 0 | 0 | 95 |
| Chips | 33.3 | 0 | 0 | 40 | 0 | 26.7 | 0 | 0 | 30 |
| Coir | 49 | 9.2 | 7.1 | 15.4 | 2 | 15.3 | 2.0 | 0 | 98 |
| Compost | 30.6 | 14.8 | 2.1 | 20.6 | 14.5 | 12.9 | 0 | 4.5 | 330 |
| Manure | 7.4 | 63 | 12.6 | 5.2 | 0 | 7.4 | 0 | 4.4 | 135 |
| Other organic material | 43.2 | 38.9 | 4.2 | 8.4 | 0 | 5.3 | 0 | 0 | 190 |
| Rice | 15 | 42.5 | 0.8 | 32.5 | 0 | 9.2 | 0 | 0 | 120 |
| Sawdust | 26.4 | 20.8 | 5.6 | 27.8 | 0 | 19.4 | 0 | 0 | 72 |
| Sludge | 44.9 | 19.6 | 0 | 22.4 | 0.9 | 7.5 | 2.8 | 1.9 | 107 |
| Wood fiber | 22.7 | 36.4 | 0 | 22.7 | 0 | 18.2 | 0 | 0 | 22 |

*No additional base* reports the percentage of case studies with alternative material as a single component of the GM. *Data not given* corresponds to the percentage of studies not reporting the proportion of materials composing the GM

**Table 4** The percentage (%) of total case studies with *promising* alternative material (i.e., positive effect on growing media characteristics) within each alternative material distinguishing between biomes according to Whittaker (1975)

| *Biome group* | *Alternative material (%)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Bark* | *Biochar* | *Chips* | *Coir* | *Compost* | *Manure* | *Other organic material* | *Rice* | *Sawdust* | *Sludge* | *Wood fiber* |
| Temperate | 56.9 (29) | 100 (16) | 0 | 75.0 (12) | 59.1 (13) | 58.3 (7) | 58.6 (17) | 58.8 (10) | 84.6 (11) | 22.7 (5) | 100 (4) |
| Tropical | 100 (19) | | 100 (8) | 48.4 (15) | 36.6 (15) | 46.2 (6) | 100 (19) | 93.3 (28) | 100 (3) | 100 (12) | 100 (8) |

The number of case studies is reported within brackets. Empty cells indicate lack of case studies. The temperate biome includes temperate seasonal forest, temperate rainforest, temperate grassland/desert, woodland/shrubland, while the tropical biome includes tropical rainforest, tropical seasonal forest/savanna, subtropical desert. The boreal biome was not reported since no data were available

A limited number of case studies ($n = 82$) have evaluated the effectiveness of alternative materials on seedling field performance, particularly for gymnosperms (Table 6). We found positive results in 57.3% of the case studies, and in most of them, the GM was composed of bark, compost, other organic material, rice, or sludge (10.5%, 17.5%, 10.5%, 26.3%, and 15.8% of the total "most promising" case studies, respectively). We found significant differences between angiosperms and gymnosperms in effectiveness when other organic materials, rice, and sludge were used (Table 6). However, other organic materials and rice hulls were found "most effective" only in angiosperms (75.0 and 77.3% of the case studies, respectively). Sludge was "most effective" in 80% of case studies in gymnosperms, while in angiosperms only 20% of case studies resulted in "most effective." In angiosperms and in all alternative materials, more of the 50% of the case studies resulted the most promising, with the only exception of bark (42.9%) and sludge (only one case study).

## Discussion

This is, to the best of our knowledge, the first study that globally reviews alternative-to-peat materials in GM composition for the forest nursery sector. Our study contributes to increasing knowledge and systematization of GM alternative materials at a global scale, which can facilitate informed decision-making for researchers, practitioners, and policymakers. This knowledge can help improve the productivity and environmental sustainability of the forest nursery sector in a world of increasing resource scarcity and climatic uncertainty.

We classified alternative materials according to their proportion in the GM composition, the biome of origin (i.e., climatic conditions), and species groups (i.e., angiosperm and gymnosperm). Such a high diversity of alternative GM underscores the interest in this topic worldwide and precludes defining the "silver bullet" alternative material or GM mixture for growing forest seedlings at the global scale. On

**Table 5** The percentage (%) of total case studies where the alternative material was *effective* (i.e., positive effect on nursery seedling growth compared to peat or other traditional materials), distinguishing by species type and the biome according to Whittaker (1975)

| | | *Alternative material* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species type | Biome group | *Bark* | *Biochar* | *Chips* | *Coir* | *Compost* | *Manure* | *Other organic material* | *Rice* | *Sawdust* | *Sludge* | *Wood fiber* |
| Angiosperms | | **61.8 (21)** | **73.1 (19)** | | **43.5 (20)** | **68.8 (77)** | **81.0 (64)** | **65.2 (43)** | **55.3 (26)** | **70.8 (17)** | **80 (20)** | |
| | Temperate | 44.1 (15) | 53.8 (14) | | 2.2 (1) | 25.0 (28) | 5.1 (4) | 15.2 (10) | 12.8 (6) | | 28.0 (7) | |
| | Tropical | 17.6 (6) | 19.2 (5) | | 41.3 (19) | 43.8 (49) | 75.9 (60) | 50.0 (33) | 42.6 (20) | 70.8 (17) | 52.0 (13) | |
| Gymnosperms | | **54.5 (12)** | **80.0 (4)** | | | **70.6 (12)** | **85.7 (6)** | **35.3 (6)** | **75.0 (3)** | **50.0 (1)** | **88.9 (16)** | **8.3 (1)** |
| | Boreal | | | | | | 28.6 (2) | | | | 16.7 (3) | |
| | Temperate | 54.5 (12) | 80.0 (4) | | | 41.2 (7) | | 11.8 (2) | 75.0 (3) | | 72.2 (13) | |
| | Tropical | | | | | 29.4 (5) | 57.1 (4) | 23.5 (4) | | 50.0 (1) | | 8.3 (1) |
| *Chi-square d.f.=1 (angiosperms vs gymnosperms,)* | | $\chi^2=2.62$ *n.s* | $\chi^2=2.293$ *n.s* | | | $\chi^2=0.95$ *n.s* | $\chi^2=0.054$ *n.s* | $\chi^2=4{,}93$ $p<0.05$ | $\chi^2=0.91$ *n.s* | $\chi^2=2.67$ *n.s* | $\chi^2=0.10$ *n.s* | |

n.s. not significant differences

The number of case studies is reported within brackets. Chi-square tests compare angiosperms vs. gymnosperms. Empty cells indicates lack of case studies. The boreal biome includes the boreal forest and the tundra, temperate biome includes the temperate seasonal forest, temperate rainforest, temperate grassland/desert, and the woodland/shrubland, while the tropical biome includes the tropical rainforest, tropical seasonal forest/savanna, and the subtropical desert

Bold values are significant at 95% level

**Table 6** The percentage (%) of total case studies where the alternative material was classified as *most effective* (i.e., positive effect on seedling field performance compared to peat or other traditional materials) distinguishing by species type and the biome according to Whittaker (1975)

| *Alternative materials* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species type | Biome group | *Bark* | *Biochar* | *Chips* | *Coir* | *Compost* | *Manure* | *Other organic material* | *Rice* | *Sawdust* | *Sludge* | *Wood fiber* |
| Angiosperm | | **42.9 (6)** | | | **50 (3)** | **66.7 (4)** | **100 (3)** | **75.0 (6)** | **77.3 (11)** | | **20.0 (1)** | |
| | Temperate | 42.9 (6) | | | 50 (3) | 66.7 (4) | | | 46.7 (7) | | 20 (1) | |
| | Tropical | | | | | | 100 (3) | 75 (6) | 26.7 (4) | | | |
| Gymnosperm | | | | | | **100 (6)** | | **0*** | **0*** | **100 (1)** | **80 (8)** | |
| | Temperate | | | | | 100 (6) | | | | | 80 (8) | |
| | Tropical | | | | | | | | | 100 (1) | | |
| *Chi-square d.f. = 1 (angiosperms vs gymnosperms)* | | | | | | $\chi^2 = 2.74$ *n.s* | | $\chi^2 = 4,842$ $p < 0.05$ | $\chi^2 = 4.46$ $p < 0.05$ | | $\chi^2 = 5.15$ $p < 0.05$ | |

n.s. not significant difference

*Total case studies = 2

The number of case studies is reported within brackets. Chi-square tests compare angiosperms vs gymnosperms. Empty cells indicate lack of case studies. The temperate biome includes temperate seasonal forest, temperate rainforest, temperate grassland/desert, and the woodland/shrubland, and the tropical biome includes tropical rainforest, tropical seasonal forest/savanna, and the subtropical desert. Boreal biomes are not reported since no data were available

Bold values are significant at 95% level

the contrary, our analysis indicates that available alternative GM materials are contingent on local ecological and economical particularities and most of them can be integrated into the local circular bio-economy scheme. Thus, the use of in situ products or by-products would efficiently contribute to global sustainability.

## Several Alternative Materials Are as Effective as Peat for Producing High-Quality Forest Container Seedlings

The production of containerized seedlings in nurseries must be sustainable and ensure stable yield and plant quality [48]. While productivity and seedling quality have traditionally been the primary focuses of nursery cultivation, the environmental impact of nursery production has become a main concern. Moreover, with the increasing demand for forest seedlings due to global restoration/reforestation initiatives, it will be necessary to replace peat with sustainable materials [49]. The selection of alternative materials should consider local availability and the environmental impacts of material processing. Our review shows that the physicochemical properties and their subsequent effectivity on seedling nursery growth and field performance vary among alternative GM materials. Bark and rice had the best GM physicochemical characteristics, while compost and manure promote greater seedling growth compared to other components, likely due to their fertilization capacity [50, 51]. Seedlings cultivated in compost and rice hull-derived materials showed the highest field performance.

There are alternative materials with suitable physicochemical properties that promote the growth and quality of both angiosperm and gymnosperm seedlings, or sometimes even better than peat [37, 52]. For example, sewage sludge induces a significant increase in seed germination, seedling above- and below-ground biomass, and morphology of *Pinus pinaster* [53]. Green compost, produced from shredded branches of three fast-growing species (*Acacia cyanophylla*, *Acacia cyclops*, and *Eucalyptus gomphocephala*), showed seed germination rates similar to peat: vermiculite substrate and high-quality seedlings of *Ceratonia siliqua* L., although these seedlings had significantly smaller shoots and root systems than those produced in peat substrate [54]. Seedlings of three *Quercus* species (*Q. robur*, *Q. pubescens*, and *Q. ilex*) grown with coir, although smaller in size when compared with those grown in compost, were compatible with standard *Quercus* forest stocktype size and showed a proportionally higher root system development and fibrosity [36]. Biochar from orchard pruning and/or compost from olive mill residues showed an improvement in the growing substrate properties leading to accelerated growth and development of *Populus euroamericana* [40•]. Raw biochar and acidified biochar improved the rooting and growth of *Rosmarinus officinalis* cuttings, and the raw biochar gave satisfactory results for both shoot and root growth of *R. officinalis* and *Phyllirea angustifolia* seedlings [55•]. Willow biochar amendment increased the aboveground growth of *Picea abies* seedlings and root biomass, as well as the root collar diameter of *Betula pendula* seedlings and boreal conifers [56•]. The addition of raw pine sawdust to a substrate composed of 25% peat moss and 50% composted bark improved *Pinus cembroides* growth, which indicates that sawdust addition may be a suitable alternative especially if the cost–benefit analysis is a concern to the nursery manager [57].

Our review identifies compost as the most studied alternative material globally and the best-performing GM component in terms of physicochemical characteristics, seedling nursery growth, and field performance. Manure, other organic material, bark, rice hulls, and sludge also showed effectiveness albeit to a lesser extent compared to compost.

The number of studies reporting the effect of alternative materials on field performance between species groups was, unfortunately, small, and therefore, we could not evaluate the effectiveness of all materials. It is important to highlight that rice hulls, which are generally associated with other alternative materials (mostly coir, manure, and other organic material) and traditional materials (soil or peat), were very effective in increasing field performance in angiosperms but had negative effects in gymnosperms. Sludge, associated mainly with bark and chips, showed the opposite trend affecting positively the growth performance of gymnosperms in both the nursery and the field.

We finally underscore that further experiments at the local scale are necessary for testing the proportions of novel and sustainable materials composing GM to define the reliability of alternative and innovative GMs for forest nurseries.

## The Effectiveness of Alternative Materials Should Be Tested According to Regional Availability

Compost, other organic materials, and bark represent almost 50% of the alternative materials studied at the global scale. Our results indicate that about 70% of compost comes from organic material generated from agriculture, forestry, and animal breeding, which reinforces the importance of such sectors in the circular economy [58–60]. The prevalence of alternative materials in GM showed remarkable differences among world regions reflecting different local socio-economic and legislation contexts, available materials, and environmental specificities. Compost and sludge obtained from waste, the by-product of urban activities, are widely used in North America and Europe representing more than 50% of the case studies while no record was found in Africa and Oceania. These regional differences likely reflect different levels of urbanization, technology, and environmental legislation among regions [61]. The importance of the local context is particularly evident in South America. The use of alternative materials originated from municipalities in Brazil, where nursery activities are thriving due to vast plantation activities [62], which is similar to North America due to the development of large metropolitan areas. In contrast, such materials are rarely considered in other South American countries.

When considering alternatives to peat, it is important to carefully assess both sustainability and cost factors. A recent review [63] found that the cost of the container (i.e., Deepot™ D40) and growing media per single cavity in a forest nursery case study in Lebanon were three times lower when using coir compared to peat. However, a life cycle assessment (LCA) of coir compared to peat and perlite for rooftop farming in Spain revealed that while coir was more environmentally friendly, it did not perform well from a social perspective in key indicators such as child labor, fair pay, gender inequality, and impact on community infrastructure [64]. Additionally, a study in Latvia raised concerns about the sustainability of coir, particularly in relation to its impact on global warming [65], and other studies have suggested that the cost of refining coir to be used as growing media and the transportation costs from tropical areas of origin could pose significant constraints [17••, 49, 66]. It is worth mentioning that the abundant unused coir by-products in many coconut-producing countries can cause serious environmental problems [22]. In this context, transportation can play an important role in accessing alternative material [22]. However, sustainability concerns related to long-distance transportation of alternative materials emphasize the importance of developing a local circular economy supply chain and promoting local infrastructure development for processing available resources. Moreover, although there are several underutilized alternative materials such as green waste, bark, and wood fibers, their other possible uses may limit the expansion of the supply of growing media, especially in some areas of the world like the EU, where the growing demand for alternative materials could lead to an increase in the prices [22].

All considered, our evidence-based review could help to develop (i) a consistent approach for the identification, selection, and characterization of alternative material and (ii) a rational understanding of the practical and economic situation involved in the use of GM aimed at choosing the most appropriate material for the cultivation of forest seedlings.

### GM Sustainability Can Be Increased by Removing and Reducing the Proportion of Peat in Mixtures

GMs can be pure or can be a mixture of materials [33, 67]. Mixtures are designed to enhance the physicochemical characteristics of GM (e.g., [53, 68, 69], according to the specific physiological requirements of plants [70]. Moreover, GM mixtures should also provide economic and environmental benefits (e.g., [71, 72]), although the value and the feasibility of alternative materials in practical nursery activities need to be further demonstrated. Traditional unsustainable materials, such as peat, vermiculite, and natural soil, are commonly mixed with alternative sustainable ones, which were part of the GM in 74% of the case studies (54% only for peat or soil). However, this aspect is also influenced by local contexts. For instance, in Europe, America, and Oceania, GMs constituted only by alternative materials are about one-third of the case studies in this review, while in Asia and Africa, GMs made of alternative materials account for less than 8%.

In many tropical areas or less developed countries, many nurseries lack the resources to obtain commercial nursery substrates and often resort to using local and sustainable materials, such as natural or forest soil. However, the use of natural forest soil as a substrate is an environmentally unsustainable practice. Harvesting topsoil for nursery purposes can be likened to mining operations, depleting a resource that has taken years to form which can cause erosion and site degradation [11]. In addition, the soil has been found to be an inadequate growing medium for containerized forest nursery production in Africa, Asia, and Latin America, producing poor-quality nursery seedlings [12]. The use of soil should be avoided for several technic reasons, including the considerable variability in its physical and chemical properties; the limited availability of nutrients; the potential presence of harmful soil microorganisms, weed seeds, insects, and other diseases; and the presence of clay and silt that can impede water drainage and soil aeration [11, 12].

## Conclusions and Future Directions

The extensive literature produced worldwide demonstrates the widespread interest in the GM sector. However, similar to meta-analytical approaches in other fields [73], one of the main challenges in conducting a study analyzing this literature is the high variability among published experiments, significantly limiting the number of studies that can be effectively included. In our case, the variability was mainly due to the type of alternative materials used, the potential inclusion of traditional materials, and the varying proportions of each material in the GM. Furthermore, inconsistencies in reporting study methodology and statistics across articles hindered the inclusion of a significant number of studies. As a result, the establishment of criteria for analyzing available information inevitably affected the evaluation and the analytical comparison of the categories of alternative materials included in our study. Nevertheless, this work represents the first significant effort to quantify and analytically describe the utilization and effectiveness of materials other than peat**.**

Forest researchers and practitioners should keep exploring suitable combinations of renewable primary materials with valuable waste compounds for forest nursery activities, which would minimize environmental impacts and costs. Our review shows that most of the tested alternative materials were effective for growing nursery forest seedlings. However, few studies evaluated the field outplanting performance of container seedlings raised in GM composed of alternative materials, despite that field performance represents the *acid test* for the effectiveness of nursery cultivation treatments. Nonetheless, bark and sludge showed the best results in field outplanting performance for angiosperms and gymnosperms, respectively. The present study represents a stepping stone toward implementing knowledge-based practices for the sustainable growth of forest seedlings in nurseries. However, detailed, repeated, and statistically consistent studies should be performed in the future to allow more quantitative analyses. Moreover, to increase the number of alternative materials that otherwise would not be suitable as GM components, it is necessary to develop knowledge of specific chemical, thermochemical, and physical treatments to optimize their physicochemical properties for seedling growth [67]. However, these treatments might have a high environmental impact, turning an innovative and sustainable material into an unsustainable one. Future research should move from just testing the effect of GM on seedling morphological traits to a more comprehensive overview of GM effectiveness by including field tests of seedling performance. In a world of increasing natural resources scarcity and climatic crisis, the use of sustainable alternative GM has much to offer in a truly green industry, utilizing sustainable resources, and minimizing waste materials while improving the productivity and efficiency of container seedling production and forest restoration. Thus, it is urgent to move toward (i) a standardization on a local scale of the alternative material production process, (ii) the development of protocols for the use of the alternative material in forest nursery and field outplanting, and (iii) the identification of the best-performing mixtures based on local materials.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s40725-023-00204-2.

**Acknowledgements** This article is based upon the work of Work Group 3 "Quality matters!" within the COST Action CA19128 PEN-CAFoRR—Pan-European Network for Climate Adaptive Forest Restoration and Reforestation — supported by COST (European Cooperation in Science and Technology). The authors thank the two anonymous reviewers for their helpful comments on the previous version of the manuscript.

**Author Contribution** Substantial contributions to the conception and design of the work: BM, AM, JAO, EA, VI, MT, PVS, CC. Acquisition, analysis, or interpretation of data for the work: BM, JAO, EA, IKJ, NB, HB, BC, KD, JH, GH, AM, IFS, VI, MT, CC. Drafting the work or revising it critically for important intellectual content: BM, JAO, EA, VI, AM, MT, PVS, CC. All authors approved the final version of the manuscript and ensure that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

**Funding** This funding was provided by the COST Action CA19128 (PEN-CAFoRR) "Pan-European Network for Climate Adaptive Forest Restoration and Reforestation," supported by COST (European Cooperation in Science and Technology) (www.cost.eu).

**Data Availability** The complete data collected in the research are available from the authors under request.

## Declarations

**Conflict of Interest** The authors declare that they have no conflict of interest.



## References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Weiskopf SR, Rubenstein MA, Crozier LG, Gaichas S, Griffis R, Halofsky JE, et al. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Sci Total Environ. 2020;733:137782. https://doi.org/10.1016/j.scitotenv.2020.137782.
2. Verdone M, Seidl A. Time, space, place, and the Bonn Challenge global forest restoration target. Restor Ecol [Internet]. 2017 [cited 2020 Oct 11];25:903–11. Available from: http://doi.wiley.com/10.1111/rec.12512. Accessed Apr 2022.
3. United Nations. About the UN Decade | UN Decade on Restoration [Internet]. 2022. [cited 2023 Apr 22]. Available from: https://www.decadeonrestoration.org/about-un-decade. Accessed April 2022.
4. Landis TD (2003) The target seedling concept—a tool for better communication between nurseries and their customers. In: Riley LE, Dumroese RK, Landis TD (tech coords) National Proc: Forest and Conservation Nursery Assoc—2002. Proc RMRS-P-28. US Dept Agric Forest Serv Rocky Mtn Res Sta, Ogden, UT, pp 12–16.
5. Landis TD, Dumroese RK. Applying the target plant concept to nursery stock quality. In: MacLennan L, Fennessy J, editors. Plant quality: A key to success in forest establishment. Dublin, Ireland: National Council Forest Res Develop; 2006. p. 1–10.
6. Landis TD (2011) The Target Plant Concept——a history and brief overview. In: Riley LE, Haase DL, Pinto JR (tech coords) National Proc: Forest and Conservation Nursery Assoc——2010. Proc RMRS-P-65. US Dept Agric Forest Serv Rocky Mtn Res Sta, Ft Collins, CO, pp 61–66.
7. Grossnickle SC, El-Kassaby YA. Bareroot versus container stocktypes: a performance comparison. New Forest. 2016;47:1–51.
8. Schmilewski G. The role of peat in assuring the quality of growing media. Mires Peat. 2008;3:1–8.
9. Grafiadellis I, Mattas K, Maloupa E, Tzouramani I, Galanopoulos K. An economic analysis of soilless culture in gerbera production. HortScience HortSci. 2000;35(2):300–3.
10. Montagnoli A, Dumroese RK, Negri G, et al. Asymmetrical copper root pruning may improve root traits for reforesting steep and/or windy sites. New Forests. 2022;53:1093–112. https://doi.org/10.1007/s11056-022-09913-1
11. Haase DL, Bouzza K, Emerton L, Friday JB, Lieberg B, Aldrete A, et al. The high cost of the low-cost polybag system: a review of nursery seedling production systems. Land. 2021;10:826.
12. Landis TD, Tinus RW, McDonald SE, Barnett JP. Containers and growing media, vol. 2. The container tree nursery manual. In: Agriculture handbook, 674. Washington, DC: U.S. Department of Agriculture Forest Service; 1990. p. 88.
13. Landis TD, Wilkinson KM. Defining the target plant. In Tropical Nursery Manual: A Guide to Starting and Operating a Nursery for Native and Traditional Plants; Agriculture Handbook 732; Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK, editors. U.S. Department of Agriculture, Forest Service: Washington, DC, USA; 2014. p. 44–65.
14. Tsakaldimi M. Research on the production and quality assessment of the container-planting stock used in the afforestations [PhD]. Faculty of Forestry and Natural Environment: Aristotle University of Greece; 2001.
15. Landis TD, Morgan N. Growing media alternatives for forest and native plant nurseries. In National Proceedings: Forest and Conservation Nursery Association — 2008. Technical coordinators R.K. Dumroese and L.E. Riley. USDA For Serv Rocky Mt Res Sta Proc. RMRS-P-58. 2009. p. 26–31.
16. Blievernicht A, Irrgang S, Zander M, Ulrichs C. Sphagnum biomass - the next generation of growing media. Peatlands Int. 2013;1:32–5.
17. •• Gruda NS. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems.

Agronomy. 2019. **This review points out that treated and untreated waste and renewable raw materials have great potential as growing media constituents and stand-alone substrates. Therefore, the author calls for a waste management strategy for obtaining growing media of the future that must be available, affordable, and sustainable and meet both quality and environmental requirements from growers and society, respectively.**

18. Belyea LR, Malmer N. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Glob Chang Biol. 2004;10(7):1043–52. https://doi.org/10.1111/j.1529-8817.2003.00783.x.
19. Gorham E, Lehman C, Dyke A, Clymo D, Janssens J. Long-term carbon sequestration in North American peatlands. Quater Sci Rev. 2012;58:77–82.
20. Leifeld J, Menichetti L. The underappreciated potential of peatlands in global climate change mitigation strategies. Nat Commun. 2018;9:1071. https://doi.org/10.1038/s41467-018-03406-6.
21.•• Alexandrov GA, Brovkin VA, Kleinen T, Yu Z. The capacity of northern peatlands for long-term carbon sequestration. Biogeosciences. 2020;17. **This paper reports the potential carbon stock amount in northern peatlands and the corresponding carbon removal from the atmosphere. Thus, the authors argue the fundamental role in reducing the atmospheric carbon dioxide concentration over the next 5000 years in northern peatlands.**
22. Olivier H, Bernhard O, Holger W, Sebastian G, Marie-Friederike O. Peat replacement in horticultural growing media: Availability of bio-based alternative materials, Thünen Working Paper, No. 190. Braunschweig: Johann Heinrich von Thünen-Institut; 2022. https://doi.org/10.3220/WP1648727744000.
23. Clarke D, Rieley JO. Strategy for responsible Peatland management. 6th ed. In: Clarke D, Jyväskylä JR, editors. Jyväskylä: International Peatland Society; 2019.
24. Kern J, Tammeorg P, Shanskiy M, Sakrabani R, Knicker H, Kammann C, Tuhkanen E-M, Smidt G, Prasad M, Tiilikkala K, Sohi S, Gascó G, Steiner C, Glaser B. Synergistic use of peat and charred material in growing media – an option to reduce the pressure on peatlands? J Environ Eng Landsc Manag. 2017;25(2) https://doi.org/10.3846/16486897.2017.1284665.
25. Blok C, Eveleens B, van Winkel A. Growing media for food and quality of life in the period 2020–2050. Acta Hortic. 2021;1305:341–56. https://doi.org/10.17660/ActaHortic.2021.1305.46
26. UN Climate Change - Secretariat of the United Nations Framework Convention on Climate Change (2021) Greenhouse gas inventory data - peat extraction. Accessed January 12th, 2022. https://di.unfccc.int/flex_annex1.4.D.1.a (Peat Extraction Remaining Peat Extraction & 4.D.2.a Land Converted to Peat Extraction).
27. Brioche A. Peat Statistics and Information [Internet]. U.S. Geological Survey. Mineral yearbook. 2021. Available from: https://www.usgs.gov/centers/national-minerals-information-center/peat-statistics-and-information. Accessed Apr 2022.
28. Dennis JH, Lopez RG, Behe BK, Hall CR, Yue C, Campbell BL. sustainable production practices adopted by greenhouse and nursery plant growers. HortScience horts. 2010;45(8):1232–7.
29. Evans MR, Taylor M, Kuehny J. Physical properties of biocontainers for greenhouse crops production. HortTechnology. 2010;20(3):549–55.
30. Schrader JA, Srinivasan G, Grewell D, McCabe KG, Graves WR. Fertilizer effects of soy-plastic containers during crop production and transplant establishment. HortScience horts. 2013;48(6):724–31.
31.•• Beaulieu J, Belayneh B, Lea-Cox JD, Swett CL. Improving Containerized Nursery Crop Sustainability: Effects of Conservation-driven Adaptations in Soilless Substrate and Water Use on Plant Growth and Soil-borne Disease Development. HortScience. 2022;57. **Authors measuring tomato plant physiological traits and disease suppression in combination with the reduced water availability highlighted that the bark has optimal characteristics for substituting peat in growing media without compromising the economic productivity of the system.**
32. Chong C. Experiences with the utilization of wastes in nursery potting mixes and as field soil amendments. Can J Plant Sci. 1999;79:139–48.
33. Tsakaldimi M, Ganatsas P. A synthesis of results on wastes as potting media substitutes for the production of native plant species. REFORESTA. 2016;1(1):147–63.
34. Tsakaldimi M. Use of inorganic and organic solid wastes for container-seedlings production. In: Proceedings of the International Conference 'Protection and Restoration of the Environment VII', 28 June-1 July 2004. Mykonos; 2004.
35. Tsakaldimi M. Kenaf (Hibiscus cannabinus L.) core and rice hulls as components of container media for growing Pinus halepensis M. seedlings. Bioresour Technol. 2006;97:1631–9.
36. Mariotti B, Martini S, Raddi S, Tani A, Jacobs DF, Oliet JA, et al. Coconut coir as a sustainable nursery growing media for seedling production of the ecologically diverse Quercus species. Forests. 2020;11:522.
37. Gabira MM, Silva RBG, Bortolheiro FPAP, Mateus CMDA, Boas RLV, Rossi S, Girona MM, Silva MR. Composted sewage sludge as an alternative substrate for forest seedlings production. iForest. 2021;14:569–75. https://doi.org/10.3832/ifor3929-014.
38.•• Błońska E, Kempf M, Lasota J. Woody debris as a substrate for the growth of a new generation of forest trees. Forest Ecol Manag 2022;525. **Considering the ongoing effects of climate change and the increasing share of beech stands in the north-temperate climate zone, the replacement of peat with beech wood in the preparation of substrates for growing forest tree seedlings should be strongly considered.**
39. Simiele M, Argentino O, Baronti S, Scippa GS, Chiatante D, Terzaghi M, Montagnoli A. Biochar enhances plant growth, fruit yield, and antioxidant content of cherry tomato (solanum lycopersicum l.) in a soilless substrate. Agriculture. 2022;12(8):1135. https://doi.org/10.3390/agriculture12081135.
40.• Simiele M, De Zio E, Montagnoli A, Terzaghi M, Chiatante D, Scippa GS, et al. Biochar and/or compost to enhance nursery-produced seedling performance: A potential tool for forest restoration programs. Forests. 2022;13. **These authors highlighted that compost could be the best solution for enhancing substrate characteristics and increasing Poplar plant growth, highlighting the great potential for its proper and effective application in large-scale forest restoration strategies.**
41. Sop TK, Kagambèga FW, Bellefontaine R, Schmiedel U, Thiombiano A. Effects of organic amendment on early growth performance of *Jatropha curcas* L. on a severely degraded site in the Sub-Sahel of Burkina Faso. Agroforest Syst. 2012;86(3):387–99. https://doi.org/10.1007/s10457-011-9421-4.
42. Aung A, Youn WB, Seo JM, Dao HTT, Han SH, Cho MS, Park BB. Effects of three biomaterials mixed with growing media on seedling quality of Prunus sargentii. For Sci Technol. 2019;15(1):13–8. https://doi.org/10.1080/21580103.2018.1557564.
43. Andivia E, Villar-Salvador P, Oliet JA, Puértolas J, Dumroese RK, Ivetić V, Molina-Venegas R, Arellano EC, Li G, Ovalle JF. Climate and species stress resistance modulate the higher survival of large seedlings in forest restorations worldwide. Ecol Appl. 202;31(6):e02394. https://doi.org/10.1002/eap.2394.

44. Leverkus AB, Gustafsson L, Rey Benayas JM, et al. Does post-disturbance salvage logging affect the provision of ecosystem services? A systematic review protocol. Environ Evid. 2015;4:16. https://doi.org/10.1186/s13750-015-0042-7.
45. Dimitrova A, Csilléry K, Klisz M, Lévesque M, Heinrichs S, Cailleret M, et al. Risks, benefits, and knowledge gaps of non-native tree species in Europe. Front Ecol Evol. 2022;10:908464.
46. Whittaker R. Communities and Ecosystems. 2nd ed. New York: MacMillan Publishing Co.; 1975.
47. Tsakaldimi M, Ganatsas P, Jacobs DF. Prediction of planted seedling survival of five mediterranean species based on initial seedling morphology. New Forests. 2013;44:327–39.
48. Pretty J, Bharucha ZP. Sustainable intensification in agricultural systems. Ann Bot. 2014;114(8):1571–96.
49. Barrett GE, Alexander PD, Robinson JS, Bragg NC. Achieving environmentally sustainable growing media for soilless plant cultivation systems – a review. Sci Hortic. 2016;212:220–34.
50. López R, Cabrera F, Madejón E, Sancho F, Álvarez JM. Urban composts as an alternative for peat in forestry nursery growing media. Dynamic Soil, Dynamic Plant. 2008(1):60–66.
51. Restrepo AP, Medina E, Pérez-Espinosa A, Agulló E, Bustamante MA, Mininni C, Bernal MP, Moral R. Substitution of peat in horticultural seedlings: suitability of digestate-derived compost from cattle manure and maize silage codigestion. Commun Soil Sci Plant Anal. 2013;44(1-4):668–77. https://doi.org/10.1080/00103624.2013.748004.
52. Chong C, Lumis GP. Mixtures of paper mill sludge, wood chips, bark, and peat in substrates for pot-in-pot shade tree production. Canadian J Plant Science. 2000;80:669–75.
53. Mañas P, Castro E, De Las Heras J. Quality of maritime pine (*Pinus pinaster* Ait.) seedlings using waste materials as nursery growing media. New For. 2009;37:295–311.
54. Bakry M, Lamhamedi MS, Caron J, Margolis H, Zine El Abidine A, Bellaka M, Stowe DC. Are composts from shredded leafy branches of fast-growing forest species suitable as nursery growing media in arid regions? New Forests. 2012;43(3):267–86.
55.• Fornes F, Belda RM. Use of raw and acidified biochars as constituents of growth media for forest seedling production. New For. 2019;50. **This study presents empirical data regarding the positive effect of both raw and acidified biochar in improving the rooting and growth of Rosmarinus cuttings. For Phillyrea, results were slightly different, with no effect due to the acidified biochar application and satisfactory results obtained from raw biochar application. This paper confirms that biochar might be a constituent of growing media, even in large proportions.**
56.• Köster E, Pumpanen J, Palviainen M, Zhou X, Köster K. Effect of biochar amendment on the properties of growing media and growth of containerized norway spruce, scots pine, and silver birch seedlings. Can J For Res. 2021;51. **The authors demonstrate that biochar amendment significantly increases carbon, nitrogen, potassium, and phosphorus concentrations and has a significant liming effect on the growing media. Also, the authors show that biochar amendment may increase the growth of spruce and birch seedlings showing the biochar potential in forest seedling production.**
57. Madrid-Aispuro RE, Prieto-Ruíz JÁ, Aldrete A, Hernández-Díaz JC, Wehenkel C, Chávez-Simental JA, Mexal JG. Alternative substrates and fertilization doses in the production of Pinus cembroides Zucc. in nursery. Forests. 2020;11(1):71. https://doi.org/10.3390/f11010071.
58. Favoino E, Hogg D. The potential role of compost in reducing greenhouse gases. Waste Manag Res. 2008;26(1):61–9. https://doi.org/10.1177/0734242X08088584.
59. Brown S, Kruger C, Subler S. Greenhouse gas balance for composting operations. J Environ Qual Madison. Jul/Aug 2008;37(4):1396-410.
60. Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J. Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops. Resour Conserv Recycl, Elsevier. 2009;53(6):340–51.
61. Dijkstra L, Florczyk A, Carneiro Freire SM, Kemper T, Melchiorri M, Pesaresi M, Schiavina M. Applying the Degree of Urbanisation to the globe: A new harmonised definition reveals a different picture of global urbanisation. J Urban Econ. 2021;125:103312.
62. Moreira da Silva AP, Schweizer D, Rodrigues Marques H, Cordeiro Teixeira AM, Nascente dos Santos TVM, Sambuichi RHR, Badari CG, Gaudare U, Brancalion PHS. Can current native tree seedling production and infrastructure meet an increasing forest restoration demand in Brazil? Restor Ecol. 2017;25:509–15.
63. Haase DL, Bouzza K, Emerton L, Friday JB, Lieberg B, Aldrete A, Davis AS. The high cost of the low-cost polybag system: A review of nursery seedling production systems. Land. 2021;10(8):826. https://doi.org/10.3390/land10080826.
64. Toboso-Chavero S, Madrid-López C, Villalba G, Durany XG, Hückstädt AB, Finkbeiner M, Lehmann A. Environmental and social life cycle assessment of growing media for urban rooftop farming. Int J Life Cycle Assess. 2021;26:2085. https://doi.org/10.1007/s11367-021-01971-5.
65. Paoli R, Feofilovs M, Kamenders A, Romagnoli F. Peat production for horticultural use in the Latvian context: Sustainability assessment through LCA modeling. J Clean Prod. 2022;378:134559. https://doi.org/10.1016/j.jclepro.2022.134559.
66. Agarwal P, Saha S, Hariprasad P. Agro-industrial-residues as potting media: physicochemical and biological characters and their influence on plant growth. Biomass Convers Biorefin. 2021;9:1–24. https://doi.org/10.1007/s13399-021-01998-6.
67. Pascual JA, Ceglie F, Tuzel Y, et al. Organic substrate for transplant production in organic nurseries. A review. Agron. Sustain Dev. 2018;38:35. https://doi.org/10.1007/s13593-018-0508-4.
68. Dede OH, Dede G, Ozdemir S. Agricultural and municipal wastes as container media component for ornamental nurseries. Int J Environ Res. 2010;4(2):193–200.
69. Silva OMDC, Hernández MM, Araújo GDCR, Cunha FL, Evangelista DV da P, Leles PSDS, et al. Potential use of coffee husk as a substrate constituent for the production of forest species seedlings. Cienc Florestal. 2020;30(4):1161–75. https://doi.org/10.5902/1980509842500.
70. Landis TD, Dumroese RK, Haase D. Seedling processing, storage and outplanting, volume 7, the container tree nursery manual. In: Luna T, Dumroese RK, editors. Nursery manual for native plants: a guide for tribal nurseries. Washington (DC): USDA Agricultural Handbook; 2010. 199 p.
71. Mañas P, Castro E, Vila P, de las Heras J. Use of waste materials as nursery growing media for Pinus halepensis production. Eur J For Res. 2010;129:521–30.
72. Seehausen ML, Gale NV, Dranga S, Hudson V, Liu N, Michener J, Thurston E, Williams C, Smith SM, Thomas SC. Is there a positive synergistic effect of biochar and compost soil amendments on plant growth and physiological performance? Agronomy. 2017;7(1):13. https://doi.org/10.3390/agronomy7010013.
73. Andivia E, Villar-Salvador P, Oliet JA, Puértolas J, Dumroese RK. How can my research paper be useful for future meta-analyses on forest restoration plantations? New Forests. 2019;50(2):255–66. https://doi.org/10.1007/S11056-018-9631-Y.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Authors and Affiliations

**Barbara Mariotti[1,2] · Juan A. Oliet[3] · Enrique Andivia[4] · Marianthi Tsakaldimi[5] · Pedro Villar-Salvador[6] · Vladan Ivetić[7] · Antonio Montagnoli[8] · Ivona Kerkez Janković[7] · Nebi Bilir[9] · Henrik Bohlenius[10] · Branislav Cvjetković[11] · Kārlis Dūmiņš[12] · Juha Heiskanen[13] · Georgi Hinkov[14] · Inger Sundheim Fløistad[15] · Claudia Cocozza[1]**

✉ Antonio Montagnoli
antonio.montagnoli@uninsubria.it

1 Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Via San Bonaventura 13, 50145 Florence, Italy

2 National Biodiversity Future Center, Consiglio Nazionale Delle Ricerche, Palermo, Italy

3 Department of Forest Resources and Systems, Universidad Politécnica de Madrid. C/ José Antonio, Novais 10, 28040 Madrid, Spain

4 Department of Biodiversity, Ecology and Evolution, Faculty of Biological Sciences, Universidad Complutense de Madrid, C\ Jose Antonio Novais 12, 28040 Madrid, Spain

5 Laboratory of Silviculture, Department of Forestry and Natural Environment, Aristotle University of Thessaloniki, P.O.Box 262, 54124 Thessaloniki, Greece

6 Universidad de Alcalá Forest Ecology and Restoration Group, Departamento de Ciencias de La Vida, 8805 Alcalá de Henares, Madrid, Spain

7 Faculty of Forestry, University of Belgrade, Kneza Višeslava 1, 11030 Belgrade, Serbia

8 Department of Biotechnology and Life Science (DBSV), University of Insubria, Via Dunant, 3, 21100 Varese, Italy

9 Forestry Faculty of Isparta, University of Applied Sciences, TR-32260 Isparta, Turkey

10 Department of Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, P.O Box 190, 234 22 Lomma, Sweden

11 Faculty of Forestry, University of Banja Luka, Blvd. Vojvode Stepe Stepanovića 75A, Banja Luka, Bosnia and Herzegovina

12 Latvian State Forest Research Institute "Silava", Rigas Str 111, Salaspils 2169, Latvia

13 Natural Resources Institute Finland (Luke), Forest Management Juntintie 154, FI-77600 Suonenjoki, Finland

14 Forest Research Institute at BAS, Sofia, Bulgaria

15 Division of Forest and Forest Resources, Norwegian Institute of Bioeconomy Research (NIBIO), N-1431 Ås, Norway