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Carbon Footprint of Masson Pine (*Pinus massoniana*) Seedlings in Southern China: A Life Cycle Inventory and Sensitivities

Feidong Lu [1,2], Meifang Zhao [1,2,*], Qianwen Liu [1,2], Mengde Sun [1,2], Peng Kang [1,2], Chunyang Zeng [3], Yibo Tan [4,5,6], Xianru Huang [7], Kunmin Xiao [7], Xinliang Zhu [8] and Shaoyong Liu [8]

[1] College of Life and Environmental Science, Central South University of Forestry and Technology, Changsha 410004, China; lufeidong73521@163.com (F.L.); qw372150503@163.com (Q.L.); sunmengdee@163.com (M.S.); jayyskang@126.com (P.K.)
[2] National Engineering Laboratory of Applied Technology for Forestry & Ecology in Southern China, Central South University of Forestry and Technology, Changsha 410004, China
[3] Guangxi Forestry Survey and Design Institute, Nanning 530011, China; zchy12000@163.com
[4] Guangxi Forestry Research Institute, Nanning 530002, China; tybrun@126.com
[5] Guangxi Lijiangyuan Forest Ecosystem Research Station, Guilin 541316, China
[6] Guilin Xing'an Lijiangyuan Forest Ecosystem Observation and Research Station of Guangxi, Guilin 541316, China
[7] Guangxi Weidu State Forest Farm, Laibin 546100, China; ms_0909ok@163.com (X.H.); wdxmwei@163.com (K.X.)
[8] Guangxi State-Owned Paiyangshan Forest Farm, Ningming 532599, China; 18878061122@163.com (X.Z.); 13737185519@163.com (S.L.)
* Correspondence: meifangzhao@csuft.edu.cn

Abstract: Masson pine is a crucial species for afforestation and timber production in China; it plays an important role in mitigating global climate warming and increasing carbon sinks. Previous studies have primarily focused on the carbon sequestration potential and carbon storage of mature Masson pine plantations, while studies on the carbon footprint have received little attention. China produces hundreds of millions of seedlings annually, and estimating the carbon footprint of seedling production is crucial for assessing the carbon sink of forestry. By surveying existing Masson pine nursery operations for primary data in Guangxi, southern China, a new process-based life cycle inventory (LCI) dataset per 4 × 8 cm seedling was created, covering all stages from seed collection to the transportation of seedlings to retailers. Incorporating the new LCI data into the life cycle assessment (LCA) method, the total global warming (GW) impact of Masson pine seedlings was estimated to be 0.0232 kg CO_2eq, equivalent to 0.873 kg CO_2eq per gallon seeding. In this case, the total environmental impact of the Masson pine seedling was dominated by energy consumption (25.76%), chemical fertilizer production and N_2O emissions generated from its application (34.84%), and woven bag use in seedling dispatch (10.77%). Our results indicated that optimizing energy structures and implementing efficient water and nutrient management strategies could significantly reduce carbon emissions during seedling cultivation. This study highlights the potential for optimizing Masson pine production as a model for low-carbon forestry practices globally.

Keywords: life cycle inventory; carbon footprint; Masson pine seedling; environmental impacts

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1. Introduction

To respond to the global problem of climate warming, many countries seek measures to reduce greenhouse gas (GHG) emissions. Accurately estimating the carbon footprint (CF) of forestry can benefit businesses and individuals because it tracks the entire production process of forestry products and highlights key emission points. Accurately estimating the CF of seedling production can help governments and companies make decisions on emissions reductions and establish low-carbon certification processes [1]. For an East African forestry enterprise, CF revealed that its silvicultural activities, while removing waste and generating large amounts of carbon dioxide, also significantly reduced carbon emissions by optimizing energy use (replacing coal with charcoal); in addition, it helped the company to identify the risk of carbon loss from forest fires and the growth of emissions in its supply chain [2].

To date, CF studies have mainly focused on producing landscape tree seedlings and potted plants. Meng et al. [3] estimated that Chinese nurseries produce about 5.34 t/ha of CO_2 per year in the production of potted seedlings. Moreover, Lazzerini et al. [4] found that the CF for container seedlings ranges from 26.100 to 34.700 t/ha in ornamental plant nurseries. Kendall and McPherson [5] revealed that the CF associated with container-grown seedlings for landscape trees in California is roughly 0.830 kg CO_2eq per equivalent unit (EQU). Their study found that electricity and fuel consumption account for 45% of the total CO_2 emission in nurseries, while using containers, potting mix, and transportation takes about 40% of total emissions. Additionally, fertilizer application emerged as one of the significant sources of emissions, comprising more than 15% of the total CO_2 emissions. A life cycle assessment (LCA) of field-grown maples revealed that the production of a single heather plant emits 8.213 kg of CO_2eq, including carbon sequestration during one year of liner production and four years of field production (0.366 and 12.1 kg CO_2eq, respectively) [6]. This total includes 2.850 kg CO_2eq from the materials used in the production process and 10.342 kg CO_2eq from fuel and electricity consumption. This study also considered the CF associated with off-site transportation. Lazzerini et al. [4] compared the CF and environmental impacts of an organic nursery with a traditional one under similar planting conditions in northern Italy. This study found that organic nurseries using organic fertilizers reduced the CF by over 90% compared to conventional methods. However, using plastic pots and peat significantly contributed to the CF, with containers accounting for 45%–63% and container mixtures accounting for 22.60%–32.10% of the total CF. However, research on GHG emissions from nursery activities is limited, particularly in China, where there is a lack of studies on carbon emissions from forest nurseries. The second problem is that the evaluation is based on secondary-level data (indirect measurement) but lacks initial-level data (direct measurement) [7]. Most of the previous studies have focused on carbon footprint assessment of forest products, for example, wood-based forest products [8], pulp [9], and bamboo products [10]. However, plantation tree seedings with carbon-stock function have received less attention.

Masson pine (*Pinus massoniana* Lamb, MP), a native and widely cultivated tree species in China, holds significant social, economic, and ecological value. This species accounts for 4.47% of the area and 3.67% of the volume of the main dominant tree species in China's tree forests. The total volume of MP in China is approximately 62.6 million cubic meters [11]. These forests play a vital role in combating global climate change by absorbing atmospheric carbon dioxide through photosynthesis and converting it into biomass. In subtropical China, the carbon stock densities of planted and natural MP forests range from 78 to 210 t/ha and 97 to 177 t/ha, respectively [12]. A 26-year-old MP forest in northwestern Guangxi has been estimated to sequester approximately 19.830 t of CO_2 per hectare annually. Given the large number of MP plantation forests existing in China, the cumulative annual carbon sequestration is significant [13].

China has vigorously promoted the construction of reserve forests through the National Reserve Forest Construction Plan (2018–2035), especially in Guangxi Province, focusing on the development of fast-growing timber forests dominated by the MP, which not only mitigates climate change through the function of carbon sinks but provides carbon credits for the carbon trading market [14]. In the US Southeast's growing forest carbon market, MP projects are generating valuable carbon credits by sequestering CO_2. This carbon sink activity not only enhances ecological health but offers landowners new income streams through carbon trading. With policy support fostering this dual benefit, the MP's role in balancing ecological and economic interests is increasingly recognized, marking a significant step towards sustainable forestry practices [15].

High-quality seeds and saplings are essential for healthy forestry. However, the pine nematode has led to a decline in the production of MP. For this reason, China has listed MP seedlings as an important resource for sustainable forestry development during the 14th Five-Year Plan. This initiative aims to ensure ecological and timber security while increasing the income of forest farmers [16]. As a result, in the coming years, it is foreseeable that the expected scale of production of the new generation of MP seedlings is expected to reach 500 million seedlings per year [17]. Given the increasing demand for young MP seedlings, there is a strong need to develop an inventory of GHG emissions from seedling production. The inventory would help to standardize production processes and guide the industry to adopt sustainable and low-carbon practices [18].

However, most existing studies have focused on the life cycle assessment of ornamental trees and the calculation of CFs in agricultural planting, with no specific life cycle assessment conducted on MP. In this study, we investigated GHG emissions from the production process of MP seedlings and analyzed the sources of emissions. In addition, we aimed to establish the first complete CF inventory of MP seedlings, filling the gap in the CF of MP; this study also sought to propose improvements to green forestry, making it a global model for low-carbon forestry practices.

2. Materials and Methods

2.1. Modeling the Plant Nursery Production System

This study followed the life cycle assessment (LCA) guidelines set by the International Organization for Standardization [19,20] and the British Standards Institute [21], and selected SimaPro 9.1 as a life cycle assessment tool [22]. ISO 14040 is used for general assessment guidelines, ISO 14044 is used for technical guidance on life cycle assessment, and PAS 2050, published by the British Standards Institution, is used for cradle-to-retailer GHG assessment. The inventory was structured into four main phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation [23–25]. These stages were chosen because they provide a comprehensive framework and are widely recognized and adopted internationally. This structured approach allowed us to conduct a systematic analysis of the environmental impacts associated with MP cultivation; most existing studies have not accounted for the forestry CF based on primary data, so we focused more on refined calculations by targeting the life cycle assessment of MP. By adhering to these stages and adopting a methodology, we have ensured the methodological robustness of our study and helped to fill the gaps in our research on the life cycle impacts of MP. Referring to the GHG protocol [26] and ISO 14044 [20], the data used in this study were classified into three levels (Tables S1 and S2): (1) Primary data included inputs and consumption of production materials, energy use, nursery time, and material transportation. These were obtained through interviews with workers and managers at the Cenle Nursery (Cenle Nursery supplies the market with tens of millions of high-quality MP seedlings each year, which is representative of the southern region of China), as well as from archival records of MP seedling production. Sales lists and financial statements provided key input data. (2) Information on upstream transportation was gathered through discussions with sales representatives. Secondary data, such as emission factors, were sourced from published literature and local standards. (3) Tertiary data, used as complementary information, were obtained from the statistics department. In a rigorous scientific approach, following the collection of information, a comprehensive evaluation was conducted. This included meticulous verification of all sources from which publicly available data were derived. The processes and methodologies for data collection and processing were meticulously documented to ensure reproducibility. A thorough assessment of data quality was undertaken to identify and exclude any unreliable discrete values that could compromise the integrity of the analysis. Furthermore, a commitment was made to utilize the most current data available, thereby minimizing potential uncertainties and ensuring the transparency of our research outcomes.

2.2. Goal and Scope Definition and Function Units

The primary objective of this GHG life cycle inventory (LCI) is to create the first comprehensive inventory for nursery operations producing containerized MP seedlings for fast-growing productive forests. This inventory is intended to serve as a foundational resource for life cycle GHG assessments of urban forestry and merchantable forests. Our investigation encompasses a cradle-to-retailer GHG inventory, including material and chemical inputs, fuel, fertilizer, electricity, and other resources, and the transportation of inputs and products for the nursery and its suppliers (Figure 1; Text S1).

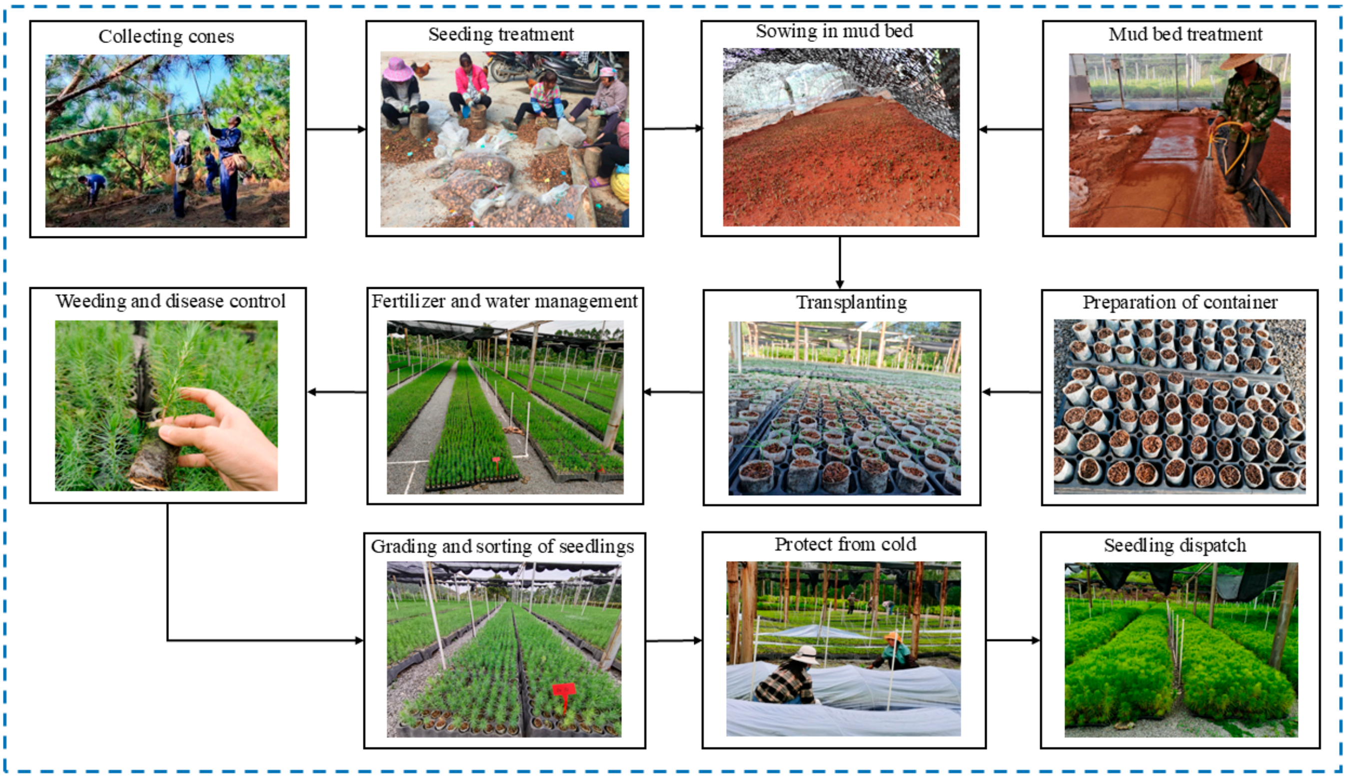

Figure 1. Process for Masson pine (*Pinus massoniana*) seedling production.

The functional unit of this study is an MP seedling at the nursery, specified at 4 × 8 cm (#4 × 8 cm, which represents the size of the sale and is the size of the seedling container required by current nursery standards [27]), with the actual size being approximately 0.0265 gallons dry (Table S3). In addition to the primary unit, we report the results using Equivalent Units (EQUs). Nurseries often use EQUs to track costs associated with producing various products, such as trees of different sizes. EQUs correspond to the following containerized tree products: #1 (nominally 1-gallon) tree = 1 EQU, #5 (nominally 5-gallon) tree = 5.5 EQUs, #7 (nominally 7-gallon) tree = 9.1 EQUs, and #15 (nominally 15-gallon) tree = 18.400 EQUs. Reporting results in EQUs allows this GHG inventory to be applicable in evaluating the potential GHG impacts of other tree product sizes beyond those considered in this study.

2.3. System Boundaries

Based on the investigation, this study references existing standards and relevant literature for the processes involved in seedling production activities [27–29]. The system boundary for MP container-seedling production primarily encompassed the flow of resources, including material and energy inputs, as well as their transport to the nursery (for example, energy consumption, fuel, chemicals, soil tillage, and other resources, Figure 2). Emissions from fertilized soil, specifically N_2O emissions due to denitrification, were also considered. However, consistent with PAS 2050 [21], emissions associated with capital goods (greenhouse and nursery field construction) were excluded from the analysis because of their small impact on emissions from nursery production.

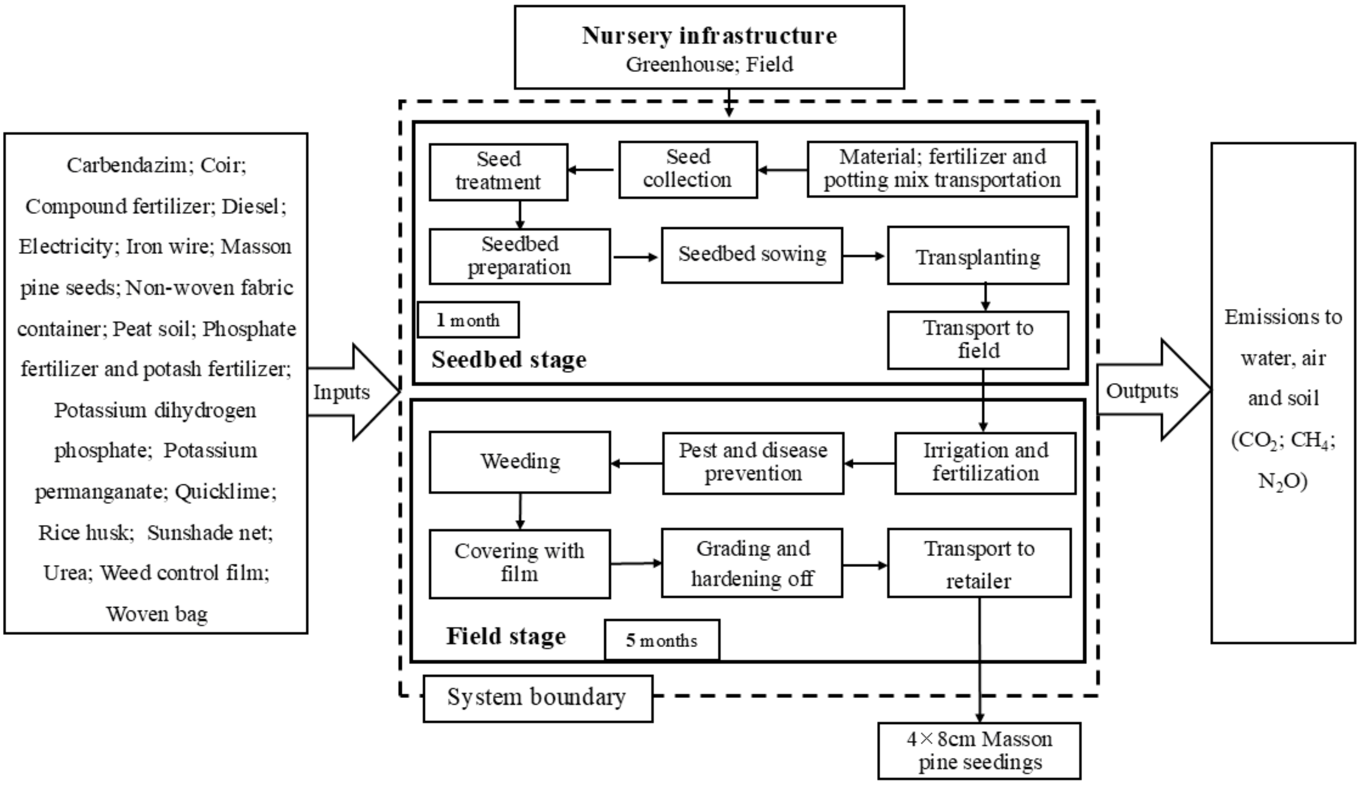

Figure 2. Cradle-to-retailer life cycle stages for MP seeding production.

2.4. Life Cycle Inventory Analysis

GHG emissions within this system, including those arising from materials and transportation, were quantified as global warming potential (GWP) in kg CO_2 equivalents (kg CO_2eq). Emissions related to transportation were calculated based on fuel consumption, while material emissions were derived using specific emission factors (Table S4).

Data collection involved comprehensive interviews and surveys with nurseries' and suppliers' representatives. Seven relevant respondents were interviewed for this study, four face-to-face: two managerial managers of nurseries and two workers who have long been engaged in nursery work; in addition, three suppliers of upstream materials were interviewed by telephone. Nurseries contributed data on on-site fuel and electricity usage by fuel type, alongside details on production activities, irrigation, and building utilities. Additionally, producers supplied annual data on container usage, agrochemical application, substrate usage, compositional materials, and total yearly production measured in Equivalent Units (EQUs) (Table S5). Supplier contacts furnished data on material production and transportation for the nurseries (Table S6).

The report from Cenle Nursery indicates that monthly electricity consumption for irrigation averages 1143 kWh, with the irrigation system itself consuming 34.700 kWh. The corresponding carbon dioxide emission factor for electricity is 0.526 kg CO_2/kWh, as determined based on electricity supplier: China Southern Power Grid [30,31].

Transportation activities encompass diesel consumption by various types, including 8 t nursery medium-heavy trucks (Foton Hill Climber), 1-ton light pickups (Foton pickup), and 20 t heavy-duty transport trucks (faw Jiefang). Investigations revealed that these vehicles consume diesel at 20 L per 100 km, 15 L per 100 km, and 33 L per 100 km, respectively. Diesel's GHG emissions are valued at 2.630 kg CO_2/L [30,32]. A thorough examination of the goods transported revealed a total diesel consumption of 195.420 L.

The chemical and fertilizers needed for the growth of the seedlings were supplied by Huawote Fertilizer Group (interview from the nursery manager, 6 March 2023), including compound fertilizers, phosphate fertilizers, potash fertilizers, and urea. Huawote's factory is located in Economic and Technological Development Zone, Nanning City, China, 220 km from the nursery. The fertilizers were first transported from Nanning to Ningming County in heavy trucks and then transported to the nursery by the supplier in medium-sized trucks. Information on the type of fertilizer and the distance of transport, as well as on the trucks was provided by the supplier (personal communication with the sales manager of Huawote, 9 March 2023). The GHG emissions for fertilizers and chemicals are as follows: Wu et al. [33] found that the average carbon emission equivalent for quicklime is 1.136 kg CO_2/kg. The emission factor for carbendazim is 15.700 kg CO_2/kg, as reported in the China Products CF Factors Database [34], with emission factors for wire, diesel, and non-woven bags also sourced from this database. Chen et al. [35] provide the emission factor of phosphorus and potassium fertilizer, 2.330 kg CO_2/kg and 0.660 kg CO_2/kg, while compound fertilizer has an emission factor of 2.470 kg CO_2/kg. The emission factor for diammonium phosphate (2.470 kg CO_2/kg) was used as a proxy for monopotassium phosphate. The emission factors for the manufacturing of urea (3.200 kg CO_2/kg), phosphorus (1.000 kg CO_2/kg), and potassium (0.700 kg CO_2/kg) were referenced from the study by Feng et al. [36].

The potting mix consisted of coir, peat soil, and rice husk. Both coir and rice husk are considered low-cost by-products, with their cost primarily attributed to transportation. Specifically, the rice husk was sourced local by famer and via truck, involving a 25 km round trip (interview from the nursery manager, 1 March 2023). In contrast, the coir and peat soil (produced by Jinkun Co., Wujin District, Changzhou City, China and Nanning Yuntian Industry and Trade Co., Heng County, Nanning, China) was transported in large trucks from Nanning to our nursery, spanning 220 km (telephone interview with the transport driver, Jinkun Co. and Yuntian Co., 1 March 2023). The emission factor for peat soil was provided by Stichnothe [37], while the transportation emissions were analyzed using the China High-Resolution Emissions Database (CHRED) [38].

Non-woven fabric containers and woven bags are widely used in seeding cultivation, alongside shade nets and weed control films These materials are purchased from four suppliers in Nanning, namely Bohang Nonwoven Fabrics Co., Xixiangtang District, Nanning, China; Huahang Wire Mesh Manufacturing Co., Xixiangtang District, Nanning, China; Shunjing Shade Netting Co., Xingning District, Nanning City, China and Shenghexing Plastics Co., Xixiangtang District, Nanning, China. The production and processing of these consumables takes place in Nanning, and the initial transportation segment from the production site to the collection site is not specified. Subsequently, the materials were transported by truck from Nanning to Ningming, a distance of approximately 220 km; and finally to the Cenle nursery, a stage where they were transported by local suppliers, also by medium truck, for approximately 25 km. Detailed information on the distance the material was transported and the specifications of the truck's internal combustion engine were provided by the supplier (personal communication with manager and supplier, 02 March 2023). The emissions from transportation were calculated using methods similar to those described previously, and emission factors for containers and plastic production were derived by integrating data from the CPCD on polypropylene production in China with data from Ecoinvent 3.0 on injection molding in Europe [32]. Specifically, emission factors are 3.820 kg CO_2/kg for non-woven fabric containers, 3.270 kg CO_2/kg for shade nets and weed control films, and 3.500 kg CO_2/kg for woven bags. Furthermore, winter protection necessitates using substantial quantities of No. 8 iron wire and plastic film, which are also transported 25 km by truck from local suppliers. The production emission factors are sourced from CPCD [34], with iron wire at 2.050 kg CO_2/kg and plastic film at 2.490 kg CO_2/kg.

From seed treatment to fertilization, the growth and production of MP seedlings are heavily reliant on water. According to interviews, irrigation water is sourced from a nearby reservoir. Water usage at each stage was meticulously estimated, and the associated emissions were calculated using emission factors from CPCD [34]. Information on electricity consumption for irrigation was gathered through interviews with management staff.

Cenle Nursery provided data on labor consumption across all production activities. Although most CF studies overlook the CF associated with human labor, it remains an integral component. Some researchers have attempted to calculate human labor in carbon flow studies on farmland, focusing solely on CO_2 exhalation without accounting for the energy consumption from food intake, which deviates from LCA principles. Following Liu [39], this study adopts a more comprehensive approach, using food intake as the basis for CF calculations, with an emission factor for human labor set at 0.86 kg CO_2/person/day.

2.5. Life Cycle Impact Assessment

Life cycle impact assessment is based on internationally recognized standards [19,20]. The impact assessment is limited to applying GWP to the three primary GHG emissions, CO_2, CH_4, and N_2O, as this study evaluates only GHG emissions. GWPs are based on the 100-year time horizon from IPCC's Fourth Assessment Report and equate to 25 for CH_4 and 298 for N_2O (Table S7). The main processes quantified are substrates, fertilizers, and chemicals used; GHGs emitted during the production of consumables; GHGs generated in the transportation of these items to the nursery; N_2O emissions to the soil from fertilization activities were also assessed.

2.6. Life Cycle Interpretation

The first step involves using the model described in Text S2 to analyze the life cycle inventory and impact assessment to identify the primary sources of greenhouse gas emissions or energy-intensive activities. This is followed by conducting sensitivity analyses, focusing on the following aspects: (1) sensitivity of activities, (2) sensitivity analysis of emission sources, and (3) sensitivity analysis of seedling production. These analyses aim to assess the impact of variations in key activities or emission sources on total emissions, thereby ensuring the robustness of the conclusions. Finally, based on the identified emission sources, emission activities, and LCIA results, this study's key findings are documented, and specific recommendations are proposed to promote green and low-carbon practices in MP seedling production. Due to the lack of domestic emission factors for producing non-woven bags, plastic films, and other consumables, we use the correlation coefficients in Ecoinvent 3.0 [32] as a substitute, and we expect that subsequent research will solve this problem.

3. Results

3.1. Life Cycle Emission Inventory

The input results for nursery production operations are presented in Table 1, which details the total annual demand of the nursery and the specific demand per 4 × 8 cm MP container seedling; transportation-related inputs, including diesel fuel consumption and freight units measured in ton-kilometers (t-km), are reported in Table 2; the use of fuel volume and t-km units aligns with supplier-provided data, enabling either direct fuel calculation or estimation based on the transport distances of the goods. Table 1 also presents the GHG emission results corresponding to each input of the production system, with emissions reported for a one-year production output of 16,000,000 (363.220 EQU) 4 × 8 cm seedlings. The total annual GHG emissions are calculated at 37.096 tons of CO_2 equivalent, indicating that the production of each EQU of seedlings results in an emission of 0.873 $kgCO_2eq$, similar to the CF results for landscape seedling production in California, USA (0.83 kg CO_2 eq per EQU) [5].

Table 1. Total GHG emission for #4 × 8 cm seedlings.

Category	Inputs Item	GHG Emissions/Nursery/Year (kg CO_2eq)	GHG Emissions/FU/Year (kg CO_2eq)	GHG Emissions/EQU/Year (kg CO_2eq)	% of Total
Energy use on site	Electricity	7277.060	9.10×10^{-3}	3.43×10^{-1}	19.65
	Diesel for transportation	1027.900	1.28×10^{-3}	4.82×10^{-2}	2.76
	Labor	1243.560	1.55×10^{-3}	5.84×10^{-2}	3.35
Fertilizer	Compound fertilizer	6422.000	8.02×10^{-3}	3.02×10^{-1}	17.30
	Urea	413.000	5.16×10^{-4}	1.94×10^{-2}	1.11
	Phosphate fertilizer and Potash fertilizer	1716.000	2.14×10^{-3}	8.06×10^{-2}	4.62
	Potassium dihydrogen phosphate	1067.040	1.33×10^{-3}	5.01×10^{-2}	2.87
Materials	Sunshade net	654.000	8.18×10^{-4}	3.08×10^{-2}	1.76
	Weed control film	80.580	1.01×10^{-4}	3.80×10^{-3}	0.22
	Plastic film	2014.70	2.52×10^{-3}	9.49×10^{-2}	5.44
	Iron wire	1014.540	1.27×10^{-3}	4.78×10^{-2}	2.74
	Non-woven fabric container	1726.640	2.16×10^{-3}	8.14×10^{-2}	4.66
	woven bags	4000.50	5.00×10^{-3}	1.88×10^{-1}	10.77
	Water	632.660	7.90×10^{-4}	2.98×10^{-2}	1.71
Chemical	Carbendazim	100.480	1.26×10^{-4}	4.75×10^{-3}	0.27
	Potassium Permanganate	935.660	1.17×10^{-3}	4.41×10^{-2}	2.53
	Quicklime	492.060	6.16×10^{-4}	2.32×10^{-2}	1.33
Potting mix	Peat soil	1152.000	1.44×10^{-3}	5.42×10^{-2}	3.11
Transportation	Transportation	1802.240	2.26×10^{-3}	8.51×10^{-2}	4.88
N_2O from fertilizer		3324.012	4.16×10^{-3}	1.56×10^{-1}	8.94
Total		37,096.632	4.64×10^{-2}	1.746	100

FU, Function Unit: a 4 × 8 cm MP seeding; EQU, Equivalent Unit = 1 gallon seeding.

Table 2. GHG emissions for transportation.

Item	Weight (kg)	Vehicle Type	Fuel Factor * ($kgCO_2$ t km^{-1})	GHG Emissions (kg CO_2 eq)
Carbendazim	3.200	8 t truck	0.129	0.091
Coir	12,040	20 t truck	0.078	341.695
Compound fertilizer	1300	20 t truck	0.078	26.497
Iron wire	247.450	8 t truck	0.129	1.107
Masson pine cones	1240	1 t truck	0.286	0.400
Non-woven fabric container	226	8 t truck	0.129	1.011
Peat soil	16,000	20 t truck	0.129	454.080
Phosphate fertilizer and potash fertilizer	1300	20 t truck	0.078	26.497
Plastic film	404.560	8 t truck	0.129	1.810
Potassium dihydrogen phosphate	216	20 t truck	0.078	4.403
Potassium permanganate	400	8 t truck	0.129	11.313
Quicklime	216.580	8 t truck	0.129	6.125
Rice shells	512	8 t truck	0.129	2.291
Sunshade net	100	8 t truck	0.129	0.448
Urea	216	20 t truck	0.078	4.403
Woven bags	571.500	8 t truck	0.129	2.558
Weed control film	12.320	8 t truck	0.129	0.055

* Diesel vehicle emission factors sourced from the "China Transportation Yearbook 2008".

The primary energy inputs consist mainly of electricity for irrigation, which accounts for 73.83% of the total energy usage. Diesel consumption for labor and freight transportation contributes 14.33% and 11.84% of the energy use, respectively (Figure 3c). Direct energy use within the nursery, including on-site fuel and electricity consumption, is the largest source of emissions, comprising nearly 21% of total CO_2eq emissions. Electricity for irrigation is the second-most contributor in this category, highlighting that enhancing power generation efficiency, optimizing water usage, and advancing irrigation technology could effectively reduce GHG emissions in nursery operations (Figure 3c).

Chemical fertilizers are the largest contributor to CO_2eq emissions, accounting for 35.59% of the total emissions. Among these, compound fertilizers have the highest impact, contributing 49.62% of fertilizer emissions, followed by N_2O emission from fertilizers (25.68%), potash fertilizer, and potassium dihydrogen phosphate at 13.26% and 8.24%, respectively (Figure 3b). Notably, CO_2 emissions from woven bags exceed those from transportation and non-woven fabric container use (Figure 3a,e). Material transportation contributes 5.34% of the total GHG emissions, with the transportation of coir and peat soil from Nanning being the largest single source (Figure 3a,f).

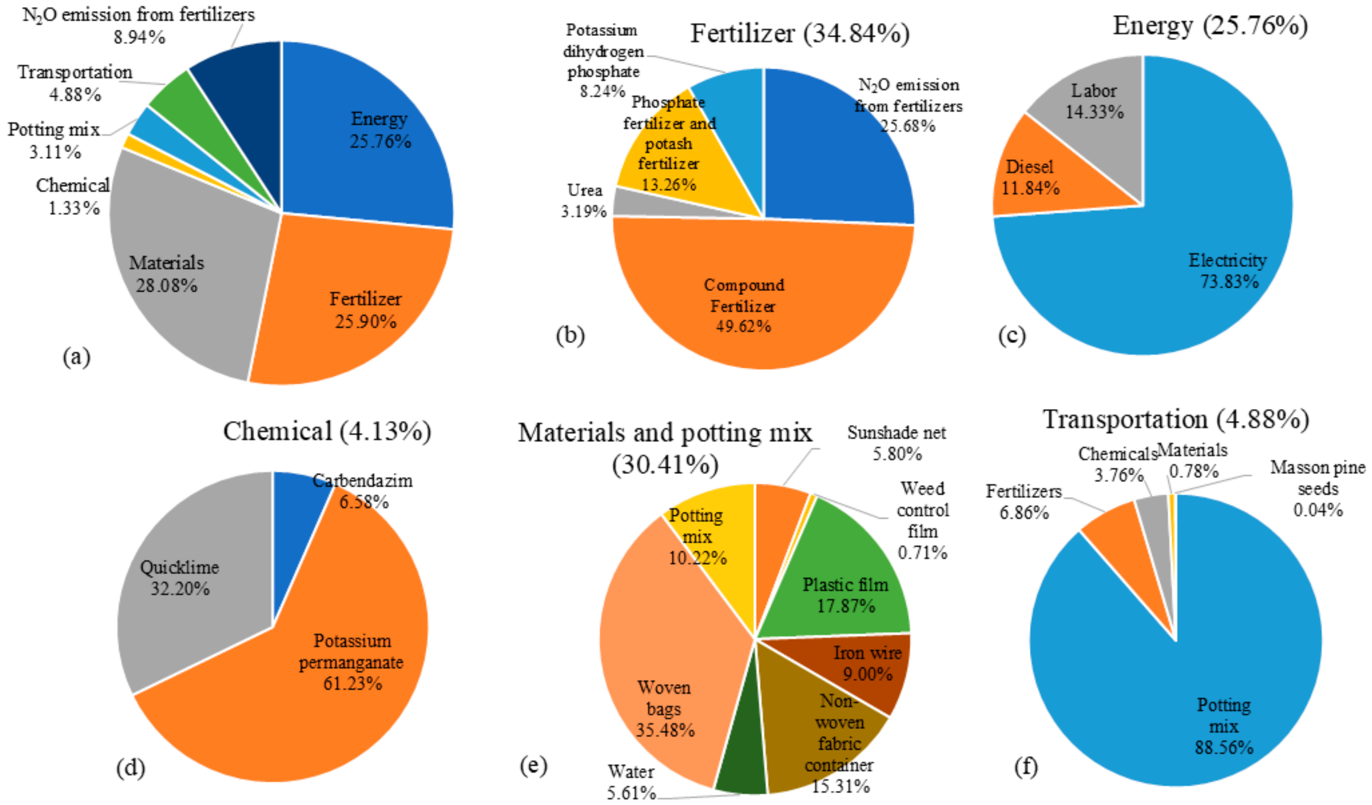

Figure 3. Breakdown of emission sources associated with fertilizer, energy, chemical, material, and transportation. (**a**) Composition of emission sources, (**b**) Fertilizer contribution, (**c**) Energy-related emission, (**d**) Chemical emission, (**e**) Material emission, (**f**) Transportation emission.

3.2. Activity Footprint

An MP seedling emits 0.0232 kg CO_2eq over a six-month growth cycle, including emissions from the nursery bed phase (0.005 kg CO_2eq) and the field phase (0.027 kg CO_2eq). Emissions during the field phase are approximately five times higher than those during the nursery bed phase (Figure 4a, Table S8). Further analysis reveals that carbon-generating activities (fertilization, watering) are concentrated in the field stage; providing direction for green emission reduction. The preparation of substrate cups is the largest source of GHG emissions in the nursery bed phase, contributing 60.33% of its total emissions; specifically, substrate cups, peat soil, labor, and electricity usage contribute 22.10%, 18.81%, and 12% of the nursery bed phase emissions, respectively. Furthermore, the carbon emissions from constructing shade nets using barbed wire and installing cold protection films account for 5.22% and 6.32% of the total carbon emissions, respectively (Figure 4b, Table S8). Water and fertilizer management are the largest contributors to GHG emissions during the field phase, accounting for 77.07%; irrigation electricity, input materials, and chemical fertilizer emissions constitute 28.41%, 21.89%, and 47.09% of field phase emissions, respectively; these factors are the primary contributors to the total emission of input materials. Labor associated with grading and fielding contributes relatively minor amounts, equivalent to 0.40% and 0.85% of field phase emissions, respectively (Figure 4c, Table S8).

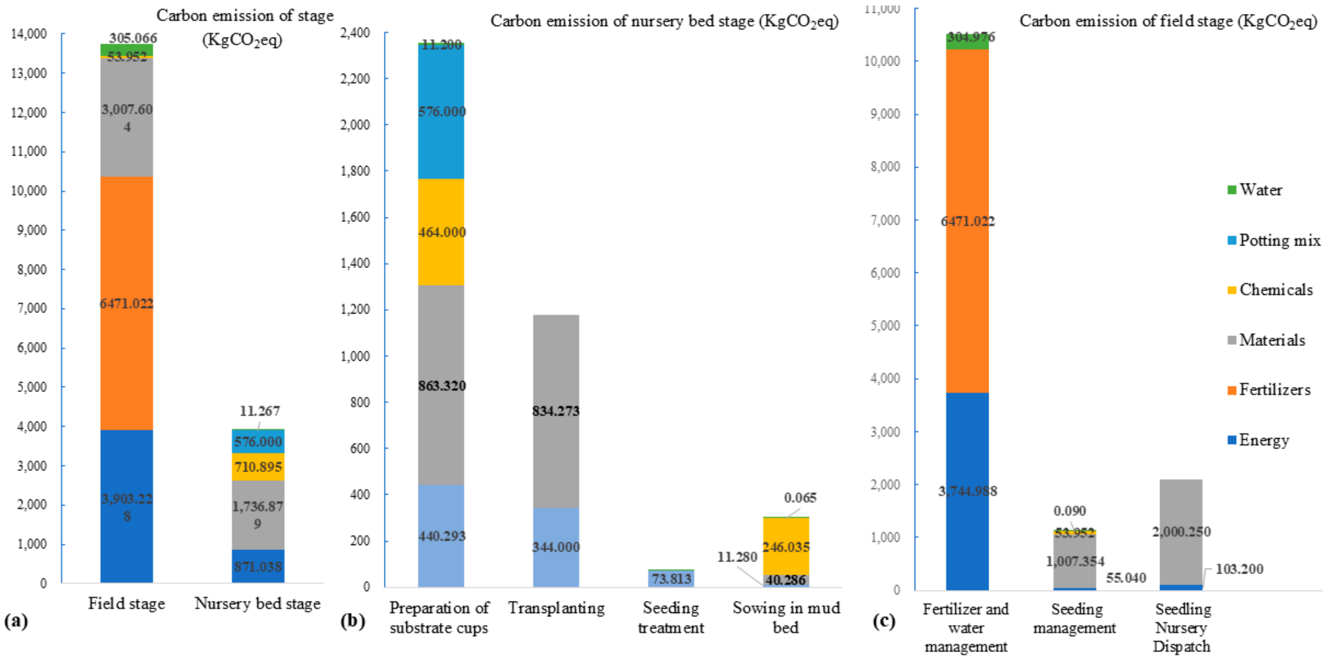

Figure 4. Contribution of each operation of the MP seedling process to the life cycle GHG emissions. Each color in the bar chart represents the distribution of carbon emissions among different emission sources for specific nursery activities or stages: green represents water, blue represents substrate, yellow represents pesticides, gray represents consumables, orange represents chemical fertilizers, and light blue represents energy. (**a**) Field cultivation and seedbed stage, (**b**) Potting mix preparation, transplanting, and sowing, (**c**) Fertilizer and water management, pest and disease control, and seeding dispatch.

3.3. Life Cycle Impact Assessment

The life cycle impact assessment indicates that water and fertilizer management activities have a significant impact on greenhouse gas (GHG) emissions. Using chemical fertilizers is the largest contributor, accounting for 26.50% of the total GHG emissions. This is due to emissions generated during the production and transportation of fertilizers, as well as indirect emissions of N_2O from soil following fertilizer application, which represent approximately 8.94% of total GHG emissions. Another major source of emissions is the irrigation system, also contributing 26.50% of the total GHG emissions.

3.4. Life Cycle Interpretation

The sensitivity analysis of the system's activities and inputs shows that chemical fertilizers have the highest sensitivity at 26%, followed by electricity at 19% and woven bags at 12% (Figure 5b,c; Tables S9–S11). Effective strategies for reducing carbon emissions in the system include optimizing irrigation methods, reducing the use of chemical fertilizers, and increasing the adoption of environmentally friendly materials. The water and fertilizer management phase exhibits significantly higher sensitivity than other activities, making it a key priority for improvements to promote greener MP production (Figure 5a). Meanwhile, based on these findings, specific recommendations were proposed to promote greener and low-carbon practices in MP seedling production; these included optimizing irrigation methods, reducing reliance on chemical fertilizers, and increasing the use of environmentally friendly materials.

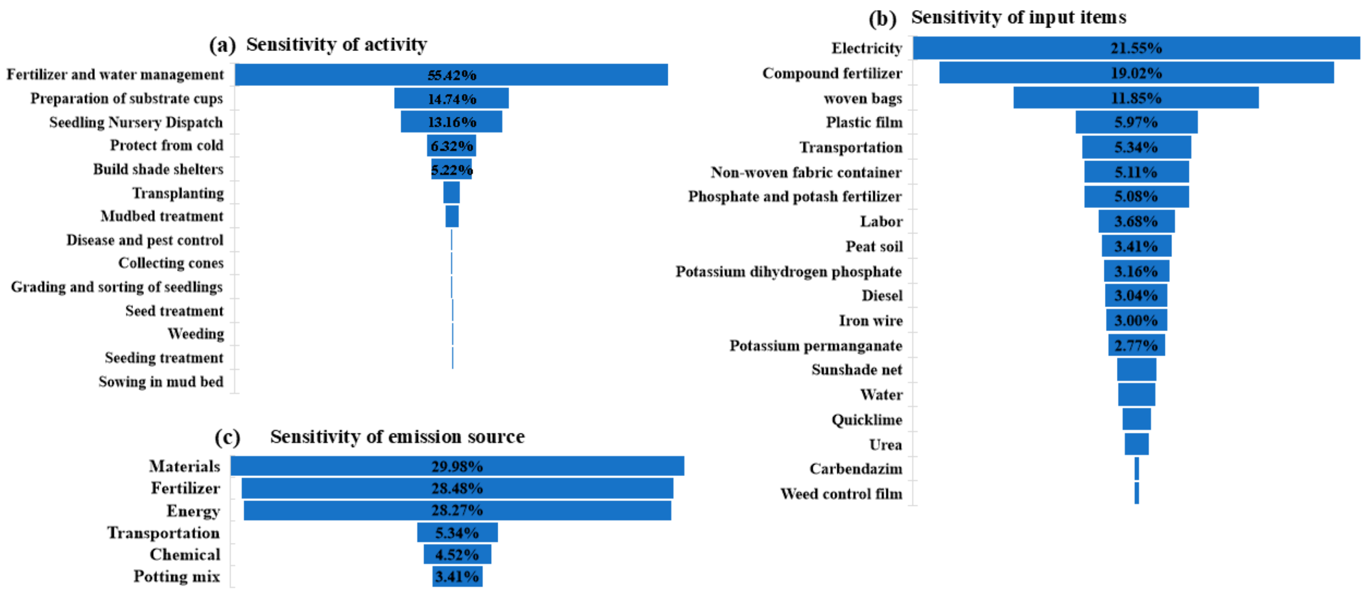

Figure 5. Sensitivity analysis results. (**a**) Activity sensitivities analysis, (**b**) Input sensitivity analysis, (**c**) Emission source sensitivity analysis.

4. Discussion

4.1. Comparison of GHG Emissions

This study examines the environmental impacts of MP seedling production by assessing the GHG emissions associated with producing various woody plant seedlings, such as ornamental trees, white spruce, green ash, caragana, Scots pine, olive trees, and oil palm; the assessments are tailored to the specific production systems for each type of seedling (see details in Table S12). The GHG emissions associated with MP seedling production are calculated at 0.0232 kg CO_2eq per 4 × 8 cm seedling, with each EQU seedling generating 0.873 kg CO_2eq; similar studies in other countries have reported varying emission levels for different types of seedling production. For example, Kendall and McPherson investigated GHG emissions from landscape tree production in California, USA, finding emissions of 0.830 kg CO_2eq per EQU [5], slightly lower than our study. Rudd et al. [40] found the CF of protective forest seedling production emissions was 2.200 kg CO_2eq per seedling, due to the significant energy required during cultivation to withstand winter conditions.

Aldentun's study showed that emission levels vary considerably by geographic location and plant species [41]. For example, forest nurseries in Sweden reported that carbon emissions from Scots pine and Norway spruce seedlings ranged from 0.025 to 0.133 kg, depending on latitude. Meanwhile, red maple seedling production in the Mid-Atlantic coastal region of the United States emits 0.142 kg CO_2eq [6], highlighting the significant impact of energy use on emissions from seedling production. The differences in GHG emissions of different plant species emphasize the influence of season, location, and production methods on the CF of large-scale seedling cultivation.

4.2. Emission Source

Table S13 compares the GHG emission source from seedling production systems in previous studies and this study. Our study indicates that chemical fertilizers are the largest source of emissions, accounting for 35.59% of total emissions from production and use, which aligns with the Meng et al. [3] and Aldentun [41] studies. Additionally, electricity used for irrigation dominates energy consumption, making up 73.83% of energy use and contributing nearly 21% to total CO_2eq emissions. The emissions from woven bags used for packaging exceed those from transportation and containers, with material transportation—

particularly of coconut coir and peat moss—accounting for 5.34% of total emissions. This is likely due to the widespread use of chemical fertilizers in the country. In comparison, Kendell et al.'s [5] study on the CF of urban greening tree species in the United States showed that energy use accounted for 44%, followed by materials at 25.10%, fertilizers at 15.00%, and transportation at 16%; this is due to the large nursery substrate and plastic containers used in the nursery process.

Fertilizer use is the main source of the CF of nursery production, with fertilizer production and transport accounting for 42.82% of total emissions, significantly higher than other inputs. Green compost from urban landscaping and pruning waste instead of chemical fertilizers can reduce these emissions [42,43]. Although peat is a common component of nursery substrates, its extraction and transport can also have considerable environmental impacts [44]. Effective strategies to reduce carbon emissions include optimizing transportation routes, reducing the transport distance for fertilizers and substrates, and utilizing biodiesel or electric-powered vehicles for transportation.

Energy consumption is the second largest source of carbon emissions during seedling growth, with electricity consumption (especially for irrigation) accounting for 97% of the total energy consumption. In most nurseries, electricity for irrigation is the dominant energy use [45]. Exploring sustainable measures for clean energy alternatives is important to reduce carbon emissions from electricity consumption, and photovoltaic-powered irrigation units can reduce the CF of energy.

Production and transport of materials (especially peat) are also important sources of CO_2 equivalent emissions; long-distance transport of fertilizers (6.86%) and substrates (88.56%) were considered to be the main sources of emissions; reducing transportation distances for these heavily used substrates and materials is considered the most effective strategy for decreasing carbon emissions, such as choosing closer suppliers or using rail transportation.

Emissions from plastic consumables and pesticides are relatively minor, accounting for just 6% of Scots pine seedling production emissions. Previous studies [46–48] suggest that chemicals contribute less to overall GHG emissions, but may have more significant impacts on other environmental factors, such as eutrophication potential, acidification potential, and human toxicity potential.

4.3. Activity Carbon Footprint

A comparison of our findings with previous studies on emissions in seedling production (see details in Table S14) reveals that the stages involving water and fertilizer management are the primary contributors to GHG emissions, accounting for 56.69% of the total. Despite the relatively short duration of the seeding dispatch stage, it still contributes 11.33% to the total emissions; in contrast, the nursery bed stage contributes 21.06% to the overall CF. In Italy's Pistoya nursery industry, container planting shows a different emission pattern, with management inputs—including water, fertilizers, and pesticides—having the most significant environmental impact, contributing 93.31% of emissions. Emissions from soil and above-ground structures follow, contributing 1.89% and 3.04%, respectively [48]. The nursery bed stage, which mainly involves seed collection, treatment, and sowing, has minimal emissions, ranging from 0.07% to 0.79%, especially due to the high level of manual labor and low energy consumption in these processes; in contrast, the seedling transport to retailer stage accounts for 13.32%, primarily due to the extensive use of polypropylene woven bags for packaging during transportation. Switching to biodegradable or reusable materials could significantly reduce the CF at this stage. The research conducted by Chen et al. [49] indicates that the use of biodegradable plastics can reduce the CF by 13.53%–62.19% compared to traditional plastics.

Transplanting and substrate cup preparation contribute 9.70% and 12.64% of total emissions, respectively. Transplanting involves labor, non-woven fabric containers, and shade nets, all essential for MP seedling production. Research on rice cultivation in Malaysia indicates that transplanting contributes over 23.11% to the environmental impact [50]. Moreover, modern seedling transplantation machinery can be up to 50 times more efficient than manual methods, significantly reducing CFs and costs [51].

The transport of coir and peat as substrates for nurseries and the extensive use of potassium permanganate in substrate soaking generate GHG emissions, and the use of locally available biomass fertilizers, such as those made from tree bark and fermented sugarcane residues, as an alternative substrate, reduces emissions associated with production and transport, while also making efficient use of wood residues.

The sources of GHG emissions at the nursery management stage are mainly due to fertilizer use and pest control, with compost accounting for nearly 30% of the total CF; there is an urgent need to replace compound fertilizers with green compost or biomass fertilizers. In addition, using fungal agents to control pests and diseases can further reduce carbon emissions [52]; using bamboo instead of wire to construct winter film also helps reduce the CF in nursery management.

This study comprehensively assesses the differences in GHG emissions at different stages of MP nursery production and develops targeted reduction strategies. By identifying the most important emission factors, companies and individuals can cooperate to take nursery production systems in a low-carbon and more sustainable direction. This research is dedicated to promoting the economic and environmental sustainability of nursery production systems to ensure the long-term sustainability of forestry.

4.4. Life Cycle Impact Assessment

The results of the life cycle impact assessment highlight water and fertilizer management as the primary drivers of GHG emissions in MP seedling production (See details in Table S8). The significant role of chemical fertilizers in contributing to emissions aligns with similar studies in agricultural systems, where fertilizer production and use often dominate GHG emissions [53]. Specifically, emissions from fertilizer production, transport, and the release of N_2O into the soil following application represent a substantial portion of total emissions. The N_2O emission, in particular, is a key factor, given its high global warming potential, which underscores the need for more sustainable fertilizer practices, such as precision application and the use of slow-release or organic fertilizers [54].

The irrigation system also emerged as a major source of emissions, reflecting the energy-intensive nature of water management in nursery operations. This finding is consistent with previous studies that highlight the environmental impacts of irrigation in terms of electricity usage, which is often derived from non-renewable sources, leading to indirect emissions [55].

4.5. Life Cycle Interpretation

Life cycle interpretation shows that water and fertilizer management activities have a critical impact on overall greenhouse gas (GHG) emissions, as evidenced by sensitivity analyses (See details in Tables S9–S11). Changes in these areas have a significant impact on total emissions, highlighting them as key levers for reducing emissions. We have therefore developed a range of targeted strategies to optimize these processes and mitigate their environmental impact.

(1) Adjusting water and nutrient management to determine the exact needs of seedlings at each growth stage to avoid overwatering and improper fertilization, and improve nutrient use efficiency. In addition, sustainable development can be achieved through

alternative fertilizers, such as organic fertilizer substitution and solar-powered irrigation systems [46].

(2) Reducing or replacing peat and coir substrates: Replacing them with agroforestry wastes such as bark and bagasse can reduce emissions to a large extent. Choosing fertilizers from nearby production sites can minimize the energy required for transportation. Additionally, utilizing new energy vehicles for transport can lower the CF generated during transit.

(3) Transitioning to clean energy sources: Shifting from fossil fuels to clean energy sources is crucial for achieving low-carbon energy goals; traditional fossil fuels like coal and petroleum, widely used in conventional agricultural practices, emit substantial amounts of carbon dioxide, contributing to environmental pollution and climate change. By adopting clean energy sources such as solar, wind, and hydroelectric power, GHG emissions can be significantly reduced, environmental impacts can be minimized, and the sustainable development of agricultural production is promoted [56].

(4) Promoting energy-efficient transportation: Encouraging new energy-powered transportation methods is highly effective in reducing the CF of the transport process. Developing new fuel technologies is essential for achieving low-carbon emissions in the transportation sector. The adoption of electric and fuel-cell vehicles is gradually increasing in road transport, with fuel-cell vehicles expected to become a key solution for heavy-duty trucks and large buses [57].

5. Conclusions

This study employs the life cycle assessment (LCA) method to evaluate the production of MP seedlings from an environmental perspective. The results indicate that each 4 × 8 cm seedling emits 0.0232 kg CO_2eq, equivalent to 0.873 kg CO_2eq per gallon seeding. Key emission points include energy consumption, chemical fertilizer production and N_2O emissions generated after application, and woven bag use in seedling dispatch, contributing 25.76%, 34.84%, and 10.77% of total emissions, respectively. Using this production estimate and the CF of seedlings calculated in this study (0.0232 kg CO_2eq per seedling), the total annual emissions from MP production would amount to approximately 10.6 million metric tons of CO_2. Based on this study's calculations, MP seeding production life cycle carbon emissions represented approximately 0.066% of the total CO_2 emissions generated by China. Sweden alone produces about 40 million seedlings per year, and in the United States, leading companies such as ArborGen (SC) and Weyerhaeuser (WC) produce tens of millions of pine seedlings annually, primarily for the southern United States and international markets. The results of this study will provide a reliable CF report for many international companies and governments. Comparing these environmental findings with Kendell [5], Lazzerini [4], and Ingram [6], it can be determined that fertilizers, electricity, and woven bags are the largest contributors to the CF of seedling production. These conclusions directly guide China's future policies targeting low-carbon technologies to enhance environmental efficiency in agriculture and forestry. Measures to effectively reduce the CF of seedling production include optimizing fossil fuel use and fertilizer application during harvesting activities, using formulated fertilizers based on soil testing, and incorporating biological control as part of integrated pest management. These improvements bring significant viability while unlocking the transformative potential to optimize the production of MP as a scalable and sustainable model for scaling up low-carbon forestry practices globally. Although this study conducted a CF study on the seedling production process of MP, seedling production only accounts for a small part of the forestry activity, and further studies should be carried out to indicate the CF of MP's whole life cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16010140/s1, Text S1: Detailed methodology for seedling production stages, including seed collection, substrate preparation, transplanting, and delivery; Text S2: Life cycle model description, including emissions from energy, materials, chemicals, fertilizers, and transportation; Table S1: Data classification for life cycle assessment (LCA); Table S2: Data categories and sources for LCA of Masson pine seedling production; Table S3: Common container specifications and applicable ranges for Masson pine container seedling cultivation; Table S4: Greenhouse gas (CO_2eq) emission factors of inputs; Table S5: Annual input and transportation requirements for nursery operations; Table S6: Distance and fuel consumption for transportation of materials in seedling production; Table S7: Global warming potential values of greenhouse gases; Table S8: Summary of life cycle carbon emissions for Masson pine seedling production; Table S9: Carbon footprint sensitivity analysis of input items in seedling production; Table S10: Carbon footprint sensitivity analysis of activities in seedling production; Table S11: Carbon footprint sensitivity analysis of emission sources in seedling production; Table S12: Comparative emissions from seedling production across different species and systems; Table S13: Emission sources in seedling production for various studies; Table S14: Activity footprints in emissions from seedling production across studies.

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Glossary

GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory
GWP	Global warming potential

Abbreviations

MP	Masson pine
CPCD	China Product Carbon Footprint Database
CF	Carbon footprint
CHRED	China High-Resolution Emissions Database

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