

Review

Wood Fibres as Partial Peat Substitutes in Forest Nursery Substrates: Practical Performance, Management Implications, and Remaining Research Questions

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Abstract

This review evaluates the current state of knowledge on the use of wood fibres and related woody materials as partial substitutes for peat in substrates used for forest nursery production, with particular emphasis on container seedlings. The review was prepared as a structured narrative synthesis of the available literature, focusing on substrate composition, physical and chemical properties, tree seedling growth, root development, water regime, fertilisation, operational handling, economic aspects and remaining research needs. The available evidence shows that wood fibres are technically promising components of peat-reduced growing media, but their performance depends strongly on the raw-material origin, processing method, substrate proportion, tree species, and cultivation management. The most reliable results have been obtained with partial substitution systems, whereas peat-free solutions remain species-specific and require careful optimisation of irrigation, nitrogen supply, pH control, and substrate quality. Although wood-based materials may improve resource efficiency and, under favourable local conditions, reduce substrate costs, wider implementation is constrained by variable material quality, limited standardisation and insufficient operational-scale validation. The main remaining research need is to define species-specific application thresholds and management protocols and to link nursery performance with outplanting success and full production economics under commercial conditions.

Keywords: wood fibres; partial peat substitute; substrate; tree seedlings; peat-reduced growing media



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1. Introduction

Peat has long been the key constituent of professional growing media for plants including tree seedlings because it combines several properties that are difficult to replicate simultaneously in alternative materials (substrates): high porosity, favourable water retention, low bulk density, low nutrient content, relatively predictable pH adjustment after liming and generally high sanitary safety. For nursery producers, these properties are particularly important because the growing medium must function reliably under intensive cultivation, standardised irrigation and fertilisation regimes and strict quality requirements for marketable planting stock. At the same time, peat extraction and use are increasingly challenged by environmental and climate considerations, which have intensified interest in renewable or residual biomass-based substitutes for peat in commercial substrates [1–3].

In forest nurseries, the need for technically robust substrate alternatives is especially acute. Container seedling production relies on small substrate volumes, rapid and uniform early development, controlled root architecture and high reproducibility among trays and seedling cohorts. In such systems, even moderate changes in substrate aeration, easily available water, nutrient buffering, or biological stability may affect germination; height growth; root-collar diameter; root-system quality; and, ultimately, field performance after planting. A recent global synthesis of forest seedling growth media confirms that the forest nursery sector is actively seeking alternatives to peat, in addition to showing that the available evidence remains fragmented across species, climatic zones, substrate formulations and production objectives [4].

Among the available peat substitutes, wood-derived materials are of particular interest because they may be regionally available, compatible with circular bioeconomy principles and already partly integrated into commercial substrate development. Wood fibres, wood wool and related woody fractions can improve air-filled porosity and reduce dependence on peat, but they also introduce technical constraints that are highly relevant for nursery practice. Earlier work on wood-fibre substrates has shown that they typically differ from peat by having greater air volume but lower water availability, which may require changes in irrigation management. In addition, their high carbon-to-nitrogen ratio (C/N) and biological activity can increase the risk of nitrogen (N) immobilisation and thereby alter fertilisation requirements. These effects do not necessarily preclude their use, but they imply that wood fibres should not be treated as a simple one-to-one replacement for peat [1,5].

Therefore, the practical challenge is not only whether wood fibres can replace peat but under which conditions they can do so without compromising seedling quality, operational stability, or economic feasibility. This question is particularly important in forest nurseries, where acceptable nursery performance must be achieved across different tree species, container systems, watering strategies and fertilisation schedules. Moreover, the technical suitability of wood fibres depends on several interacting factors, including tree species, origin of the woody raw material, processing method, particle-size distribution, substrate proportion, decomposition dynamics and compatibility with existing nursery infrastructure. At the same time, broader adoption depends on cost, local availability of suitable feedstock, processing logistics and competition with other wood-based uses [2–4].

Against this background, the aim of this review is to synthesise the current state of knowledge on the use of wood fibres as partial substitutes for peat in substrates used in forest nurseries, with particular emphasis on container seedling production. The review is practitioner-oriented and focuses on issues that determine operational applicability: suitable substrate composition; tree-species compatibility; water regime; fertilisation; and other management implications, including weed control and the physical stability of the growing medium. Several supporting studies on woody ornamental nursery crops and greenhouse substrate systems were also included to interpret substrate behaviour, especially where they addressed water retention, aeration, shrinkage, rewetting, and nutrient immobilisation, although they cannot fully substitute for direct evidence of forest seedling quality and planting performance. In addition, the review addresses economic considerations and identifies the most important remaining research questions that must be resolved before wider operational implementation can be recommended with confidence. This review continues the works initiated in recent syntheses in the field but is distinct from them. For instance, Mariotti et al. [4] provided a global review of innovative and sustainable materials composing growing media for forest seedling production, covering a wide range of peat alternatives and concluding that most outcomes are species- and site-specific. Sdao et al. [6] reviewed wood fibre, together with two other agro-industrial byproducts, coffee silver-

skin and brewer's spent grain, but framed their analysis around horticultural use, with plant-performance evidence drawn mainly from vegetable transplants and ornamental crops. This review focuses specifically on wood fibres and related woody materials in container-plant systems for seedlings in forest nurseries, emphasizing species-specific thresholds, seedling cultivation protocols, operational handling, outplanting links, and commercial-scale economics. Throughout, wood fibres and the wider family of related woody materials are assessed as components of mixed growing media, in conjunction with retained peat and other co-constituents, rather than as stand-alone materials.

2. Materials and Methods

This paper was prepared as a structured narrative review with transparent literature identification, screening and thematic synthesis, with emphasis on practical applicability in forest nursery production. The review focused on the use of wood fibres, wood wool and related woody materials as partial substitutes for peat in substrates used for forest reproductive material, particularly in container seedling production, while also considering evidence from bare-root systems and propagation by cuttings where relevant. The choice of a structured narrative review was motivated by the breadth of the topic, the diversity of study designs and production systems and the need to integrate both experimental findings and practice-oriented evidence. Such an approach is consistent with published guidance indicating that narrative or structured reviews are appropriate when the literature is heterogeneous and multidisciplinary and requires interpretative synthesis rather than narrowly standardised quantitative aggregation [7,8].

The initial evidence base was generated using the Elicit literature discovery platform (Ought, San Francisco, CA, USA, <https://elicit.com> [9]), which performed a semantic search across more than 138 million academic papers (scientific publications) from the Elicit search engine, including all records from Semantic Scholar and OpenAlex. The resulting evidence base was subsequently refined through a transparent eligibility-screening process. The search strategy was designed to capture studies addressing wood-derived substrate materials in nursery growing media, with particular attention to substrate composition, physical and chemical properties, seedling performance, management implications, economic aspects and unresolved research needs. The retrieval and screening workflow was inspired by the principle of transparent review reporting reflected in PRISMA 2020, although the present work was not designed as a full systematic review or meta-analysis [10]. Titles and abstracts were screened against predefined relevance criteria. Papers were considered eligible when they (i) addressed forest tree species or directly relevant woody nursery crops; (ii) evaluated wood-based materials as peat substitutes in growing media; (iii) were conducted in nursery or protected cultivation settings; and (iv) reported at least one relevant outcome related to substrate properties, plant performance, management requirements or operational feasibility.

Studies were excluded when they focused exclusively on agricultural crops, ornamental bedding plants or vegetable production without clear transferable relevance to forest nurseries; when wood materials were used for purposes other than peat substitution in growing media; when the work was limited to post-transplant field performance without nursery-stage substrate assessment; and when the publication did not provide original empirical evidence. The final evidence base prioritised studies with direct relevance to forest nursery substrates, but selected papers from adjacent nursery and greenhouse systems were retained as supporting evidence where they helped explain mechanisms important for nursery practice, particularly substrate aeration, water retention, rewetting behaviour, nutrient immobilisation and decomposition processes. This approach is consistent with

recommendations that literature reviews should explicitly define their scope, selection boundaries and rationale for inclusion of adjacent evidence domains [7,8].

For each included source, information was extracted on the type and origin of woody material, the processing method, substrate formulations, tree species, production systems, measured physical and chemical substrate properties, seedling performance indicators, management implications, economic aspects and reported knowledge gaps. The extracted information was consolidated into a manual thematic synthesis. The synthesis followed the logic of thematic analysis by organising evidence into descriptive and analytical themes, an approach widely recognised as suitable for integrating heterogeneous evidence and generating higher-level interpretation across diverse studies [11]. For the purposes of this review, the extracted information was grouped into five analytical domains: (i) wood fibre source and processing characteristics; (ii) substrate composition and physical performance; (iii) effects on seedling growth and root development; (iv) implications for irrigation, fertilisation and other nursery management practices; and (v) economic feasibility and barriers to wider implementation.

Given the substantial heterogeneity among studies in terms of tree species, substrate materials, processing technologies, mixture ratios, fertilisation regimes, irrigation strategies, cultivation systems and response variables, the evidence was synthesised qualitatively rather than by formal meta-analysis. Therefore, the review aimed to provide a critical and practice-oriented synthesis of the state of knowledge, identify conditions under which wood fibres can function as a technically feasible partial peat substitute and highlight the most important unresolved questions for further experimental and operational validation. This type of qualitative synthesis is methodologically justified where study comparability is limited and where the objective is not only to summarise outcomes but also to interpret implementation conditions, success factors and remaining uncertainties [7,8].

The initial Elicit search found 500 records covering the time period from 1975 to 2026, of which 73 met the main selection criteria for direct relevance to the review question; an additional five records were retained as supporting evidence (published between 1995 and 2026; Figure 1, Table 1 and Table S1 in the Supplementary Materials) [12–89]. A more detailed description of the evidence base and scope of application is provided in Section 3.1.

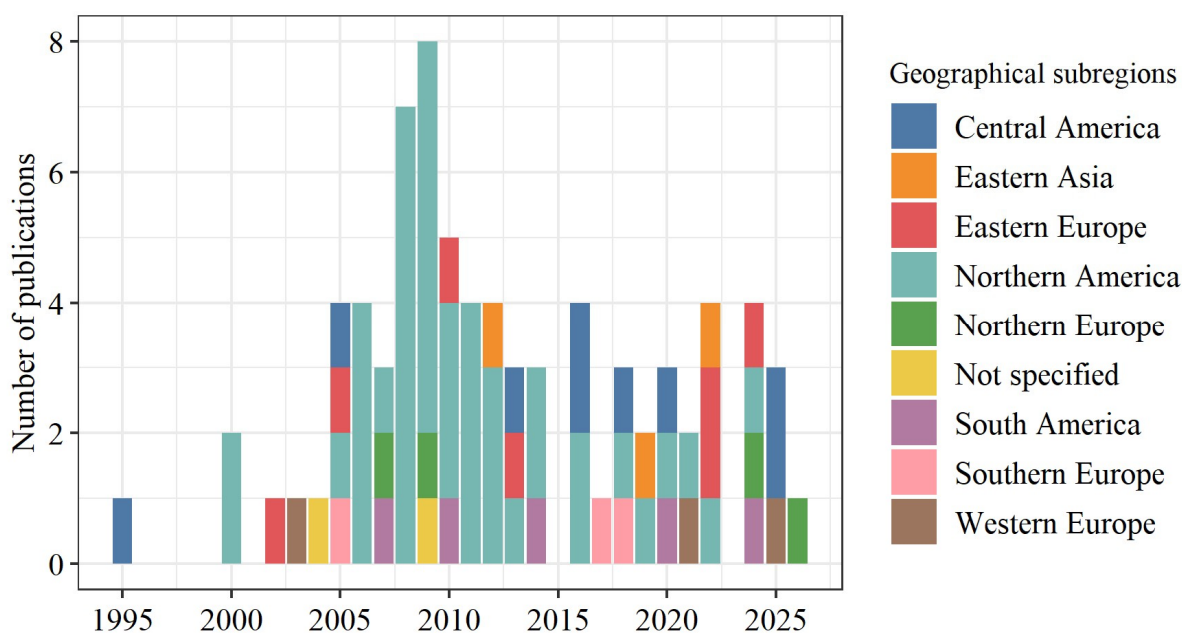


Figure 1. Temporal distribution of scientific publications (1995–2026) included in the review ($n = 78$ [12–89]) by world region (geographical subregions).

Table 1. Scientific publications (studies published between 1995 and 2026) included in the review ($n = 78$, [12–89]).

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Amaya Medina et al., 1995 [12]	<i>Pinus</i> spp.	Multiple mixtures with pine sawdust, rice hulls, bagasse, coffee pulp, and coconut fibre	<i>Eucalyptus camaldulensis</i> and <i>Acacia mangium</i>
Rose, Haase, 2000 [13]	<i>Pseudotsuga menziesii</i>	Peat moss, peat moss amended with sawdust, and two sources of coir (coconut fibre) mixed with and without peat moss	<i>Pseudotsuga menziesii</i>
Chong, Lumis, 2000 [14]	<i>Pinus</i> spp.	Pine bark, wood chips, compost, paper mill sludge, and peat in various combinations	<i>Fraxinus pennsylvanica</i> Marsh., <i>Betula platyphylla</i> var. <i>japonica</i> (Miq.) Hara, and <i>Acer saccharinum</i> L.
Kullmann et al., 2003 [15]	<i>Pinus sylvestris</i> L., <i>Picea abies</i> L. Karst., <i>Pseudotsuga menziesii</i>	Wood fibre substrates	<i>Brassica cernua</i> , <i>Lycopersicon esculentum</i> , <i>Petroselinum crispum</i> , and <i>Ocimum basilicum</i>
Prasad, Maher, 2004 [16]	-	Wood fibres, composted coir, and peat	-
Wright, Browder, 2005 [17]	<i>Pinus taeda</i> L.	Ground pine logs (100%), pine bark (100%), and pine chips (75%): bark (25%)	<i>Ilex crenata</i> Thunb. ‘Chesapeake’, <i>Rhododendron obtusum</i> Planch. ‘Karen’, and <i>Tagetes erecta</i> Big. ‘Inca Gold’
Reyes-Reyes et al., 2005 [18]	<i>Pinus</i> spp.	80% sawdust + 20% pine bark, forest soil, peat, moss, or agrolite	<i>Pinus pseudostrobus</i> var. <i>Apulcensis</i>
Hernández-Apaolaza et al., 2005 [19]	<i>Pinus</i> spp.	Pine bark with/without sewage sludge compost (15%, 30%)	<i>Pinus pinea</i> , <i>Cupressus arizonica</i> , and <i>C. sempervirens</i>
Wright et al., 2006 [20]	<i>Pinus taeda</i> L.	Fresh pine wood chips vs. aged pine bark	18 different plant taxa
Rau et al., 2006 [21]	<i>Pinus taeda</i> , <i>Pinus strobus</i> , <i>Platanus occidentalis</i> , <i>Acer rubrum</i> , <i>Quercus alba</i>	Wood substrates from different tree species (debarked logs)	<i>Lycopersicon esculentum</i>
Yu, Zinati, 2006 [22]	<i>Pinus</i> spp.	Composted pine bark (40%–90%), peat (0%–50%), and sand (10%–2%)	-
Maeda et al., 2007 [23]	<i>Pinus</i> spp.	Multiple mixtures with pine bark, wooden sawdust, and other organic waste	-

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Veijalainen et al., 2007 [24]	-	Forest nursery waste compost (100%) and peat mixtures containing 25 or 50% compost	<i>Picea abies</i> (L.) Karst.
Buamscha et al., 2007 [25]	<i>Pseudotsuga menziesii</i> (Mirbel) Franco	Douglas fir bark from two sources: fresh vs. aged	-
Wright et al., 2008 [26]	<i>Pinus taeda</i>	Pine tree substrate vs. peat-lite (45% peat, 15% perlite, 15% vermiculite, and 25% bark)	<i>Chrysanthemum</i> × <i>grandiflora</i> ‘Baton Rouge’
Fain et al., 2008 [27]	<i>Pinus taeda</i> L.	Whole tree alone or with 20% or 50% peat	<i>Tagetes patula</i> ‘Little Hero Yellow’ and <i>Petunia</i> × <i>hybrida</i> ‘Dreams Pink’
Fain et al., 2008 [28]	<i>Pinus taeda</i> L.	Whole tree alone or with 20% or 50% peat	<i>Petunia</i> × <i>hybrida</i> Vilm. ‘Dreams Purple’ and <i>Tagetes patula</i> L. ‘Hero Spry’
Boyer et al., 2008 [29]	<i>Pinus taeda</i> L.	Pine bark (100%) and a pulpwood harvesting by-product called clean chip residual (alone or amended with peat moss 4:1 by volume)	Nine perennial species
Jackson et al., 2008 [30]	<i>Pinus taeda</i> L.	Pine tree substrates with/without 25% peat	<i>Euphorbia pulcherrima</i> Willd. Ex Klotzsch
Marble et al., 2008 [31]	<i>Pinus</i> spp.	Whole tree, clean chip residual, and pine bark with the addition of composted poultry litter or peat as a substrate amendment	<i>Rhododendron</i> ‘Iveryana’, <i>Buxus sempervirens</i> L., <i>Ilex crenata</i> Thunb. ‘Compacta’, <i>Loropetalum chinense</i> Oliv. f. <i>rubrum</i> ‘Chang’s Ruby’, and <i>Ternstroemia japonica</i>
Lu-Min Vaario et al., 2009 [32]	<i>Pinus</i> spp.	Low- humified <i>Sphagnum</i> peat mixed with woody material (wood fibre and pine bark)	<i>Picea abies</i> (L.) Karst.
Davis et al., 2009 [33]	<i>Pseudotsuga menziesii</i>	Peat with sawdust (80:20), peat with bark (75:25), and 100% peat	<i>Larix occidentalis</i>
Jackson et al., 2009 [34]	<i>Pinus taeda</i> L.	Pine tree substrate, peat-lite, and aged pine bark	-
Wright et al., 2009 [35]	<i>Pinus strobus</i> L.	White pine chips with 25% or 50% peat moss	<i>Tagetes erecta</i> Big. ‘Inca Gold’, <i>Chrysanthemum</i> × <i>morifolium</i> ‘Mary’, and <i>Spiraea</i> × <i>bumalda</i> ‘AnthonyWaterer’

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Jackson et al., 2009 [36]	<i>Pinus taeda</i> L.	Pine tree substrate vs. peat-lite	-
Boyer et al., 2009 [37]	<i>Pinus</i> spp.	Clean chip residual (~50% wood-fibre, 40% bark, 10% foliage, and other material (pine cones, etc.)) vs. pine bark	<i>Buddleia davidii</i> ‘Black Knight’, <i>Lagerstroemia indica</i> ‘Hopi’, and <i>Rhododendron</i> × ‘Fashion’
Altland et al., 2008 [38]	<i>Pseudotsuga menziesii</i>	Bark with peat and pumice	-
Gabriel et al., 2009 [39]	<i>Pseudotsuga menziesii</i>	Bark with 0%–30% peat and 0%–30% pumice	-
Schaefer, 2009 [40]	<i>Pseudotsuga menziesii</i>	Peat/sawdust blend	<i>Pinus ponderosa</i> and other <i>Pinus</i> spp., <i>Larix occidentalis</i> , <i>Pseudotsuga menziesii</i> , and <i>Abies</i> spp.
Jackson et al., 2010 [41]	<i>Pinus taeda</i> L.	Wood chips, peat moss, aged pine bark, and sand	<i>Tagetes erecta</i> L. ‘Inca Gold’, <i>Spiraea nipponica</i> Maxim. ‘Snowmound’, and <i>Rhododendron</i> × <i>hybrida</i> ‘Girard Pleasant White’
de Freitas et al., 2010 [42]	<i>Eucalyptus</i> spp.	Coconut fibre, eucalyptus bark, and sugarcane filter cake	<i>Eucalyptus urophylla</i>
Marble et al., 2010 [43]	-	Whole tree, clean chip residual with composted poultry litter	<i>Rhododendron</i> × ‘Iveryana’ and <i>Rhododendron</i> × ‘Amelia Rose’; <i>Buxus sempervirens</i> L.; <i>Ilex crenata</i> Thunb. ‘Compacta’; <i>Loropetalum chinense</i> Oliv. ‘Chang’s Ruby’; <i>Ternstroemia gymnanthera</i> Thunb., and <i>Ternstroemia gymnanthera</i> ‘Bronze Beauty’
Зайцева et al., 2010 [44]	<i>Betula pendula</i> Roth, <i>Alnus incana</i> L., <i>Salix caprea</i> L.	Peat with compost from logging residues	<i>Pinus sylvestris</i> L. and <i>Picea abies</i> L. Karst.
Cochran et al., 2006 [45]	<i>Pinus taeda</i> L.	Pine wood chips; chipped <i>Pinus taeda</i> , including needles; pine bark; and sand	Prostrate spurge
Gaches et al., 2010 [46]	<i>Pinus taeda</i> L.	Whole tree vs. chipped pine logs, both with peat	<i>Catharanthus roseus</i> L. ‘Grape Cooler’, and <i>Impatiens walleriana</i> Hook.f. ‘Dazzler Apricot’
Gaches et al., 2011 [47]	<i>Pinus taeda</i> L.	Fresh vs. aged whole tree with peat	<i>Petuhia xhibrida</i> ‘Dreams White’ and <i>Tagetes patula</i> ‘Little Hero Yellow’

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Murphy, 2011 [48]	<i>Pinus</i> spp.	Pine bark with 25%–75% clean chip residual or whole tree	<i>Lantana camara</i> L. ‘New Gold’, <i>Spiraea japonica</i> L.f. ‘Gold Mound’, <i>Rhododendron</i> × ‘Amaghasa’, <i>Osmanthus fragrans</i> Lour., <i>Ligustrum japonicum</i> Thunb. ‘Rotundifolia’, and <i>Ilex crenata</i> ‘Soft Touch’
Murphy et al., 2011 [49]	<i>Pinus taeda</i> L.	Whole tree, sweetgum, hickory, eastern redcedar, and peat	<i>Petunia</i> × <i>hybrida</i> Juss. ‘Dreams Sky Blue’, <i>Catharanthus roseus</i> (L.) G. Don ‘Cooler Peppermint’, and <i>Impatiens walleriana</i> Hook.f. ‘Super Elfi n Salmon’
Witcher et al., 2011 [50]	<i>Pinus taeda</i> L.	Whole pine tree vs. peat-lite substrates	<i>Petunia</i> × <i>hybrida</i> Hort. ex E. Vilm. ‘Wave Purple’ and ‘Celebrity Rose’
Marble et al., 2012 [51]	<i>Pinus taeda</i> L.	Pine bark, whole tree, and clean chip residual	<i>Lagerstroemia indica</i> × <i>faurei</i> ‘Acoma’, <i>Magnolia grandiflora</i> ‘D.D. Blanchard’, and <i>Quercus shumardii</i>
Altland, Krause, 2012 [52]	<i>Pinus taeda</i> L.	Pine bark with pine wood substitution (chipped pine logs, including bark and wood but excluding branches and needles)	-
Boyer et al., 2012 [53]	<i>Pinus taeda</i> L.	Clean chip residual (two screen sizes) vs. pine bark and peat moss	-
Ren-an et al., 2012 [54]	-	Multiple mixtures of peat, perlite, rice hulls, and sawdust	<i>Liquidambar formosana</i>
Banach et al., 2013 [55]	-	Peat-sawdust and peat-perlite, with/without mycorrhizal inoculum	<i>Abies alba</i> Mill. and <i>Fagus sylvatica</i> L.
Owen et al., 2013 [56]	<i>Pinus taeda</i> L.	Pine wood chips vs. perlite in peat substrates	<i>Helianthus annuus</i> ‘Pacino Gold’

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Witcher et al., 2014 [57]	<i>Pinus taeda</i> L., <i>Pinus</i> spp.	Whole pine tree and pine bark, with/without peat moss	<i>Chrysanthemum</i> × <i>morifolium</i> ‘Dazzling Stacy’, <i>Cupressus</i> × <i>leylandii</i> ‘Murray’, <i>Ligustrum japonicum</i> ‘Texanum’), <i>Salvia leucantha</i> , <i>Euonymus fortunei</i> ‘Kewensis’, <i>Evolvulus glomeratus</i> ‘Blue Daze’, <i>Polygonum microcephalum</i> ‘Red Dragon’, and <i>Rosa</i> ‘Red Cascade’
Nogueira et al., 2014 [58]	<i>Pinus</i> spp.	Pine bark, peat, and wood shavings	<i>Eucalyptus grandis</i>
Fields et al., 2014 [59]	<i>Pinus taeda</i> L.	Peat with shredded pine wood or pine wood chips	-
Sánchez-Córdova et al., 2016 [60]	<i>Pinus</i> spp.	Pine bark, sawdust, peat moss, vermiculite	-
Owen et al., 2016 [61]	<i>Pinus taeda</i> L.	<i>Sphagnum</i> peat-based substrates amended with perlite or pine wood chips	<i>Zinnia</i> × <i>hybrida</i> ‘Profusion Orange’ and <i>Tagetes erecta</i> ‘Moonsong Deep Orange’
Picchioni et al., 2016 [62]	<i>Carya illinoensis</i> (Wangenh.) K. Koch.	Peat with 0%–100% pecan wood chips	<i>Dendranthema</i> × <i>grandiflorum</i> ‘Carpino’
Buendía Velázquez et al., 2016 [63]	-	Peat moss vs. sawdust	<i>Pinus leiophylla</i>
Larcher et al., 2017 [64]	-	Peat (30%–40%), coconut fibres (40%), wood fibres (0%–20%), rice husk (0%–20%), and pumice (10%–20%)	<i>Phyllostachys pubescens</i> (Carrière) J. Houz
González-Orozco et al., 2018 [65]	Bark of <i>Pinus douglasiana</i> Martínez, fresh pine sawdust from <i>Pinus engelmannii</i> Carr., <i>Pinus cooperi</i> Blanco, <i>Pinus durangensis</i> Martínez	Peat moss (15%–50%), composted pine bark (15%–50%), and fresh pine sawdust (20%–70%)	<i>Pinus engelmannii</i> Carr.
Slávik et al., 2005 [66]	<i>Picea abies</i> [L.] Karst.	Peat, spruce bark compost, and agropperlite mixtures	<i>Picea abies</i> [L.] Karst.
Prieto Ruiz et al., 2013 [67]	<i>Pinus</i> spp.	Composted pine bark (50%–80%) with base mix (50% peat moss, 24% agrolite, and 21% vermiculite)	<i>Prosopis laevigata</i>

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Salaš et al., 2002 [68]	-	Crunched bark (25%–100%), filiform peat (25%–50%), coarse-grained sand (20%–100%), chips (30%), and sawdust (30%)	<i>Alnus glutinosa</i> , <i>Fraxinus excelsior</i> , <i>Salix alba</i> , and <i>Salix matsudana</i>
Bretzel et al., 2018 [69]	-	Municipal green waste compost (61%), paper mill sludge (20%), pumice (13%), and zeolites (6%)	<i>Quercus ilex</i> , <i>Lagerstroemia indica</i> and <i>Prunus serrulata</i> ‘Kanzan’
Altland et al., 2018 [70]	<i>Pinus taeda</i> L.	Pine bark from six sources: fresh vs. aged and with/without sand	-
Seo et al., 2019 [71]	<i>Pinus</i> spp.	Rice husk (10%–20%), mushroom sawdust (10%–20%), and pine bark (10%–20%)	<i>Quercus serrata</i>
Smith et al., 2019 [72]	-	Peat with 20%–100% wood fibre	-
Madrid-Aispuro et al., 2020 [73]	-	Peat moss (25%–50%), composted bark (25%–50%), and raw pine sawdust (0%–50%)	<i>Pinus cembroides</i> Zucc.
Owen et al., 2020 [74]	<i>Pinus taeda</i> L.	Peat with 0%–50% pine wood chips or perlite	<i>Chrysanthemum</i> × <i>morifolium</i> ‘Mildred Yellow’
Marcolino Vieira et al., 2020 [75]	<i>Pinus</i> spp.	Biostabilised compost pine bark, coconut husk fibre, peat, and rice straw with slow-release fertilizers	<i>Araucaria angustifolia</i> (Bertol.) Kuntz
Durand et al., 2021 [76]	Conifers	Peat with wood fibre	-
Mouandhoime, Brouillette, 2021 [77]	-	Peat moss with phosphorylated wood fibres and zeolite	-
Błońska et al., 2022 [78]	<i>Fagus sylvatica</i> , <i>Pinus sylvestris</i> L.	Woody debris and peat	<i>Fagus sylvatica</i> L., <i>Pinus sylvestris</i> L., and <i>Abies alba</i> Mill.
Reho et al., 2022 [79]	Softwood	Peat mixtures with different ratios of soil, humus, and softwood sawdust	<i>Quercus robur</i> L.
Yang et al., 2022 [80]	<i>Jacaranda mimosifolia</i> , <i>Osmanthus fragrans</i> , <i>Elaeocarpus sylvestris</i> , <i>Morus alba</i> , <i>Cinnamomum camphora</i>	Steam-exploded pruning waste, mainly stems and barks, replacing peat (5%–40%)	<i>Brassica rapa</i> subsp. <i>chinensis</i> ‘Jinguan’
Robert, Braghiroli, 2022 [81]	<i>Picea</i> spp.	Peat with bulk or pelletized biochar (25%) from spruce wood residues	<i>Picea mariana</i>

Table 1. Cont.

Study	Tree Species of Woody Material Source Used for Substrate	Short Description of the Substrate (Including Type of Woody Material)	Species Tested for Growth/Planting Material Production
Ferrer-Villasmil et al., 2024 [82]	<i>Eucalyptus globulus</i>	Extracted and non-extracted eucalyptus bark fibre	<i>Pinus radiata</i> , <i>Quillaja saponaria</i>
Heiskanen et al., 2024 [83]	<i>Pinus sylvestris</i> L.	Wood fibre, <i>Sphagnum</i> peat, harvested <i>Sphagnum</i> moss, cow manure digestate, and a common reed compost	<i>Pinus sylvestris</i> L., <i>Picea abies</i> L. Karst., <i>Betula pendula</i> Roth, <i>Larix archangelica</i> P. Lawson & C. Lawson ex Trautv., and <i>Alnus glutinosa</i> (L.) Gaertn.
Grafova et al., 2024 [84]	<i>Pinus</i> spp.	Sewage sludge with pine shavings and pine bark	<i>Pinus sylvestris</i> L.
Mizell, 2024 [85]	<i>Abies concolor</i> , <i>Calocedrus decurrens</i> , <i>Pinus lambertiana</i> , <i>Psuedotsuga menziesii</i> , <i>Pinus ponderosa</i> , <i>Pinus taeda</i> L.	Peat:perlite (85:15) with 30% hammermilled wood fibres	Roses and petunias
Gustavsson Ruus et al., 2026 [86]	-	Varying proportions of sawdust (45%–70%), composted fibre sludge (20%–30%), composted bark (20%–30%), and wood fibre (20%–30%), both with and without biochar amendment	<i>Pinus sylvestris</i> L.
Osorio-Espinoza et al., 2025 [87]	<i>Pinus</i> spp.	Mixtures of cocoa husk (20%–60% or 100%), coconut fibre (20%–60% or 100%), and pine sawdust (20% or 100%)	<i>Swietenia mahagoni</i> (L.) Jacq.
Reyes-Reyes et al., 2025 [88]	-	Tropical agro-industrial by-products (70%–80%) with peat moss (20%–30%)	-
Coniglio et al., 2025 [89]	<i>Picea</i> spp., <i>Pinus</i> spp.	50%–100% wood fibres mixed with white peat and nitrogen-enriched lignins	Chinese cabbage

3. Results and Discussion

3.1. Evidence Base and Scope of Application

The evidence base assembled for this review confirms that the use of wood-derived materials as peat substitutes in nursery substrates is an active but still uneven field of research. The initial Elicit search retrieved 500 records (published in 1975–2026), of which 73 met the core screening criteria for direct relevance to the review question. An additional five papers were retained as supporting evidence because they provided mechanistic or operationally important information on substrate physics, hydraulic behaviour, decomposition, or nutrient dynamics that was directly applicable to forest nursery interpretation. Therefore, the final synthesis covered 78 sources (published in 1995–2026; Table 1 and Table S1 in the Supplementary Materials). Taken together, this body of evidence is sufficiently broad to identify recurring technical patterns, but it remains too heterogeneous to support simple univer-

sal recommendations on substrate composition or management. The studies examined diverse wood fibre materials, including processed whole trees, e.g., [43,47,48]; wood chips, e.g., [17,61]; sawdust, e.g., [60,63,65]; shredded pine wood, e.g., [59]; bark, e.g., [68,73,82,86]; and woody debris [78]. Processing methods varied from simple chipping to hammermilling through different screen sizes [17,36,41] and wood fibre extraction [82]. Studies were conducted primarily in greenhouse or nursery settings [41,68,83], with production periods ranging from less than one month [56,61,82] to multiple years [24,32,55,68,79,87].

A first important characteristic of the evidence base is the dominance of container seedling production. In the extracted dataset, container systems clearly prevailed, whereas studies dealing with bare-root seedlings or cuttings were scarce. This is consistent with the practical development of peat-reduced substrates because container production is the nursery segment in which substrate formulation has the greatest direct effect on crop quality, irrigation response and fertilisation management. At the same time, this means that current conclusions are most robust for container stock and should be transferred to bare-root systems only with caution.

A second characteristic is the taxonomic and functional unevenness of the literature. Conifer species, especially those widely used in temperate and boreal nursery practice, were better represented than broadleaved forest species, both as wood-based material for substrate and as seedlings for the testing of growing media. Norway spruce (*Picea abies* (L.) H.Karst.) [15,24,32,44,66,83], Loblolly pine (*Pinus taeda* L.) [53,56,57,59,61,70,74,85], Scots pine (*Pinus sylvestris* L.) [15,44,78,83,84,86] and Douglas fir (*Pseudotsuga menziesii*) [15,25,33,38–40,85] appeared repeatedly in the screened literature, whereas broadleaf evidence was more fragmented and often limited to a smaller number of species or short-duration trials. Some studies addressed European beech (*Fagus sylvatica*) [55,78], English oak (*Quercus robur* L.) [79] and other hardwoods, but the range of tested species remained narrow relative to the diversity of planting material used in operational nurseries. In addition, part of the supporting evidence came from woody ornamental nursery crops or greenhouse substrate studies rather than strictly from forest nursery experiments [28,47,49,50,85]. These studies were useful for interpreting substrate behaviour, especially where they addressed water retention, aeration, shrinkage, rewetting and nutrient immobilisation, but they cannot fully substitute for direct evidence on forest seedling quality and planting performance. Similar fragmentation of the evidence base has also been noted in broader reviews of alternative materials for forest seedling production and peat replacement in horticultural growing media [1,4].

The temporal distribution of the literature (Figure 1) also suggests that this is not an entirely new topic but one that has re-emerged with renewed intensity in response to environmental, climate and supply-chain pressures related to peat use. In the extracted dataset, publication years extended from the mid-1990s to 2026, with most studies published after 2005. Earlier work often focused on physical suitability and short-term plant growth, while more recent studies have increasingly considered peat reduction as part of broader sustainability, circular bioeconomy and resource-efficiency agendas. Nevertheless, despite this renewed interest, the literature still contains relatively few nursery-scale validation studies under operational production conditions. Much of the evidence derives from greenhouse or experimental nursery trials conducted under controlled conditions, which are highly informative for identifying mechanisms but less informative for assessing year-to-year robustness in commercial practice.

In thematic terms, the strongest part of the evidence base concerns the physical properties of substrates and short-term nursery performance. Many studies have reported changes in porosity [22,26,39,43,60,80]; air-filled porosity [29,39,60,82]; water-holding capacity [22,29,76,79,82]; bulk density [26,39,43,60,82]; and seedling growth variables such as

height, diameter and biomass [13,14,20,24,32,33,37,42,46,65,78,79,86]. By contrast, several topics of high practical importance have been addressed less consistently. These include long-term substrate stability during the cultivation cycle [16,36]; calibration of fertilisation regimes [32,34,56,63,64,68,73,74]; compensation for N immobilisation [21,34,53,90]; weed and moss dynamics and their effects on mycorrhization [32]; and compatibility with nursery automation, particularly with respect to the field performance of seedlings after outplanting [32]. This imbalance is important for interpretation: current evidence is relatively strong in showing that wood fibres can alter substrate function in predictable ways but much weaker in defining the operational limits within which those changes remain acceptable for different forest species and nursery systems.

Therefore, for the purposes of this review, the scope of application was defined deliberately and conservatively. Priority was given to studies examining wood fibres, wood wool, chipped or processed woody fractions and related wood-based materials used as meaningful components of peat-reduced substrates for forest nursery production. Studies focusing exclusively on non-forest crops were not treated as core evidence, but some were used as supporting material when they clarified mechanisms directly relevant to nursery substrate management. This distinction is important because many of the fundamental processes involved, such as microbial immobilisation of N, the structural instability of fresh lignocellulosic materials, or changes in water availability, are not species-specific in principle, whereas the practical tolerance thresholds are highly species- and system-dependent. Accordingly, the following subsections interpret the literature with primary emphasis on direct forest nursery evidence while drawing on adjacent studies only where they strengthen mechanistic understanding or help explain contradictory results.

Overall, the evidence base supports three general conclusions at the outset of the discussion. First, wood fibres should be treated as a family of substrate materials rather than a single uniform product because their behaviour depends strongly on raw-material origin and processing. Second, the currently available evidence is sufficient to justify cautious operational use in some forest nursery contexts, particularly in container systems, but not sufficient to define one universally optimal substitution strategy. Third, the principal research need is no longer to demonstrate that wood-derived materials can function in principle but to define the practical boundaries of successful use across species, substrate formulations and management regimes.

3.2. Substrate Materials, Processing and Recommended Formulation Ranges

The reviewed literature clearly shows that wood fibre should not be treated as a single substrate category. Under the common label of wood-based peat substitutes, studies have evaluated fresh sawdust [65], extracted wood fibre [82], wood wool and shredded or hammer-milled whole-tree biomass [27,28,46,47,59], clean chip residual [29,31,37,43,48,51,53], wood shavings [58], woody debris [78], bark-derived fibres [14,17–20,22] and mixed woody fractions. These materials differ markedly in particle-size distribution, bulk density, porosity, stability, decomposition rate and nutrient dynamics, and these differences largely determine whether a given formulation functions well in nursery practice. Accordingly, the practical question is not simply how much peat can be replaced but which wood-derived material is used, how it is processed and how the resulting physical structure is balanced with water and nutrient supply [4,76].

Processing intensity appears to be one of the most important determinants of substrate suitability. Several studies indicate that finely processed or extracted fibres are generally more promising than coarse, poorly graded woody particles because they provide a more balanced combination of air space and container water-holding capacity. Coarse wood particles tend to produce excessively aerated substrates with low container capacity and

rapid drainage, whereas finer fractions or mixtures containing peat and bark move the physical properties closer to the range required for intensive nursery cultivation. This effect has been demonstrated particularly clearly in studies on pine tree substrates, where finer particle sizes improved container capacity and reduced the physical disparity with peat-lite media, while peat addition further stabilised the substrate structure [41,76]. For practitioners, this means that recommendations based only on the volumetric substitution rate are insufficient unless the material is also described in terms of processing method and particle-size composition.

The evidence does not support one universal optimal peat-to-wood fibre ratio across forest tree species. Instead, the reviewed studies suggest a gradient of operational feasibility. The most conservative and best supported option is partial substitution, in which peat remains the dominant component of the substrate. Recent evidence from the Nordic region in Europe (Finland) indicates that peat-reduced media containing at least 50% peat can maintain seedling growth close to that achieved by pure peat for key species such as Scots pine, Norway spruce and silver birch (*Betula pendula* Roth), although the exact outcome depends on fertilisation and substrate formulation [83]. From a nursery implementation perspective, this range is the most defensible starting point because it reduces peat use while retaining much of the buffering and water-holding behaviour of conventional media.

A second, more ambitious formulation range includes mixtures in which wood-derived materials account for roughly one-third to one-half of total substrate volume. This range appears technically feasible in several forest nursery contexts, but only where the woody component is physically suitable and nutrient management is adapted. In practice, mixtures in this range often represent the most realistic compromise between peat reduction and cultivation stability. They allow for substantial reduction in peat consumption but still leave room for peat or other stabilising components to buffer the water regime, pH and nutrient supply. The literature also suggests that this range is broad enough to accommodate species-specific optimisation. For example, European beech woody debris performed very well as a substrate component for forest tree seedlings [78], while modified substrate mixtures containing woody material have also produced good results for Norway spruce in nursery and post-planting assessments [32].

Higher substitution levels, including 50%–70% or even peat-free formulations, are reported in the literature [22] but should be interpreted as species-specific and management-intensive solutions rather than general recommendations. In Apache pine (*Pinus engelmannii*), substrates containing 50%–70% fresh sawdust performed well when combined with optimal fertilisation, and the study reported acceptable seedling morphology and nutritional status, together with notable cost reductions relative to peat-based media [65]. Similarly, a recent study on Scots pine demonstrated that peat-free sawdust-based media can produce seedlings of acceptable quality, showing that complete peat replacement is technically possible under well-controlled conditions [86]. However, such results should not be generalised without caution. The same evidence base also contains examples where high proportions of woody material reduced growth or quality, particularly where the raw material was unstable, the fraction was too coarse, or fertilisation did not compensate for N immobilisation.

Material origin also matters. Some studies indicate that chemically or physically distinct raw materials may perform better than generic wood residues. Extracted southern blue gum (*Eucalyptus globulus*)—for instance, bark fibre—produced very strong results in germination and early growth tests for Monterey pine (*Pinus radiata*) and soap bark tree (*Quillaja saponaria*), with some formulations outperforming peat controls [82]. Likewise, woody debris originating from European beech showed high suitability for tree seedling growth and favourable nutrient supply patterns [78]. These findings suggest that substrate

development should increasingly move from the concept of “wood fibre” as a generic peat substitute toward more precisely defined material classes with known physical and biochemical properties.

Taken together, the literature supports three practical formulation principles. First, wood fibre should generally be introduced as a partial substitute, not as a direct universal replacement for peat. Second, finer and better standardised materials are preferable to coarse, heterogeneous woody residues. Third, the currently best supported operational strategy for forest nurseries is to begin with peat-reduced formulations in which peat still accounts for approximately one-half or more of the substrate volume, then move toward higher substitution levels only after local validation for the target tree species, container type and fertigation regime. Higher wood-fibre shares can be successful, but the probability of management failure increases unless physical properties, nutrient supply and irrigation are simultaneously optimised.

For the purposes of a practitioner-oriented review, it is therefore reasonable to distinguish between a recommended operational range and an experimental optimisation range. The recommended operational range is a partial substitution approach with approximately 20%–50% wood-derived material, preferably in finely processed form and supported by species-specific fertilisation adjustment. The experimental optimisation range includes substrates with more than 50% wood-derived material and peat-free formulations; these are scientifically promising and sometimes economically attractive, but they require considerably stronger local validation before they can be recommended for routine nursery production across species and sites.

A potential limitation of using wood fibres as partial peat substitutes in forest nursery growing media is the increased content of phenols, phenolic compounds, and other bioactive organic constituents (e.g., flavonoids and alkaloids) present in both fresh and processed woody materials [21,32,80]. These compounds may exert phytotoxic effects and negatively affect plant development, as well as microbial development and activity within the substrate. Consequently, this aspect represents one of the main disadvantages of woody materials as substrate components and should receive greater attention in future studies evaluating substrate quality, functionality, and long-term performance.

3.3. Effects on Seedling Growth, Root Development and Species-Specific Suitability

The literature indicates that the biological response to wood fibre-based substrates is clearly species-specific and cannot be reduced to a simple “peat replacement percentage”. A broader review of forest seedling growing media concluded that most case studies were species- and site-specific, which limits direct generalisation across nursery systems, even though alternative materials enhanced nursery growth relative to peat-based media in more than 60% of the analysed cases. This is an important starting point for interpretation: the evidence supports technical feasibility but not universal equivalence to peat for all forest species and cultivation conditions [4].

Among the best supported species groups are temperate and boreal conifers grown in containers. In a recent study conducted in the Nordic region in Europe (Finland) covering Scots pine, Norway spruce, silver birch, Russian larch (*Larix archangelica* P. Lawson & C. Lawson ex Trautv.), and common alder (*Alnus glutinosa* (L.) Gaertn), peat-reduced media containing at least 50% (v/v) peat provided seedling growth similar to pure *Sphagnum* peat across the tested species and container types [83]. This suggests that, under northern nursery conditions, moderate peat reduction is already biologically defensible for the main operational species. At the same time, the same study did not imply that all peat-free formulations were equally reliable, which reinforces the conclusion that species suitability depends on both the substrate recipe and the cultivation protocol [83].

Scots pine appears to be relatively promising, but the evidence also shows that successful use of woody materials depends on formulation and management. The recent sawdust-based peat-free study on Scots pine demonstrates that acceptable seedling quality can be achieved without peat, indicating that complete substitution is biologically possible for at least some conifer systems [86]. However, older and more practice-oriented evidence from Norway spruce points to a more nuanced interpretation: in nursery conditions, Norway spruce seedlings grown on substrates modified with wood fibre and pine bark were initially shorter than those grown on unmodified peat, but they developed significantly higher root-to-shoot ratios and greater ectomycorrhizal diversity; after outplanting, the modified substrates supported higher growth rates, and the treatment containing 50% woody material with organic fertilisation performed best over the first three years [32]. From a practitioner perspective, this is highly relevant because it shows that a slight reduction in nursery shoot growth does not necessarily imply inferior planting stock if root-system quality and post-planting performance improve [32,86].

Evidence from southern and montane pines further confirms that relatively high shares of sawdust can be biologically acceptable, but only under adequate nutritional support. For Apache pine, mixtures containing 50%–70% fresh pine sawdust combined with 6 g L^{−1} controlled-release fertiliser produced superior root-collar diameter and biomass while maintaining acceptable N, phosphorus (P) and potassium (K) concentrations and reducing substrate costs [65]. In contrast, pinyon pine (*Pinus cembroides*) responded more conservatively: although all fertilised treatments exceeded the minimum morphological standards, the peat-and-composted-bark control produced the best overall growth response, while the mixture containing 25% peat moss, 50% composted bark and 25% raw pine sawdust with the high fertiliser dose was considered an acceptable lower-cost option [73]. Together, these studies suggest that some pine species tolerate or even benefit from substantial woody fractions, but the probability of success declines when fertilisation is not specifically adjusted to compensate for nutrient immobilisation and altered substrate dynamics [65,73].

Broadleaved species are less uniformly represented, but the available evidence is encouraging for selected cases. In the study by Błońska et al. [78], European beech woody debris fully replaced peat and produced the best growth parameters, the highest above- and belowground biomass, the best nutritional status and the best developed root systems among the tested substrates, indicating that some broadleaves may perform exceptionally well on carefully selected woody materials. More recent work on peat-free organic media (blends of various organic and inorganic materials excluding peat) for European beech and English oak also suggests beneficial effects on seedling growth and nutrient allocation, although the authors explicitly describe these results as preliminary and in need of broader validation [91,92]. At the same time, species-specific optimisation remains essential: for example, extracted southern blue gum bark fibre performed very well in early-stage tests, but the best mixture differed between Monterey pine and soap bark tree—75% extracted fibre with 25% peat for Monterey pine versus 50% extracted fibre with 50% coconut fibre for soap bark tree [82]. This reinforces the practical conclusion that “species suitability” should be interpreted as a property of the species × substrate × management combination, not of the species alone [78,82,91,92].

Overall, the evidence supports a three-level interpretation of species-specific suitability. First, several conifers used in operational forestry, especially Scots pine and Norway spruce, can be grown successfully in peat-reduced substrates when wood-based components are combined with appropriate fertilisation and water management. Second, some species and formulations can tolerate very high woody fractions or even peat-free media, but these cases should currently be treated as validated for specific conditions rather than as broadly transferable recommendations. Third, root development often responds more

positively than shoot growth, which is important because root-to-shoot balance, root morphology and mycorrhizal status are closely linked to field establishment. Therefore, for a practitioner-oriented review, the most defensible conclusion is that biological suitability should be evaluated primarily through integrated seedling quality, not through height growth alone [4,32,78,83].

3.4. Nursery Management Implications: Water, Nutrients, pH and Operational Handling

A consistent finding across the reviewed literature is that successful use of wood-fibre-based substrates depends less on the nominal substitution rate alone than on the nursery's capacity to adapt cultivation management. In practice, wood-derived materials alter the physical and biochemical behaviour of the growing medium in ways that directly affect irrigation, fertilisation, pH regulation and crop handling. This is also consistent with recent forest nursery evidence showing that alternative media can produce marketable seedlings, although commonly of smaller size and with a need for specific adjustments in growing management compared with conventional peat substrates [83].

Water management is one of the most immediate operational challenges. Wood fibres generally increase air-filled porosity and improve drainage, but at the same time, they usually reduce water retention and the fraction of readily available water compared with peat-dominated substrates [5,76]. This combination may be advantageous in poorly aerated media, but in container seedling production, it also means that the substrate dries faster and becomes more sensitive to short irrigation intervals or uneven watering. Durand et al. [76] further showed that adding wood fibre to peat-based substrates can reduce the risk of hydrophobicity after drying, which is a useful property under operational nursery conditions, although this benefit does not eliminate the lower water-holding capacity of the fibre-rich mix. For practitioners, the implication is clear: irrigation scheduling should be recalibrated whenever a substantial share of wood fibre is introduced, and standard peat-based watering routines should not be transferred to peat-reduced substrates unchanged [5,76].

Nutrient management, particularly N supply, is the second major control point. Wood-derived materials usually have a high C/N ratio and active microbial populations, which can lead to immobilisation of plant-available N during the cultivation cycle, causing plants to become N-deficient [34]. This mechanism is widely recognised in reviews of peat alternatives and has been one of the main reasons why processed wood fibres are often supplemented with N during manufacture or require higher N inputs during crop production [1]. Experimental evidence also supports this interpretation: Harris et al. [90] found that pine wood fibre in peat-based substrate can immobilise fertiliser N and may increase the amount of fertiliser N needed during container production. Similarly, Jackson et al. [34] concluded that pine tree substrate ($\approx 90\%$ wood and 10% bark) immobilized more N than aged pine bark or peat-lite (80% peat and 20% perlite, v/v) beginning shortly after potting and continuing throughout production, thereby increasing the risk of N deficiency; this effect can be mitigated by adding 25% peat or using coarser substrate particles [30]. Forest nursery studies point in the same direction. For Norway spruce, Vaario et al. [32] showed that substrate and fertilisation interacted strongly, affecting not only nursery growth but also ectomycorrhizal development and subsequent field performance. Further work on mycorrhization in nursery containers should focus on whether wood fibre-based substrates consistently support a functionally diverse and stable ectomycorrhizal community across different fertilisation regimes and nursery conditions. Likewise, successful use of high sawdust proportions in Scots pine seedling production has generally been reported only where fertilisation was carefully adjusted. In operational terms, wood fibre substrates should therefore be accompanied by species-specific fertilisation trials, with particular attention

to early N availability, controlled-release fertilisers and visual or analytical monitoring of nutrient deficiency symptoms [1,32,90].

pH management is also different from standard peat practice. Fresh wood-based substrates, especially pine-derived materials, may have inherently higher pH than conventional peat-lite media, which changes the response to liming and the target pH range required for optimal nutrient availability. Jackson et al. [93,94] demonstrated that pine tree substrate has a higher intrinsic pH than peat-based substrate and that additions of peat moss and dolomitic limestone substantially affect plant growth through changes in the substrate reaction. This has two practical implications for forest nurseries. First, liming recommendations developed for pure peat substrates cannot be transferred automatically to wood fibre mixtures. Second, pH should be measured directly in the actual substrate formulation rather than assumed from recipe composition. When wood fibres are combined with peat, bark, compost or fertiliser salts, pH development may also change during the cultivation cycle, so periodic monitoring is preferable to one-time correction at mixing [93,94].

Operational handling issues are less frequently quantified than water and nutrient relations, but they are highly relevant for commercial application. Wood-fibre-rich substrates may settle, shrink or change their physical structure during cultivation as microbial activity progresses and finer particles redistribute within the container. Long-term nursery studies with pine-tree-derived substrates have shown that physical and chemical properties can change substantially during production, which implies that tray filling, compaction, transport stability and irrigation uniformity may also change over time [94]. For automated nursery systems, this means that consistency of fibre processing, moisture content at mixing and filling density are not minor technical details but key quality-control variables. More broadly, Barrett et al. [1] noted that processed wood fibres are valued partly because industrial processing can increase substrate uniformity and stability relative to raw woody residues. For practitioners, the main operational lesson is that substrate quality assurance must include not only chemical composition but also particle-size grading, bulk density, moisture status and physical stability during the cultivation cycle [1,94].

In summary, the reviewed evidence suggests that wood fibres can be integrated successfully into forest nursery substrates, but only as part of an adjusted management package. The most important practical changes are more responsive irrigation, more carefully targeted N management, direct pH monitoring instead of peat-based assumptions and stricter quality control of substrate preparation and handling. Under these conditions, wood-fibre-based media can function well in nursery production; without them, the risk of reduced seedling quality or inconsistent crop performance increases markedly [1,32,83].

3.5. Economic Aspects, Implementation Barriers and Remaining Research Questions

The economic rationale for using wood fibres in forest nursery substrates is strong in principle but still insufficiently quantified for routine decision-making. Wood-derived materials may reduce dependence on peat; improve the use of local by-products; and, in some cases, lower substrate cost substantially when suitable feedstock is available near the nursery. A clear example is provided by Apache pine seedling production, where fresh sawdust-based substrates were reported to be up to 67% cheaper than peat- and bark-containing mixtures, largely because sawdust was locally available and peat had to be imported [65]. However, broader reviews also indicate that cost comparisons cannot be reduced to raw-material price alone because processing, transport distance, consistency of supply, additional fertiliser demand, and crop-management adjustments all affect the final economics of peat substitution [1,2].

A second key point is that economic feasibility and implementation feasibility are closely linked. Even when wood fibres are physically available, nurseries still need a material of sufficiently stable quality, volume and timing to support operational production. Hirschler et al. [2] emphasised that the potential availability of alternative constituents is one of the major concerns in peat replacement, while Hirschler and Thrän [95] showed, from producer interviews, that sufficient quantity and consistent quality of substitute materials are critical constraints in practice. For forest nurseries, this is particularly important because container seedling production depends on narrow quality tolerances: variation in the particle-size distribution, moisture content, decomposition stage, or contamination risk may translate directly into uneven tray filling, unstable irrigation response and non-uniform seedling growth. Accordingly, implementation barriers are not limited to the biological suitability of wood fibres but also include industrial standardisation, logistics, storage, seasonal supply stability and compatibility with existing nursery mixing and filling systems [2,95].

At the nursery level, the main barrier to adoption is that wood fibre is not a drop-in replacement for peat. The current evidence indicates that wood-fibre-rich media often require adapted fertigation, more responsive irrigation scheduling, closer pH monitoring and stronger quality control of substrate preparation and handling. In the Nordic forest nursery study of Heiskanen et al. [83], all tested alternative media had potential to reduce or replace peat but generally required adjustments of physical and chemical properties, together with changes in fertigation and growth management. This finding is consistent with earlier forest nursery evidence showing that substrate effects interact strongly with fertilisation and influence both nursery-stage development and later seedling performance [32]. From an implementation perspective, this means that adoption costs include not only substrate purchase but also calibration trials, staff learning, monitoring effort and the risk of temporary production instability during the transition from standard peat-based regimes [1,32,83].

The remaining research questions are therefore highly practical rather than merely descriptive. First, more species-specific evidence is needed to define acceptable substitution ranges for major forest tree species under operational nursery conditions. Second, the literature still lacks robust thresholds linking wood-fibre origin, processing method and particle-size distribution to predictable physical and biological substrate performance. Third, nutrient dynamics—especially N immobilisation and its interaction with controlled-release fertilisation—remain insufficiently quantified for routine nursery recommendations. Fourth, field validation remains a major gap: many studies have assessed nursery morphology, but comparatively few have followed seedlings after outplanting, even though post-planting performance is decisive for forestry practice. Fifth, there is still limited integration of biological performance with techno-economic analysis, meaning that nurseries lack decision tools combining substrate cost, management requirements, seedling quality and supply-chain reliability. These gaps are broadly consistent with the conclusions of Mariotti et al. [4], who noted that most studies are species- and site-specific, limiting generalisation, and those of Heiskanen et al. [83], who showed that promising peat-reduced media still require further optimisation for routine production. It should be noted that challenges may arise when transferring findings obtained under controlled experimental conditions to commercial nursery operations. Therefore, validation at the operational scale, including specially adapted nursery cultivation practices and the evaluation of seedling growth outside the greenhouse (in the field), with particular attention to irrigation regimes and overall field performance following outplanting, is essential before broader implementation in operational forest nursery production [24,96].

Overall, the present evidence supports a cautious but positive interpretation. Wood fibres are already credible components of peat-reduced substrates for forest nurseries, and under favourable local conditions, they may also improve cost-efficiency and resource security. Nevertheless, the main obstacle to wider adoption is not whether wood fibres can work in principle but whether they can be delivered and managed with sufficient consistency to support large-scale, standardised seedling production. For this reason, the most urgent next step is not another broad demonstration that wood can be substituted for peat but coordinated operational research that links substrate specification, fertigation strategy, nursery performance, outplanting success and full production economics under real nursery conditions [4,95].

4. Conclusions

The reviewed evidence shows that wood fibres are credible and technically promising components of peat-reduced substrates for forest nursery production, but they should not be regarded as a universal drop-in replacement for peat. Their suitability depends on the interaction between raw material origin, processing intensity, substrate formulation, tree species and nursery management. In general, the current evidence most strongly supports partial substitution strategies, especially in container seedling production, whereas peat-free formulations should still be considered species-specific and management-intensive solutions rather than broadly transferable recommendations.

From a biological and operational perspective, the main practical message is that successful implementation depends less on the nominal proportion of wood fibre than on the nursery's ability to adapt irrigation, fertilisation, pH control and substrate quality assurance. Wood-derived materials can support acceptable or even very good seedling performance, including favourable root development and, in some cases, improved post-planting growth, but these benefits are conditional on species-specific optimisation and careful control of nutrient dynamics, especially N availability.

The evidence also indicates that economic attractiveness alone is not sufficient to justify immediate large-scale substitution of peat. Although locally available woody materials can markedly reduce substrate cost under favourable conditions, the real feasibility of implementation depends on reliable raw-material quality, sufficient supply, compatibility with existing nursery infrastructure and the additional management effort required to maintain crop uniformity. In this respect, the transition from peat-based to wood-fibre-based substrates should be viewed as a change in the whole production system rather than simply as a change in one substrate ingredient.

Therefore, the most important remaining research need is not to demonstrate, once again, that wood fibres can function as peat substitutes in principle but to define the operational boundaries of their successful use. Future research should prioritise species-specific formulation thresholds; links between fibre properties and substrate performance; fertilisation strategies that minimise N immobilisation; and, most importantly, studies that connect nursery performance with field establishment and full production economics under commercial conditions. For practitioners, the present state of knowledge supports a cautious but positive conclusion: wood fibres already offer a realistic pathway for reducing peat use in forest nurseries, provided that implementation is gradual, evidence-based and accompanied by local validation trials.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f17070761/s1>, Table S1: Scientific publications (studies published between 1995 and 2025) included in the review [12–89] (supplemented Table 1).

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